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RPPR Final Report
as of 18-Sep-2023

Agency Code: 21XD

Proposal Number: 73234PE

Agreement Number: W911NF-18-1-0272

INVESTIGATOR(S):

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Report Date: 17-Sep-2023

Date Received: 17-Sep-2023

Final Report for Period Beginning 22-Jun-2018 and Ending 17-Jun-2023

Title: Towards Uncooled Thermal Imaging Focal Plane Devices with NETD near 1mK

Begin Performance Period: 22-Jun-2018

End Performance Period: 17-Jun-2023

Report Term: 0-Other

Submitted By: Joseph Talghader

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 4

STEM Participants: 5

Major Goals: The major goals of the program, slightly modified from the text used in the original proposal, are:

- 1) Develop a theory of optomechanical infrared detection in the presence of thermomechanical noise including the frequency, temperature, and Q dependence of that noise.
- 2) Develop a theory of operation and performance for near-1mK thermal detectors. This will include an analysis of mechanics, noise, laser readout, and bimorph transduction.
- 3) Construct and demonstrate high sensitivity single pixels that will have an uncooled NETD near 1mK for light in the long-wave infrared.

Accomplishments: See Detailed Final Report Uploaded

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Training Opportunities:

In the first year, two primary graduate students were trained. They were: Eric Konitzer (US citizen) and Avijit Das (Bangladesh citizen). Eric Konitzer graduated in May 2019 and then worked at the Johns Hopkins Applied Physics Laboratory on DoD work. Eric's work consisted of both theoretical and experimental parts, primarily involving buckling microstructures that could be applied to high sensitivity infrared detectors. Avijit Das was a second year graduate student and continued work on the project to his PhD in the final year of the program. IN the first year of the program, his contributions involved theoretical analysis of a number of resonant cavity transducer thermal detectors. In addition, a Senior Honors, undergraduate student, Marley Stephens (US citizen), participated in the project, learning both microfabrication and modeling and presenting his work at multiple Senior Honors presentations.

In the second year, COVID hit, and the program was shut down temporarily. In years 2 and 3 of the program, student Avijit Das left the university temporarily to see his father, who tragically passed away due to COVID, and then to work at Seagate Technologies. Yu-Jen Lee (Taiwan citizen), contributed substantially to the program during this time. He developed LWIR diamond-based microresonators with a concept of eventually using them in LWIR detectors. Two publications resulted from Yu-Jen's work this year and helped him complete the final months of his PhD program. Upon Avijit's return, he helped make a major advance in our understanding of absorption in high sensitivity thermal detectors. Specifically, we were able design absorption structures with gaps or open holes within them, while still maintaining high absorption. Finally, another graduate student, John Hunt, investigated amplifying passive LWIR signals using multi-resonant metastructures to create sub-1mK detectors. A small part of his support will come from this program.

In Years 4 and 5, the primary graduate student trained on the project was Avijit Das. He completed his PhD in January of 2023, and published multiple papers in his final two years. We gratefully thank the ARO for Add-On funding that allowed Avi to complete his degree and this project. Avi is now an engineer at Intel in Oregon.

Thesis Citation:

Avijit Das, "High Absorption per unit Thermal Mass Subwavelength Perforated Membrane as Uncooled Thermal Infrared Detector," Doctoral Dissertation, University of Minnesota, January 26, 2023.

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Results Dissemination:

Y.-J. Lee, A. Das, and J. J. Talghader, "Long-Wave Infrared Diamond Microdisk High-Q Resonator," Symposium Latsis 2019 on Diamond Photonics, Lausanne, May 19-22, 2019, pp. 21-22.

Prof. Talghader also gave a presentation for the Raytheon uncooled detector group.

J. Talghader, "Future Directions for Uncooled Infrared Detectors," Raytheon Vision Systems, Goleta, CA, November 9, 2018.

Editor's Choice Paper:

Y. Lee, A. Das, and J. Talghader, "High-Q diamond microresonators in the long-wave infrared," Optics Express, vol. 28, pp. 5448-5458, 2020.

Y.-J. Lee, A. Das, M. L. Mah, J. J. Talghader, "Long-wave infrared absorption measurement of undoped germanium using photothermal common-path interferometry" Applied Optics, vol. 59, no. 11, pp. 3494-3497, 2020.

Among JOSA B Most Downloaded Papers

A. Das and J. J. Talghader, "Enhanced absorption per unit mass for infrared arrays using subwavelength metal-dielectric structures," Journal of the Optical Society of America B, vol. 38, no. 1, pp. 183-193, January 2021.

Invited Webinar J. J. Talghader, "Fundamental properties and real-world breakdown of low absorption thin films from the visible to infrared," OSA Thin Film Technical Group, 12 October, 2021.

https://www.optica.org/en-us/meetings/webinar/2021/10_october/fundamental_properties_and_real-world_breakdown_of/

A. Das, M. L. Mah, J. Hunt, and J. J. Talghader, "Thermodynamically limited uncooled infrared detector using an ultra-low mass perforated subwavelength absorber," Optica, vol. 10, no. 8, pp. 1018-1028, August 2023. doi.org/10.1364/OPTICA.489761

A. Das, M. Mah, and J. Talghader, "Design and Fabrication of a Subwavelength Perforated Infrared Absorber with Reduced Thermal Mass," IEEE Photonics Conference, Vancouver, BC, 13-17 November 2022, doi: 10.1109/IPC53466.2022.9975511

A. Das, M. L. Mah, and J. J. Talghader, "High Absorption per Unit Mass Subwavelength Structure as Uncooled Infrared Detector," IEEE Optical MEMS and Nanophotonics, Campinas, Brazil, July 31-August 4, 2023, 2 pages.

In addition there were 3 theses or reports that either focused primarily on the work of this project (Avijit Das, PhD dissertation and Eric Konitzer, MSEE report) or secondarily (Yu-Jen Lee, PhD dissertation) with partial overlap with the work of this program.

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Honors and Awards: J. Talghader was elevated to Optica Fellow (Optical Society of America Fellow), Citation: "For advances in high optical power thin film physics and thermal infrared coating design"

J. Talghader was awarded a Fulbright Futures award for a program in Australia for 2023-2024 at the University of Western Australia in Perth for the high absorption per unit mass materials that were developed in this program.

A. Das was awarded his PhD at the University of Minnesota on January 26, 2023 for his research related to this program.

Our 2021 paper, "Enhanced absorption per unit mass for infrared arrays using subwavelength metal-dielectric structures" by Avijit Das and Joseph J. Talghader J. Opt. Soc. Am. B 38(1) 183-193 (2021) was listed as a JOSA B Top Downloaded Paper in a February 2021 email and other later emails from the JOSA B Editor-in-Chief, Kurt Busch.

Our 2020 paper, received an Editor's Choice citation: Y. Lee, A. Das, and J. Talghader, "High-Q diamond microresonators in the long-wave infrared," Optics Express, vol. 28, pp. 5448-5458, 2020.

Yu-Jen Lee, a graduate student supported by the program, received his PhD Degree from the University of Minnesota in Electrical and Computer Engineering in February 2020. His thesis was entitled, "Spectrally Dependent Radiation Noise in Thermal Emission and Long-Wave Infrared High-Q Diamond Microdisks."

Eric Konitzer, a graduate student supported by the program, received his Master's Degree from the University of Minnesota in Electrical and Computer Engineering in May 2019.

Protocol Activity Status:

Technology Transfer:

Prof Talghader visited Raytheon in this program period (November 2018) to discuss new materials that can reduce $1/f$ noise and overcome thermal/electrical conductivity limitations given by the Wiedemann-Franz Law for common metals. Prof. Talghader gave a talk that covered much of the work of the current program, entitled, "Future Directions for Uncooled Infrared Detectors" to the uncooled infrared group at Raytheon.

We are currently in discussion with Tania Paskova and Dennis Waldron

Uncooled Thermal Sensing Special Projects Office
Chief, IR Camera Technologies Branch
US Army C5ISR Center, RTI, EO Components Division
about a possible program to examine the issues of applying some of the technology developed in this program to practical uncooled arrays.

We are also currently in discussion with Raytheon to assess a collaboration based on the concepts developed in this program.

PARTICIPANTS:

Participant Type: PD/PI

Participant: Joseph John Talghader

Person Months Worked: 5.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Eric Konitzer

Person Months Worked: 8.00

Project Contribution:

National Academy Member: N

Funding Support:

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Participant Type: Graduate Student (research assistant)

Participant: Yu-Jen Lee

Person Months Worked: 7.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: John Hunt

Person Months Worked: 3.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: Avijit Das

Person Months Worked: 15.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Undergraduate Student

Participant: Marley Stephens

Person Months Worked: 7.00

Funding Support:

Project Contribution:

National Academy Member: N

ARTICLES:

RPPR Final Report as of 18-Sep-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Optics Express

Publication Identifier Type: DOI

Publication Identifier: 10.1364/OE.387255

Volume: 28

Issue: 4

First Page #: 5448

Date Submitted: 9/13/20 12:00AM

Date Published: 2/1/20 12:00PM

Publication Location:

Article Title: High-Q diamond microresonators in the long-wave infrared

Authors: Yu-Jen Lee, Avijit Das, Joseph J. Talghader

Keywords: infrared, microresonator, quality factor

Abstract: High quality factor (Q) photonic devices in the room temperature thermal infrared region, corresponding to deeper long-wave infrared with wavelengths beyond 9 microns, have been demonstrated for the first time. Whispering gallery mode diamond microresonators were fabricated using single crystal diamond substrates and oxygen-based inductively coupled plasma (ICP) reactive ion etching (RIE) at high angles. The spectral characteristics of the devices were probed at room temperature using a tunable quantum cascade laser that was free space-coupled into the resonators. Light was extracted via an arsenic selenide (As₂Se₃) chalcogenide infrared fiber and directed to a cryogenically cooled mercury cadmium telluride (HgCdTe) detector. The quality factors were tested in multiple microresonators across a wide spectral range from 9 to 9.7 microns with similar performance. One example resonance (of many comparables) was found to reach 3648 at 9.601 μ m. Fourier analysis of the many resonances of ea

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Applied Optics

Publication Identifier Type: DOI

Publication Identifier: 10.1364/AO.390374

Volume: 59

Issue: 11

First Page #: 3494

Date Submitted: 9/13/20 12:00AM

Date Published: 4/1/20 5:00AM

Publication Location:

Article Title: Long-wave infrared absorption measurement of undoped germanium using photothermal common-path interferometry

Authors: Yu-Jen Lee, Avijit Das, Merlin L. Mah, Joseph J. Talghader

Keywords: germanium, infrared, absorption

Abstract: Germanium is one of the most commonly used materials in the longwave infrared (8-12 microns), but ironically, its absorption coefficient is poorly known in this range. An infrared photothermal common-path interferometry system with a tunable quantum cascade pump laser is used to measure the absorption coefficient of >99.999% pure undoped germanium as a function of wavelengths between 9 and 11 microns, varying between about 0.15 and 0.45 cm⁻¹ over this range.

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Journal of the Optical Society of America B

Publication Identifier Type: DOI

Publication Identifier: 10.1364/JOSAB.410656

Volume: 38

Issue: 1

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Date Submitted: 8/30/21 12:00AM

Date Published: 12/1/20 6:00AM

Publication Location:

Article Title: Enhanced absorption per unit mass for infrared arrays using subwavelength metal–dielectric structures

Authors: Avijit Das, Joseph J. Talghader

Keywords: infrared, metastructure, absorption, mass, thermal emission, detector

Abstract: The absorption-to-mass ratio of the infrared arrays is enhanced to ~ 1.33 – 7.33 times larger than the previously reported structures by incorporating two design characteristics: first, the coupling of evanescent fields in the air gaps around pixels to create effectively larger pixel sizes, and, second, the use of guided mode resonance (GMR) within the subwavelength metal-dielectric gratings. The bilayer Ti-Si₃N₄ gratings achieve broadband long-wave infrared (LWIR, 8 – 12 μ m) absorption by the combined effects of free carrier absorption by the thin Ti films and vibrational phonon absorption by the thick Si₃N₄ films. In the presence of GMR, this broadband absorption can be enormously enhanced even with low fill factor subwavelength grating cells. Further, the spacing and design of the cells can be modified to form a pixel array structure that couples the light falling in the air gaps via evanescent field coupling. Calculations are performed using the finite difference time domain (FD

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
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Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Optica

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Volume: 10

Issue: 8

First Page #: 1018

Date Submitted: 8/30/23 12:00AM

Date Published: 7/1/23 5:00AM

Publication Location:

Article Title: Thermodynamically limited uncooled infrared detector using an ultra-low mass perforated subwavelength absorber

Authors: Avijit Das, Merlin L. Mah, John Hunt, Joseph J. Talghader

Keywords: uncooled, infrared, detector, thermodynamic limit

Abstract: An uncooled detector has reached the thermodynamic temperature fluctuation limit, such that 98% of its total noise consisted of phonon and photon fluctuations of the detector body. The device has performed with a detectivity of 3.8×10^9 , which is the highest reported for any room temperature device operating in the long-wave infrared. The device has shown a noise-equivalent temperature difference of 4.5mK and a time constant of 7.4 ms. The detector contains a subwavelength perforated absorber with an absorption-per-unit-thermal mass per-area of 1.54×10^{22} kg⁻¹ m⁻², which is approximately 1.6–32.1 times greater than the state-of-the-art absorbers reported for any infrared application. The perforated absorber membrane is mostly open space, and the solid portion consists of Ti, SiN_x, and Ni layers with an overall fill factor of 28%, where subwavelength interference, cavity coupling, and evanescent field absorption among units induce the high absorption-per-unit-therma

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CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation

Publication Status: 1-Published

Conference Name: Diamond Photonics, Symposium Latsis on

Date Received: 24-Sep-2019

Conference Date: 19-May-2019

Date Published: 19-May-2019

Conference Location: Lausanne, Switzerland

Paper Title: Long-Wave Infrared Diamond Microdisk High-Q Resonator

Authors: Y. J. Lee, A. Das, and J. J. Talghader

Acknowledged Federal Support: Y

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Publication Type: Conference Paper or Presentation

Publication Status: 1-Published

Conference Name: IEEE Photonics Conference

Date Received: 30-Aug-2023

Conference Date: 13-Nov-2022

Date Published: 13-Nov-2022

Conference Location: Vancouver, BC

Paper Title: Design and fabrication of a subwavelength perforated infrared absorber with reduced thermal mass

Authors: Avijit Das, Merlin Mah, Joseph Talghader

Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation

Publication Status: 1-Published

Conference Name: 2023 International Conference on Optical MEMS and Nanophotonics (OMN) and SBFoton

International Optics and Photonics Conference (SBFoton IOPC)

Date Received: 17-Sep-2023

Conference Date: 31-Jul-2023

Date Published: 31-Jul-2023

Conference Location: Campinas, Brazil

Paper Title: High Absorption per Unit Mass Subwavelength Structure as Uncooled Infrared Detector

Authors: A. Das, M. L. Mah, J. J. Talghader

Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation

Institution: University of Minnesota

Date Received: 22-Sep-2020

Completion Date: 3/1/20 4:47AM

Title: Spectrally Dependent Radiation Noise in Thermal Emission and Long-Wave Infrared High-Q Diamond Microdisks

Authors: Yu-Jen Lee

Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation

Institution: University of Minnesota

Date Received: 22-Sep-2020

Completion Date: 5/31/20 10:00AM

Title: Foundational Experiments in Passive Thermal Actuation in MEMS Structures for Thermal Detector Technologies

Authors: Eric Konitzer

Acknowledged Federal Support: **N**

Publication Type: Thesis or Dissertation

Institution: University of Minnesota

Date Received: 30-Aug-2023

Completion Date: 1/27/23 3:09AM

Title: High Absorption per unit Thermal Mass Subwavelength Perforated Membrane as Uncooled Thermal Infrared Detector

Authors: Avijit Das

Acknowledged Federal Support: **Y**

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as of 18-Sep-2023

Partners

,

I certify that the information in the report is complete and accurate:

Signature: Joseph Talghader

Signature Date: 9/17/23 10:47PM

W911NF-18-1-0272

**Towards Uncooled Thermal Imaging Focal
Plane Devices with NETD near 1mK**

PI: Joseph Talghader, University of Minnesota, joey@umn.edu

Final Report

I. Executive Summary:

During the performance period of this program, our team made major advances in uncooled infrared detection. The program successfully demonstrated optomechanical thermal detectors, with application to optomechanical thermal imaging, with an NETD of 4.5mK, detectivity $D^* = 3.8 \times 10^9 \text{ cmHz}^{1/2}/\text{W}$, and NEP = 0.96 pW/Hz^{1/2}. These metrics substantially exceed the reported performance of prior art. This report proceeds chronologically with an initial analysis of optomechanical designs that were rejected due to instabilities or fabrication difficulties. It then proceeds to describe the concept of high absorption per unit mass, and the reports successful demonstrations of uncooled detectors incorporating this concept, with extensive results reported in air and in the commercial standard vacuum conditions of current uncooled camera detector arrays.

II. Program Objectives:

- 1) Develop a theory of optomechanical infrared detection in the presence of thermomechanical noise including the frequency, temperature, and Q dependence of that noise.
- 2) Develop a theory of operation and performance for near-1mK thermal detectors. This will include an analysis of mechanics, noise, laser readout, and bimorph transduction.
- 3) Construct and demonstrate high sensitivity single pixels that will have an uncooled NETD near 1mK for light in the long-wave infrared.

III. Chapter 1: Early Discarded Designs

Design Analysis 1

Preliminary Investigation of Micromechanical Buckling Actuation for Optomechanical Detectors

This portion of the report consists of the Master's report of Eric Konitzer, a graduate student supported by the project under the supervision of Prof. Talghader. It is an analysis of buckling and resonance in MEMS structures. The original goal was to see if the response of a thermal detector could be increased by tapping stored energy in the structure. However, the device-to-device fabrication imperfections inherent in standard micro- and nano-fabrication technologies were ultimately deemed to be too high to make a buckling transducer practical. In addition, the

transduction mechanism is still subject to the same thermodynamic temperature fluctuations as other designs.

Buckling MEMS structures of SiN_x and SiO_2 are explored as an option for passive read-out uncooled thermal detectors. Structures with sizes on the order of a pixel ($<30\mu\text{m}$) are of most interest. Buckling is demonstrated in structures of this size that are fabricated in a ring configuration for tensile films and as a clamped beam for compressive films. Thermal influence on out of plane deflection is demonstrated, but it remains unproven that the rate of change in detection achievable in this manner is sufficient for 1mK NETD uncooled performance.

Euler Buckling

The simplest case of buckling, and the basis of all further discussion, is a doubly clamped beam at a critical loading as is developed in [1]. By solving the deflection curve differential equation with appropriate boundary conditions, the equation

$$P_{cr} = \frac{\pi^2 EI}{L^2} \quad (1.1)$$

is obtained, giving the critical load for a simply supported beam at which a stable equilibrium only exists if the structure deflects. E is the elastic modulus of the material, while L is the length of the beam. I is the moment of inertia, given as $I = wh^3/12$ where w and h are the width and height of the beam. The associated strain for a beam with a rectangular cross section would then be

$$\epsilon_s = \frac{P_{cr}}{AE} = \frac{\pi^2 h^2}{12L^2} \quad (1.2)$$

where A is the cross sectional area of the beam and of the beam material.

A better model than simply supported for a typical microfabricated beam would be as a clamped-clamped structure. This theory is developed as a method of determining thin lm deposition stress on a given substrate in [2]. With the appropriate boundary conditions for a doubly clamped beam, the critical strain takes a slightly different form, the factor of 4 larger as a consequence of different boundary conditions.

$$\epsilon_c = \frac{\pi^2 h^2}{3L^2} \quad (1.3)$$

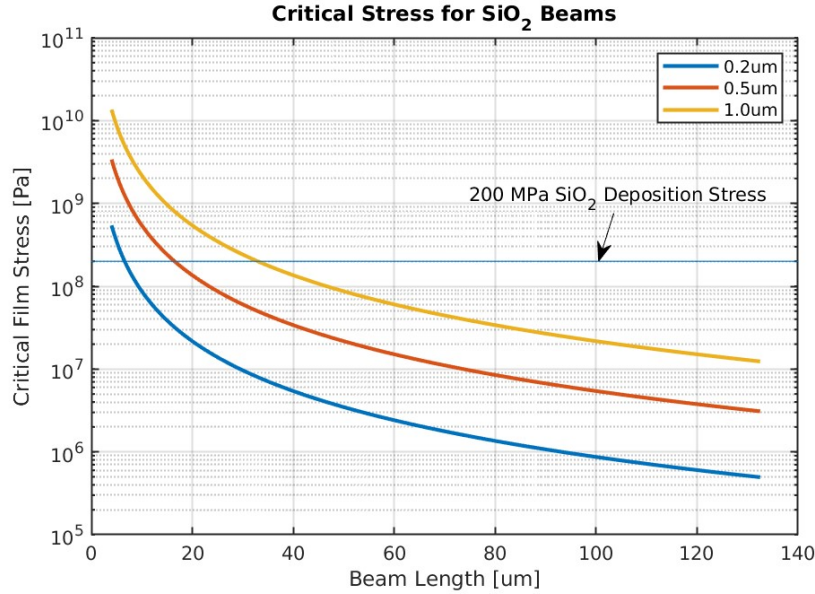


Figure 1.1: Buckling stress of SiO₂ beams from 4 to 130 μm in length and at 200nm, 500nm and 1μm film thicknesses.

As a practical example, Figure 1.1 shows the required stress in SiO₂ at which one would expect to see buckling behavior to be induced. Assuming a value of $E = 66$ GPa for SiO₂, Figure 1.1 follows directly from equation 1.3 as $\sigma = E\epsilon_c$. A plausible value of deposition stress of PECVD SiO₂ is in the range of 200 MPa, given as a reference line in the plot. If the stress required to buckle a given beam is above that line, it is not expected that the beam will be buckled, and that beams below the line will be buckled. It is seen that the critical stress of the beam increases with film thickness.

It is known that the solution to the differential equation will be sinusoidal in form, that is the beam deflection profile will take on a sinusoidal shape, but the maximum buckled deflection is undetermined. The classical Euler Buckling relationship serves as a good estimator of where buckling behavior will occur, but does not fully explain the physical phenomenon of buckling. Further models must be developed to predict the buckled behavior of beams.

Extended Model for Euler Buckling

The limitation of the standard Euler buckling criterion (equations 1.2 and 1.3) is that they can provide the critical strain at which the beam will buckle but not the shape of the deflected beam. Intuition tells us that a beam will have greater deflection as more strain is applied, and we may even expect to see some plastic deformation even before the buckling transition due to imperfections in the geometry.

Fang and Wickert develop a general model for deflections of an imperfect beam with the governing relationship

$$EI(w_{,xxxx} - w_{,xxxx}^*) + EA\left(\epsilon + \frac{1}{2L} \int_0^L (w_{,x}^2 - w_{,x}^{*2}) dx\right) w_{,xx} = 0 \quad (1.4)$$

where w corresponds to the displacement of the beam along its length and the comma notation indicating differentiation [3]. This model relies on some amount of deformation in the beam's pre-stressed state. The maximum deflection due to the imperfection is given as $w_{max}^* = \gamma L$, where γ is a parameter relating to the net imperfection of the structure.

If the solution to relationship 1.4 is presumed to be sinusoidal, then the shape of the deformation can be taken as

$$w(x) = \frac{1}{2} w_{max} * \left(1 - \cos \frac{2\pi x}{L}\right) \quad (1.5)$$

with the assumption that x ranges from 0 to L . Using this form as the shape equation for both $w(x)$ and $w^*(x)$ in equation 1.4, the fourth order differential relationship reduces to the algebraic relationship

$$w_{max}^3 + \left(16 \frac{I}{A} - \frac{4}{\pi^2} L^2 \epsilon - \gamma^2 L^2\right) w_{max} - 16 \frac{I}{A} \gamma L = 0 \quad (1.6)$$

the roots of which make up a very interesting set of solutions for finding the maximum deflection. A solution for w_{max} can be substituted in to equation 1.5 to describe the deflection of the beam across its length under a given strain.

The authors provide a closed for solution for the roots of equation 1.6, but the form obscures the true nature of the solution space and in practice is not a smooth function when considering the deflection as a function of length.

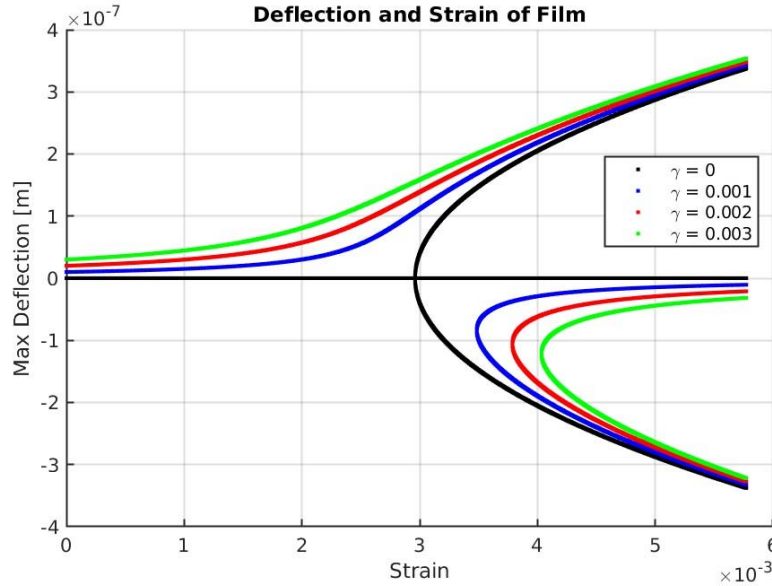


Figure 1.2: Qualitative illustration of the real roots of equation 1.6 with varying imperfection.

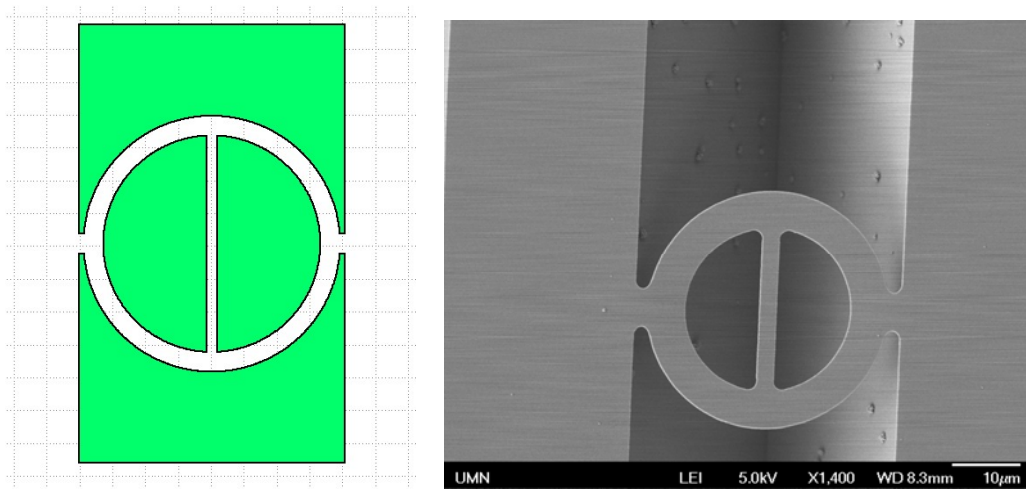
Figure 1.2 shows all real solutions to equation 1.6 regardless of stability. The black line shows the theoretical solutions for a perfect structure ($\gamma = 0$). In this case, there is no deflection up to the critical strain, after which point three possible solutions exist. The trivial solution of $w = 0$ while mathematically possible, is an unstable root of the differential equation making it physically impractical. Any perturbation and it would snap into either the up or down fully buckled positions. As γ increases, the assymetry arises due to the fact that w^* gives a bias in one direction (in this case, w^* is taken to be positive). However, the same stable and unstable roots exist, albeit with a more complicated relationship. It can be intuited that only the outermost solutions in a set are stable.

An important takeaway is that given a certain pre-deformation, the beam is very likely to always buckle in the same direction unless acted on by some perturbation. Additionally, the region with the greatest ratio of change in deflection due to change in strain ($\frac{\partial w}{\partial \epsilon}$) occurs near the critical strain value.

Guckel Rings

To expand on the strain measurement capabilities of buckling structures, it would be beneficial to have a structure that can buckle due to tensile stress rather than compressive stress. To achieve this, Guckel et. al. constructed "ring and beam" structures such that a suspended ring of a film under tensile strain will buckle a beam spanning the inside of the ring perpendicular to where the ring is attached to the surrounding material [2,5]. An example of this structure as designed and as seen after fabrication can be seen in Figure 1.3.

This structure can be thought of as a converter from tensile strain to compressive strain. As such, Guckel and Burns first develop the function $g(R)$ as the ratio of tensile strain from the lm deposition to compressive strain experienced on the beam. This is referred to as the conversion



(a) Basic example of a Guckel ring (b) SEM Image of a SiN_x Guckel Ring Fabricated for tensile stress diagnostics. using a KOH etch. ($15 \mu\text{m}$ radius)

Figure 1.3: Basic examples of Guckel Rings

efficiency and is given by

$$g(R) = -\frac{2b_r f_2}{2b_r f_1 + b_b f_1^2 - b_b f_2^2} \quad (1.7)$$

$$f_1 = \left(\frac{\pi}{4} - \frac{2}{\pi}\right) \left(\frac{R}{e}\right) - \frac{2e}{\pi R} + \frac{4}{\pi} - \frac{\pi}{4} + k_f \frac{1+\nu}{2} \quad (1.8)$$

$$f_2 = \left(\frac{1}{2} - \frac{2}{\pi}\right) \left(\frac{R}{e}\right) - \frac{2e}{\pi R} - \frac{1}{2} + \frac{4}{\pi} - k_f(1+\nu) \quad (1.9)$$

where b_r is the width of the ring, b_b is the width of the beam, ν is the Poisson ratio, R is the median radius of the ring such that with R_o and R_i corresponding to the outer and inner radii respectively, $R = (R_o + R_i)/2$. The parameter e is known as the eccentricity and is given by

$$e = R - \frac{b_r}{\ln(R_o/R_i)}. \quad (1.10)$$

The parameter k_f is a form factor, which is given to be 1.2 for a rectangular cross section.

We note that while $g(R)$ typically has an optimal solution (as can be seen in figure 1.4), it is not always practical to fabricate rings with what the mathematics say is the optimal geometry.

For the desired case of out of plane beam buckling, Guckel shows that the torsional moment on the ring can be found as

$$\alpha_o = \frac{4C_r E b_r h^3}{\pi R (6C_r + 1 + \nu) \left[1 - 4 \frac{(1+\nu-6C_r)^2}{\pi^2(1+\nu+6C_r)^2}\right]} \quad (1.11)$$

where E is the elastic modulus, h is the thickness of the ring and beam, and C_r is the torsion coefficient, which tends to 1/3 as the ratio b_b/h tends to infinity.

To find the beam buckling criteria in this framework, the parameter kR must be determined numerically where R is the radius and $k^2 = P_{cr}/EI$ where P_{cr} is the critical buckling force for the beam with moment of inertia I . The parameter kR is determined by numerically solving the transcendental equation

$$\frac{kEI_b}{\alpha_o} + \tan(kR) = 0 \quad (1.12)$$

which is easily achieved using the MATLAB symbolic solver, looking past the trivial solution and past the $\pi/2$ asymptote.

Having numerically solved for kR , the relationship between tensile lm stress and the critical radius at which a ring structure will buckle can be examined using

$$\epsilon_0 = \frac{\epsilon_{cr}}{g(R)} = \frac{(kR)^2 (h/R_{cr})^2}{12g(R)}. \quad (1.13)$$

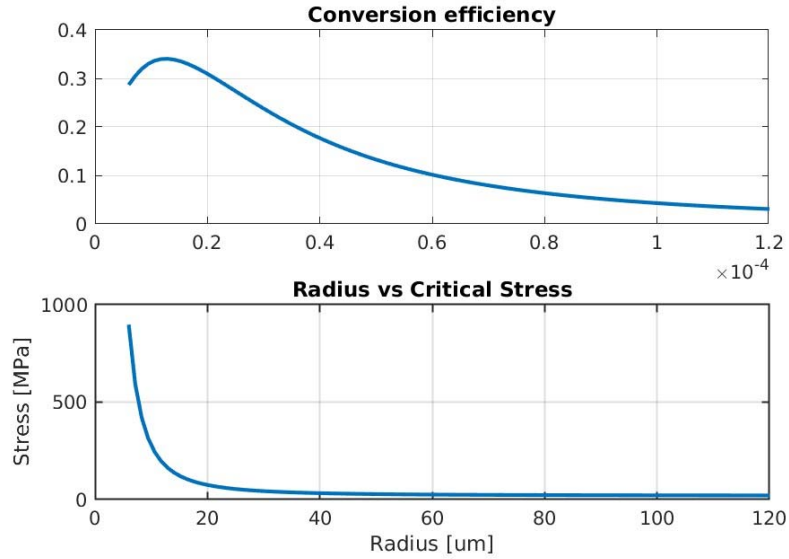


Figure 1.4: Design example of a Guckel ring structure considering conversion efficiency and critical stress.

The lower plot of Figure 1.4 shows how the critical stress relates to the radius of a SiN_x ring when the ring width $b_r = 6\mu\text{m}$, and beam width half that of the ring width, taking $E = 200\text{MPa}$, $\nu = 0.23$ and the thickness to be 300nm . By controlling the film thickness during deposition in fabrication, the stress at which a given ring will buckle can be controlled.

Experiments with Doubly Clamped Beams

Design and Fabrication of Doubly Clamped Beams

A set of micromachined doubly clamped beams are created as to gauge the models of simple Euler buckling and the model proposed by Fang and Wickert. In order for buckling to occur, the design must account for compressive stress to act on the beams, and for the beams to be completely released from the substrate but rigidly attached at the ends.

Material Choice

As noted above, the beams must experience compressive stress in order to buckle. An easy film to work with that is typically deposited under conditions that lead to compressive film stress is SiO_2 .

Beam Design

A series of doubly clamped beams were programmatically generated on the mask design, as illustrated in Figure 2.1. Of most interest in the following experiments, beams which are $2\mu\text{m}$ in width are used. On the mask, these beams are arranged in an array of lengths from 4 to $132.5\mu\text{m}$, each $0.5\mu\text{m}$ longer than the last. A second row of beams is also made which include a plate at the center of the beam that is square, 3 times the width of the beam on a side.

SiO₂ Clamped-Clamped Beam Fabrication Process

Doubly clamped SiO₂ beams were fabricated using the following process.

1. Film stress baseline: FSM tool is used to record the initial curvature of a clean silicon wafer.
2. SiO₂ Deposition: The SiO₂ was deposited using PECVD, using the 100°C SIO2100 recipe for its minimal deposition stress. Deposition was split into two runs of 4.5 minutes

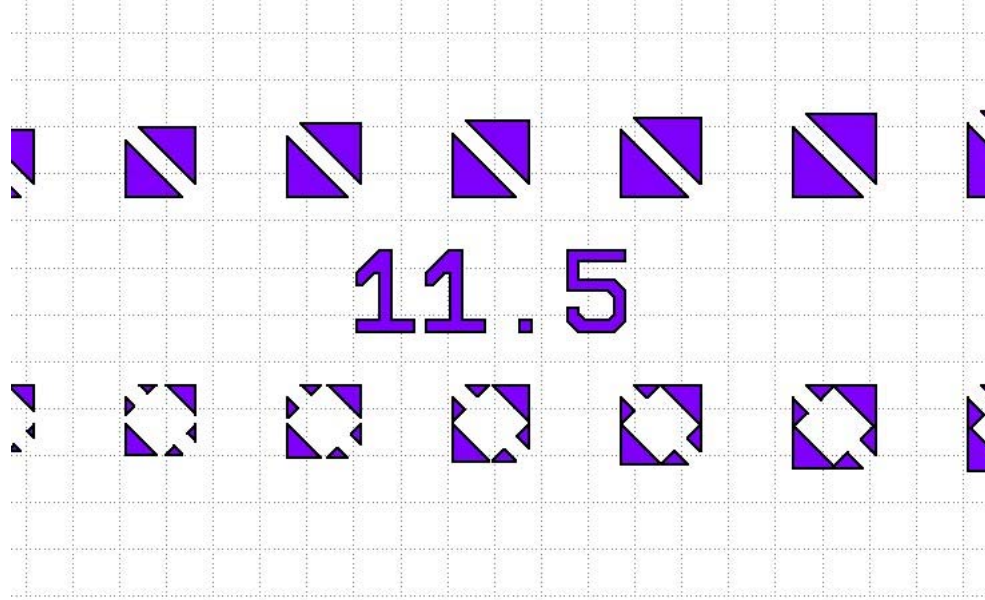


Figure 2.1: A portion of the array of 2 μm wide beams defined in the dark field mask design. The number indicates the length of the beam in μm and each beam is 0.5 μm longer than the last. The full array extends from 4 to 132.5 μm in length.

and 5 minutes, turning 90 degrees between runs to minimize pinholing. In April 2019, this yielded an average of 3090 Angstrom film thickness, with irregularly thick areas in the center where the plasma was presumably the strongest.

3. Film Stress Evaluation: The FSM is again used to record the new curvature of the wafer with PECVD SiO₂ deposited on one side of wafer and deduces the stress of the film
4. Lithography: Standard lithography process with a dark field mask using AZ1512 photoresist exposed using vacuum contact.
5. Oxide Etch: Remove the oxide from the wafer as defined by photomask. RIE etching with Ar, CHF₃ and CH₄ 50:50:25 (STS recipe pjsoxide) removes SiO₂ with good directionality and selectivity to silicon and photoresist. Etch ran 12 minutes to ensure consistent oxide layer removal to expose silicon.
6. Silicon Etch: Remove just enough silicon from exposed areas to release beams from the substrate. RIE etching with O₂ and SF₆ (STS recipe fastpoly) removes silicon with good selectivity to oxide. Three minutes is sufficient to release beams up to 5 μm in width, one or two minutes recommended for beams around 2 μm wide, with much longer time required for

wider structures needing more undercutting. This etch is isotropic and removes material from around the defined etch pit.

7. O₂ Photoresist Removal: A 10 minute O₂ clean is recommended to remove remaining photoresist from structures. A solvent clean after release leads to risk of collapsing structures and sticking, a solvent clean prior to release etch seems to damage oxide film.

Figure 2.2 illustrates the above fabrication process as a cross section of a fully released beam.

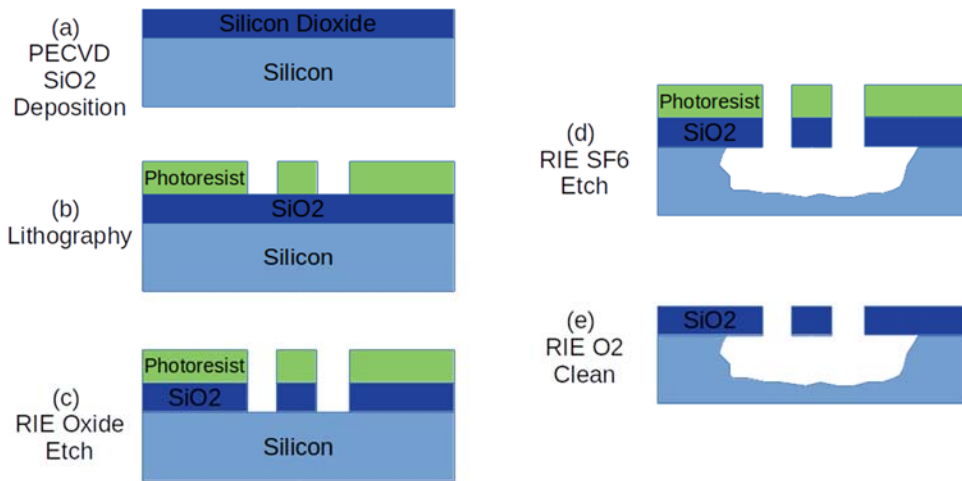


Figure 2.2: Silicon dioxide doubly clamped beam fabrication on silicon

An important parameter in the fabrication of these beams is how long of an isotropic silicon etch to perform to release the beams. For 2 μ m and 5 μ m beams, 3 minutes of etching is more than enough to fully release the beams from the substrate, however, wider beams will still be attached to silicon.

Figure 2.3 shows how differing etch durations affect the amount of SiO₂ still in contact with the silicon substrate. At excessive duration, the etch pits will run into each other and stress in the SiO₂ lm may become less predictable. It is desired to remove the minimum amount of silicon necessary for any given beam to release.

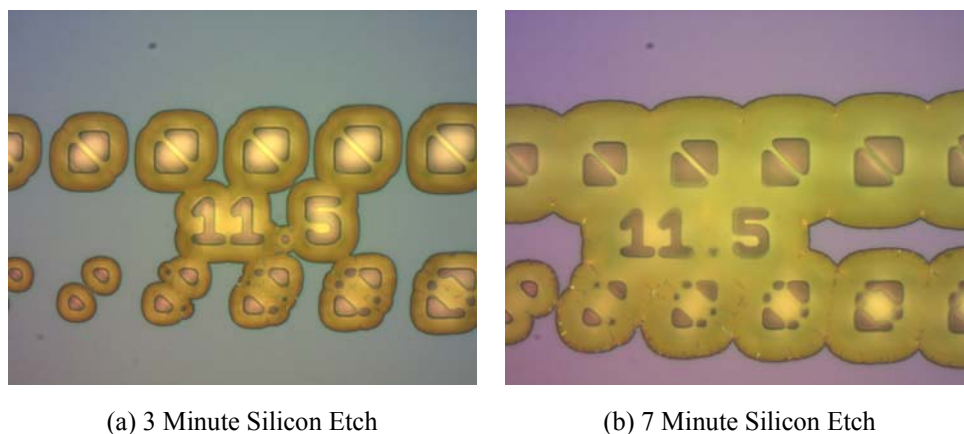


Figure 2.3: $2\mu\text{m}$ wide beams released with different durations of SF_6 RIE etching

Experiment: Buckling with Length (room temperature)

It is desired to verify the model against varying lengths of beams at room temperature to predict the baseline Im stress and derive the net imperfection quantity (γ) of the clamped beam structures that have been fabricated. Steady-state deflection over varying beam lengths is analyzed and fit to the extended, non-linear model with imperfection for clamped-clamped beam profiles (equation 1.6).

The structures of interest in these experiments are quite a bit smaller than the structures Fang and Wickert used to illustrate their model. Despite limitations and low refinement of the micromachining processes used, it is found that the imperfection level and strain determined experimentally compare favorably to Fang and Wickert's results and fabrication predictions.

Data Collection

Data was collected on the deflection of each beam from $6\mu\text{m}$ to $22.5\mu\text{m}$ for the $2\mu\text{m}$ wide beams and 10.5 to $42\mu\text{m}$ for the $5\mu\text{m}$ wide beams. From ellipsometer measurements, the thickness of the SiO_2 is taken to be 3200 angstroms. With each consecutive beam in the array being $0.5\mu\text{m}$ longer than the last, 28 two micron beams are measured and 23 five micron beams are measured.

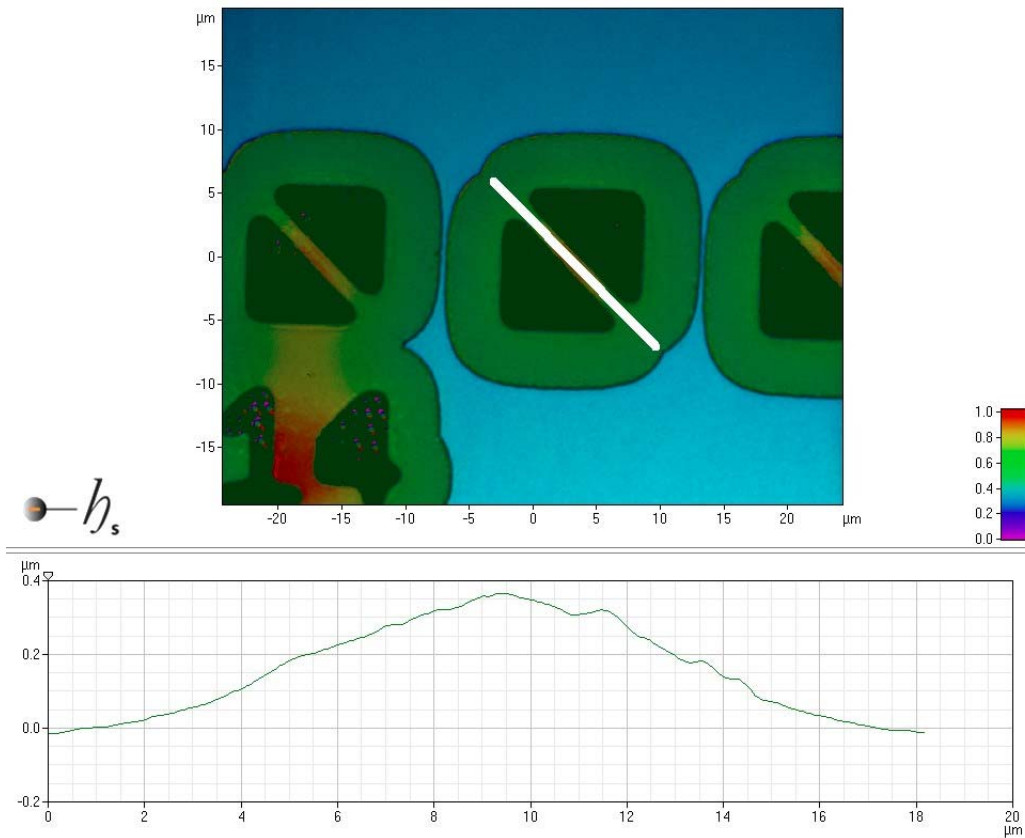


Figure 2.4: An example of the confocal scope measuring the profile over a line, averaged over $1\mu\text{m}$. The image is colored to reflect the height of the device at a given point.

Figure 2.4 shows an example of one measurement for a beam that is $14.5\ \mu\text{m}$ long and $2\ \mu\text{m}$ wide. The white line is drawn in the HS Scope software and the height profile averaged across the width of that line ($1\ \mu\text{m}$) is plotted below the image. This data is leveled with respect to the (green) unsupported SiO_2 near the ends of the beam.

Data Processing

The deflection curve data from each beam was exported from the HS Scope software as a CSV file and imported into MATLAB. Each data series was processed such that each curve was centered with respect to each other and any remaining offsets are removed such that each curve starts and ends at zero deflection. Any data that was collected past the actual length of the beam is thrown out.

After this initial processing, data is ready to be collected on the maximum deflection of each beam. Figures 2.5 and 2.6 presents the raw data collected for each beam in both the $2\ \mu\text{m}$ and $5\ \mu\text{m}$ wide beam arrays. It is seen from this presentation that the deflection measurements for short beams has a much lower signal to noise ratio as compared to long beams with large deflections. These beam sizes are at the threshold of measurement for the confocal scope and software. Further filtering and fitting may be used to obtain a more realistic deflection curve, but simple averages at the midpoint of the beam are used for the maximum deflection of each beam. Due to more visible surface area, the data for the $5\ \mu\text{m}$ beams appear much smoother because the measurements were averaged over a wider distance than the $2\ \mu\text{m}$ beams.

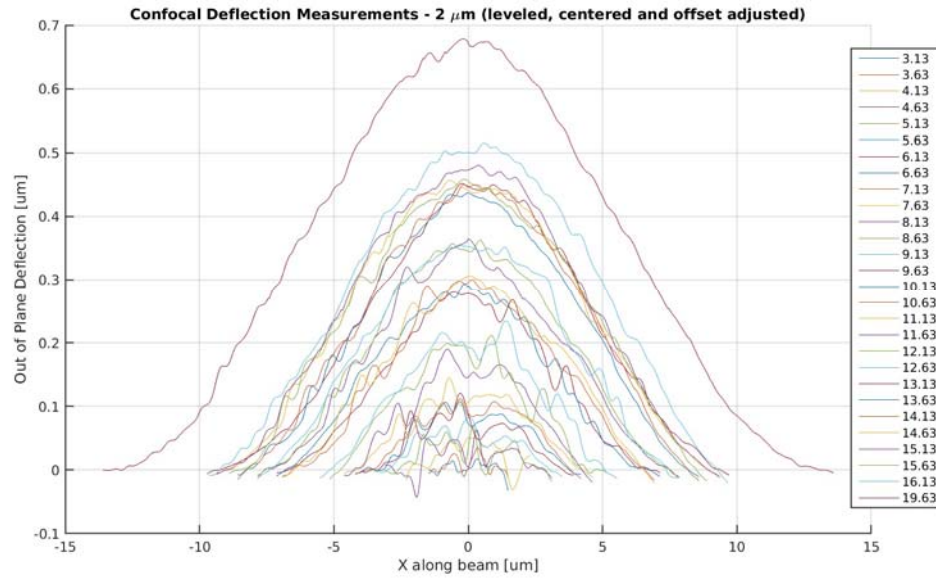


Figure 2.5: Processed data for $2\ \mu\text{m}$ wide beam deflections for different beam lengths.

In order to match the model to the data collected on the beams, a crude coordinate descent optimizer was written. Given a manual guess for the range of strain and imperfection level, the optimizer can find the values for γ to any desired degree of accuracy. For the purposes of this experiment, the optimizer was run for 10 iterations, which proved to

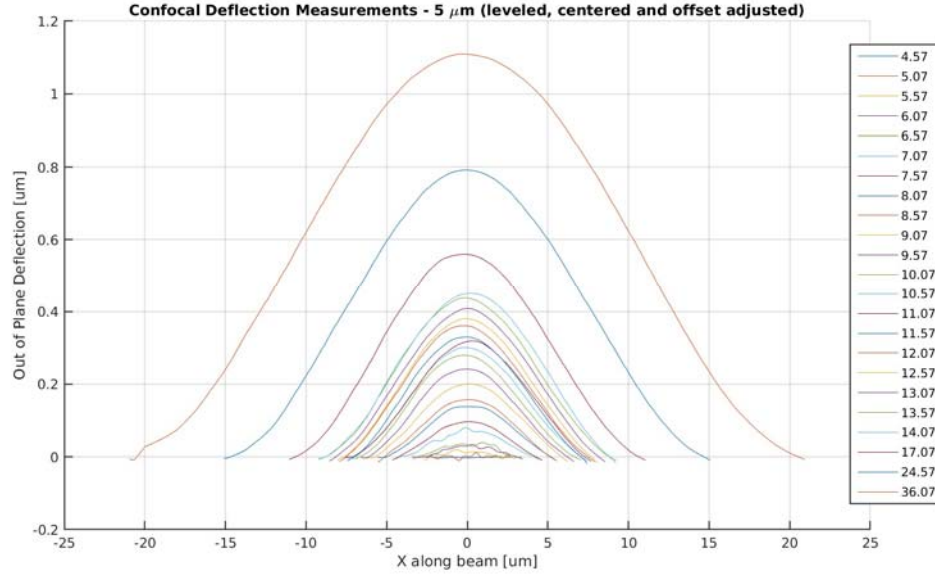


Figure 2.6: Processed data for 5 μ m wide beam deflections for different beam lengths.

be sufficient for convergence. The optimizer minimizes the mean absolute error, that is it minimizes the objective function

$$\eta(\epsilon, \gamma) = \frac{1}{N} \sum_{k=0}^N |(w_{max})_k - (\hat{w}_{max})_k| \quad (2.1)$$

where $\hat{w}_{max}$ is the maximum deflection expected from equation 1.6. The optimizer strategy here differs from the regression used in Fang and Wickert's paper as they fit their results to a fitting parameter I/A as well as γ .

Results

When the optimizer is used on the datasets for the 2 μ m and 5 μ m, values for strain and net imperfection are arrived at. Since both sets of beams come from the same wafer with the same SiO₂ film, neglecting differences in geometric imperfections, we should expect that we arrive at the same strain from each dataset.

Table 2.1 compares the results of the model fitting to the two datasets. Along with dimensionless strain and net imperfection parameter (γ), the stress (σ) in the SiO₂ film on Si wafer at room temperature is calculated assuming $E = 66$ GPa. For the PECVD recipe used, a film stress of about 134 MPa (compressive) was expected, and the film stress instrument measured 127 MPa (compressive) when analyzing the radius of curvature over the entire unpatterned wafer. The model fit indicates a film stress in the SiO₂ of 250 - 270 MPa, which is quite a bit larger than what was predicted, but still a very plausible value for the PECVD oxide film. This discrepancy may be due to variations in film thickness over the wafer (these beams were fabricated in the thickest area of the wafer) or somehow related to the way strain manifests in etch released devices.

Width	γ		σ
$2\mu\text{m}$	0.0038	0.0078	250.8 MPa
$5\mu\text{m}$	0.0041	0.0044	270.6 MPa

Table 2.1: Fitting Results

Qualitatively, it makes sense that the imperfection level is higher in the $2\mu\text{m}$ beams because any geometric imperfections due to lithography (i.e. the radius of the rounded corners) have a proportionally larger effect on smaller structures.

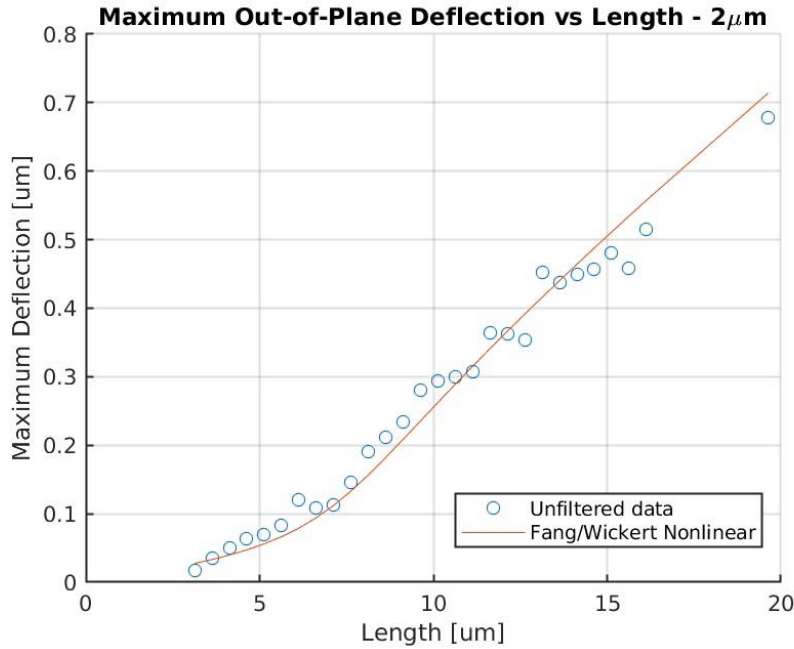


Figure 2.7: Raw and modeled maximum deflections for $2\mu\text{m}$ wide beams of varying lengths.

Figures 2.7 and 2.8 show the maximum deflection of each beam length measured for both the $2\mu\text{m}$ and $5\mu\text{m}$ sets of beams along with the numerically evaluated deflection that the Fang and Wickert model predicts, taken to be the largest positive real root of equation 1.6. For reference, without imperfection we would expect from the Euler buckling criterion (equation 1.3) that a beam of length $9.4\mu\text{m}$ to be at the buckling transition regardless of width. The inflection point where the imperfect buckling transition may be approximated is somewhere around $6\text{--}7\mu\text{m}$ for both datasets.

Overall, there is probable correlation between the data collected and the model's prediction. However, closer examination shows that from figure 2.7, there is a higher slope in the "pre-buckling" lengths region than is predicted by the model for the $2\mu\text{m}$ width beams, and at the longer "post-buckled" lengths in figure 2.8, there is a lower slope than predicted. Further, there is an offset in values in the "pre-buckled" lengths where the measured values were consistently smaller than the model would predict.

The source of the discrepancies are uncertain. It could be possible that there exists

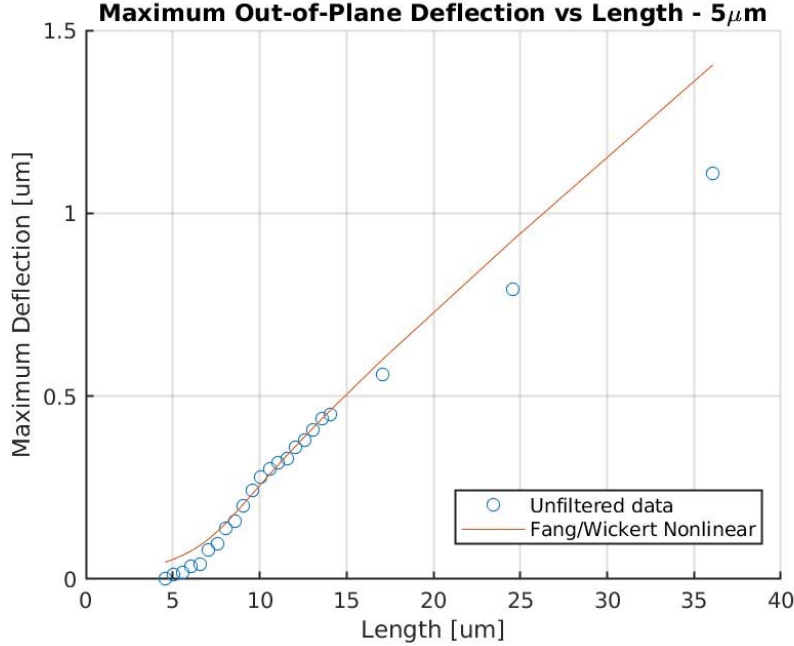


Figure 2.8: Raw and modeled maximum deflections for $5\mu\text{m}$ wide beams of varying lengths.

systematic errors in the measurement process. There is a human element to making the measurements, so perhaps the choice areas to measure changed during the experiment. The confocal scope was not calibrated and its absolute accuracy is unknown.

Alternatively, the optimizer could just be ill suited to the model, and parameters which were assumed actually remain uncertain. Fang and Wickert used the moment of inertia as a fitting parameter, and it is plausible that the value assumed does not accurately depict the actual value resulting from the real world fabrication.

It is interesting to note that in this experiment all of the beams deflected upwards. This seems to suggest that a result of this particular fabrication process is that the moment of inertia may be slightly affected uniformly across all beams such that the unbuckled imperfection is more stable in the upward deflected state.

Conclusion

Overall, the experiment shows correlation of clamped SiO_2 beam behavior to the nonlinear model with imperfection developed by Fang and Wickert. The results agree favorably with the results found by Fang and Wickert, who used similar materials and processed but with much larger and thicker structures. Their model found a net imperfection parameter of $\gamma = 3.7 \times 10^{-4}$ using an array of beams $2\mu\text{m}$ thick, $15\mu\text{m}$ wide and up to $100\mu\text{m}$ long. This is an order of magnitude smaller than the imperfection level found experimentally, but the beams are much smaller and created with an un-optimized fabrication process. Low resolution lithography led to many rounded corners and irregularities, while non-uniform SiO_2 deposition may have caused difficult to predict irregularities in stress across the wafer. Nevertheless, the model appears to be a good reference for designing and predicting the behavior of structures even at the small scales of interest.

Experiment: Buckling over Temperature

It is of more interest to explore the behavior of clamped beams as they are heated and cooled. For this experiment, two beams around the buckling transition for the given film stress are analyzed over a range of temperatures, from room temperature to 100°C at 5° intervals.

For SiO₂ on Si, the thermal expansion of the silicon substrate outpaces that of the SiO₂ film. Thus, to analyze the buckling transition with this structure, we take a beam that is near the transition region yet clearly buckled. When heat is applied, the strain will relax and the beam will unbuckle at the critical stress.

The relationship between temperature and strain can be taken to be linear in most modes of operation, with the relationship

$$\epsilon = \Delta T \Delta \alpha \quad (2.2)$$

where ΔT is the change in temperature and $\Delta \alpha$ is the difference in the coefficients of thermal expansion (CTE) of the two materials.

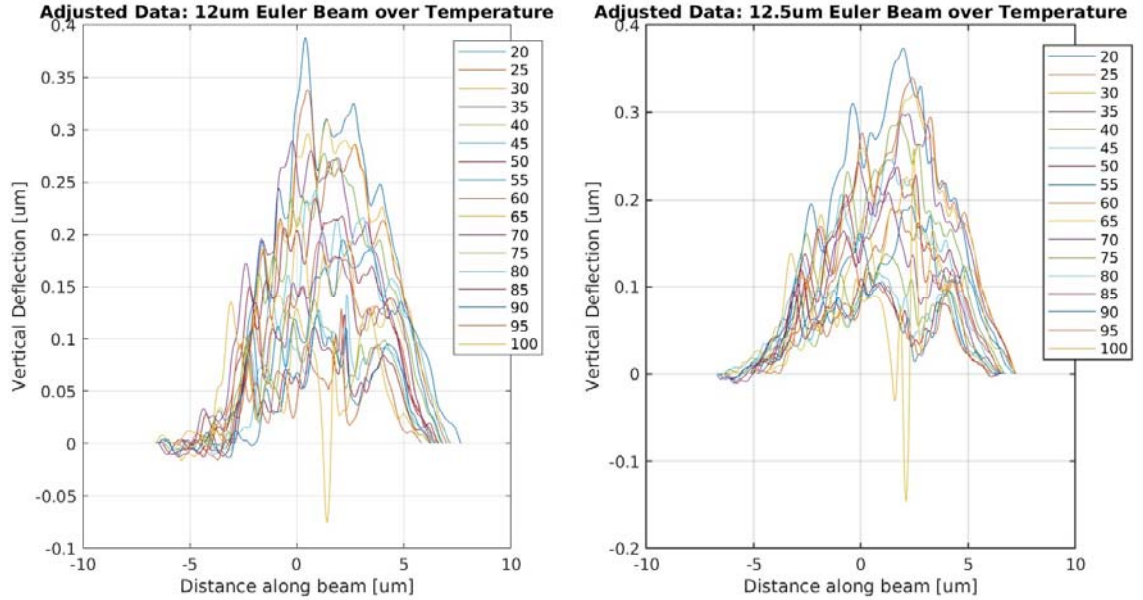


Figure 2.9: Adjusted measurement data for 12 and 12.5 μm long beams from 20 to 100 °C.

The data is adjusted roughly by removing the DC bias. MATLAB then uses nonlinear least squares to fit the curve to a first order sum of sines. A frequency solution range is provided to ensure that MATLAB converges to a solution at a period equal to the length of the beam. Phase information is thrown out. The result of the sinusoidal fit is shown in figure 2.10. The amplitudes of the fit are used to compare to the maximum deflections as directly measured.

Results

From the adjusted data, the maximums of each temperature series are recorded and plotted for the 12 and 12.5 μm beams in Figure 2.11. Although, upon investigation of Figure 2.9, we may suspect that the maximums in the data set are artificially high. For comparison, Figure 2.12 shows the maximum amplitudes of the sinusoidal fit (w_{max} in equation 1.5). It is seen that the sinusoidal

amplitudes trend lower than the maximums of the measurement data, giving a more conservative estimate of the maximum deflection heights of the beams.

Of particular interest in this experiment is to find the maximum rate of change in deflection with respect to temperature. As temperature is inversely related to strain in this example, we would expect Figures 2.11 and 2.12 to correspond to the behavior of equation 1.6 as seen in Figure 1.2, however we see that the actual data is not as well behaved as the model would predict. Figure 2.13 shows the approximate derivatives of the deflection data presented with respect to temperature. While the data as collected presents challenges to analysis due to poor consistency in measurements, we can see that even conservatively the rate of change does not exceed $15 \text{ nm}/^{\circ}\text{C}$ in magnitude. The maximums in the rate of change occur consistently $70\text{-}75^{\circ}\text{C}$, which seems to indicate that the buckling transition occurs at that temperature.

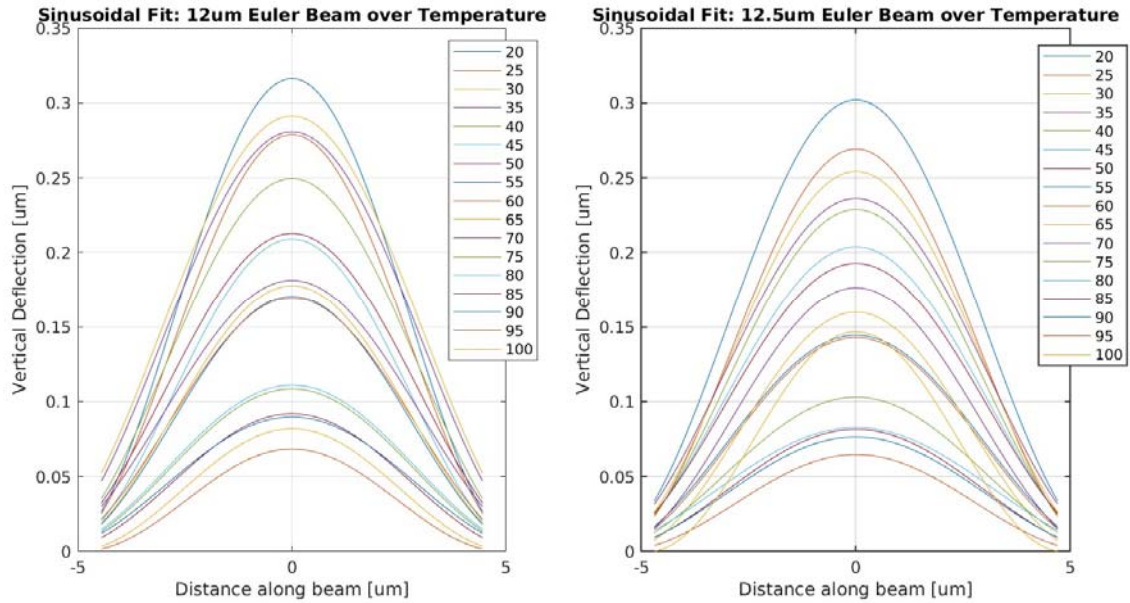


Figure 2.10: Non-linear least squares sinusoidal fit for adjusted data over several different temperatures.

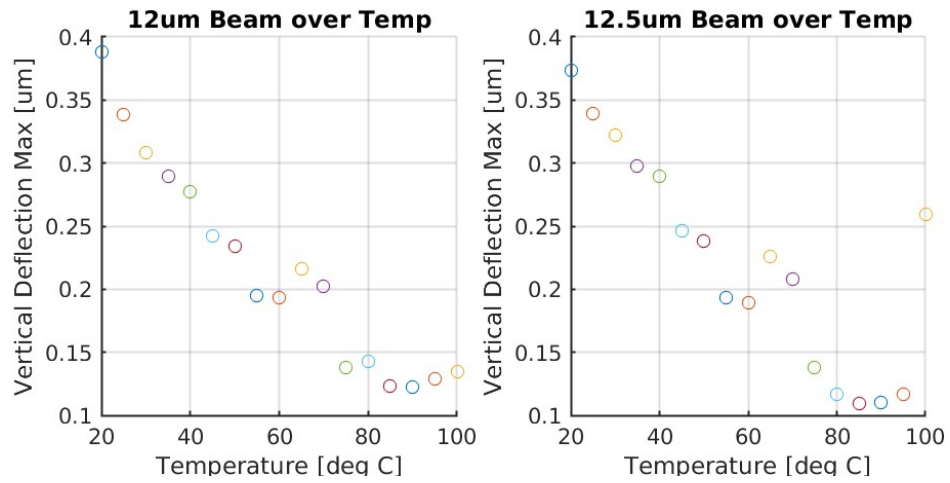


Figure 2.11: Maximum deflections of the clamped beam at different temperatures

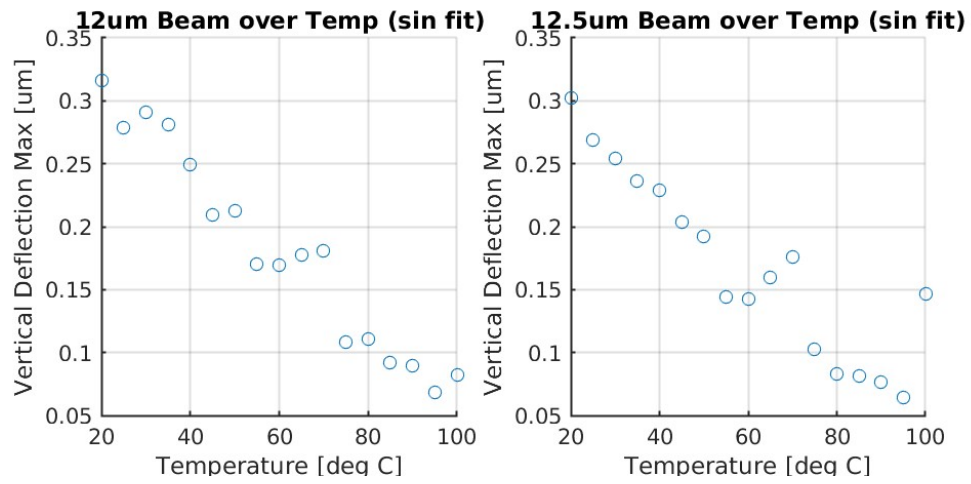


Figure 2.12: Maximum deflections of beams over temperature as determined by NLSS sinusoidal fit.

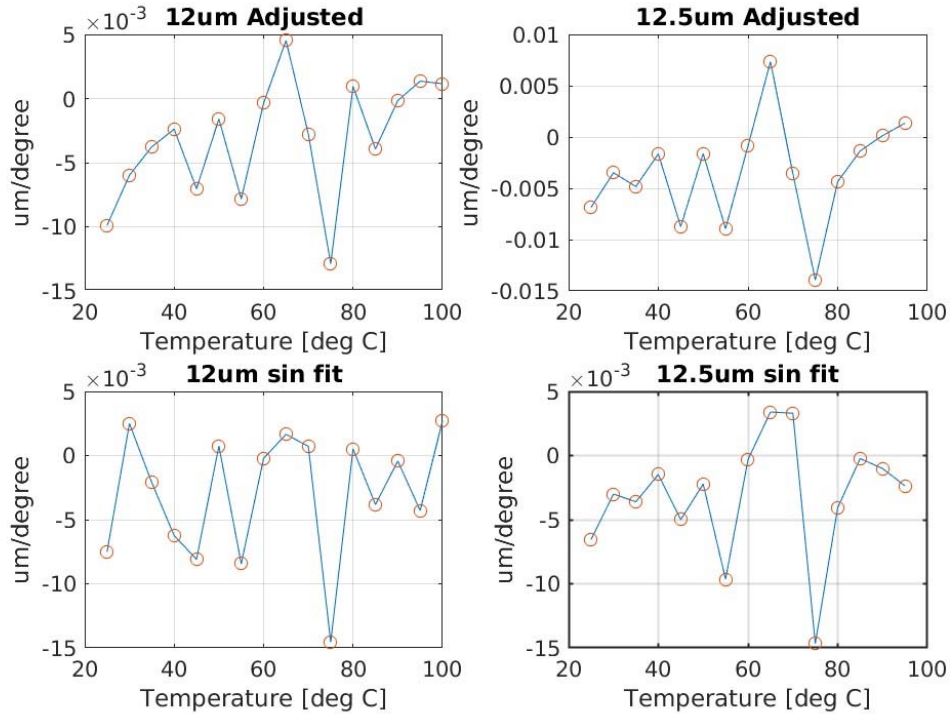


Figure 2.13: Rate of change in deflection with respect to temperature with adjusted data maximums and sinusoidal fits for each beam.

Experiments with Guckel Rings: Design and Fabrication of Guckel Rings

Material Choice

Silicon nitride is chosen as the material of interest for Guckel rings primarily for being an easy to work with film that typically exhibits tensile stress. The film achievable from the LPCVD machine is of high quality such that it is easy to predictably etch with an RIE process and is strongly resistant to KOH processing. Furthermore, the stress value can be altered by using different recipes. The low stress nitride recipe LSN-33 promised typical stress values in a convenient range for rings in the target range of $30\mu\text{m}$ diameter to be near their buckling transitions.

Ring Design

Figure 3.1 shows a sample of the ring mask design where square plates were included at the centers of the beams. Rings were created suspended over a rectangular etch pit with their radii differing by $0.5\mu\text{m}$ to each of their neighbors. Two support designs were included on the mask (discrete legs and overlapping sides), as well as two styles of beams (straight and with a plate).

Silicon Nitride Ring Fabrication Process

Arrays of Guckel rings were fabricated in Silicon Nitride using the following process:

1. Film stress baseline: FSM tool is used to record the initial curvature of a clean silicon wafer.
2. Piranha clean: Wafers were cleaned with piranha for maximum Bay 1 cleanliness.

3. SiN_x Deposition: Low-stress nitride is deposited on the wafer using LPCVD recipe LSN-33 (good luck ever doing this again in Keller...)
4. Film stress evaluation: The FSM is again used to record the new curvature of the wafer with the LPCVD SiN_x deposited on. A sacrificial wafer is masked with photoresist on

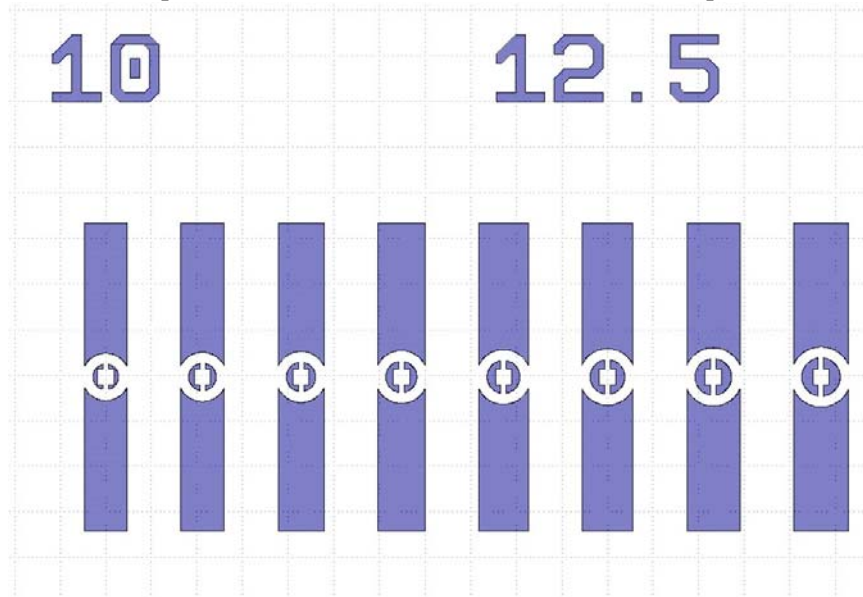


Figure 3.1: An example of the dark field design of some Guckel rings with plates at the center of the beam and with overlapping side supports.

one side and the nitride is etched from the opposite side using an RIE process and the stress measurement is taken.

5. Lithography: Standard lithography process with a dark eld mask using AZ1512 photoresist exposed using any contact mode (Vacuum might be a good choice as no alignment is needed later for the single mask process).
6. Nitride etch: STS etcher recipe nit1.set is used to remove nitride until silicon is exposed. Etch is evaluated visually for completion.
7. Solvent clean: A simple 3 solvent rinse has always been suitable to remove all photoresist.
8. KOH Etch: A solution of 40% KOH is used to anisotropically etch the silicon beneath the ring structures to release them from the substrate. KOH bath was typically kept at 80°C and etched to depths of typically $60\text{-}80\mu\text{m}$, with some smaller structures self-limiting well before then.
9. Controlled Rinse: In order to rinse the dies after the hot KOH etch, great care must be taken to prevent thermal shock, clean etching residue and to prevent capillary forces from collapsing delicate structures as the die dries. Once the KOH is complete, the following steps are taken to rinse and dry the newly released structures:
 - Hot water rinse at $50\text{-}70^{\circ}\text{C}$ for 3 minutes, light agitation
 - Methanol rinse in shallow dish, 2 minutes, light agitation

- Repeat methanol rinse with fresh methanol twice more.
- Dab excess solvent on cleanroom wipe
- Quickly set die on 100-110°C hotplate for 1 minute to rapidly evaporate the methanol

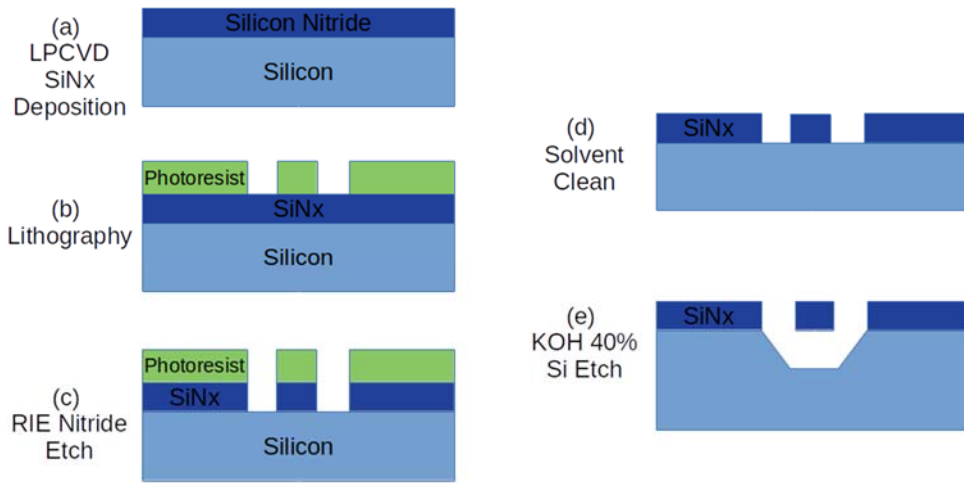


Figure 3.2: Silicon nitride Guckel Ring fabrication on silicon

Figure 3.2 illustrates the fabrication process outlined above.

This is overall a very robust process. The quality of the nitride film made the KOH etch worry free. However, as different tools other than the LPCVD may need to be used in the future, adjustments may need to be made on the etch. The main difficult point of this process is knowing when the RIE etch is through the nitride layer and etching into the silicon. The one indicator is that the color stops changing and under the microscope the silicon surface appears rougher than the nitride and resist because it etches so much faster.

It is important to align the mask with the crystal plane of the wafer as much as possible as the etch pits are defined in rectangles and will limit to the edges of the nitride in the KOH etch and allows for close spacing of the structures. If misaligned with the crystal plane, the etch pits could run into each other.

3.2 Experiment: Guckel Ring Buckling over Temperature

Two fabricated SiN_x Guckel rings were examined under the confocal microscope as the temperature was changed from room temperature to 100°C in 5° increments. The two rings each had a ring width of 6μm and a beam width of 3μm and a nitride thickness of 2200 Angstrom. The first ring had a nominal radius of 15μm and the second one had a radius of 17.5μm, leading to beam lengths of 24 and 29μm respectively.

3.2.1 Data Collection

These rings were chosen because they appear nominally unbuckled at room temperature (21°C) and are believed to have a beam buckling critical stress just above room temperature.

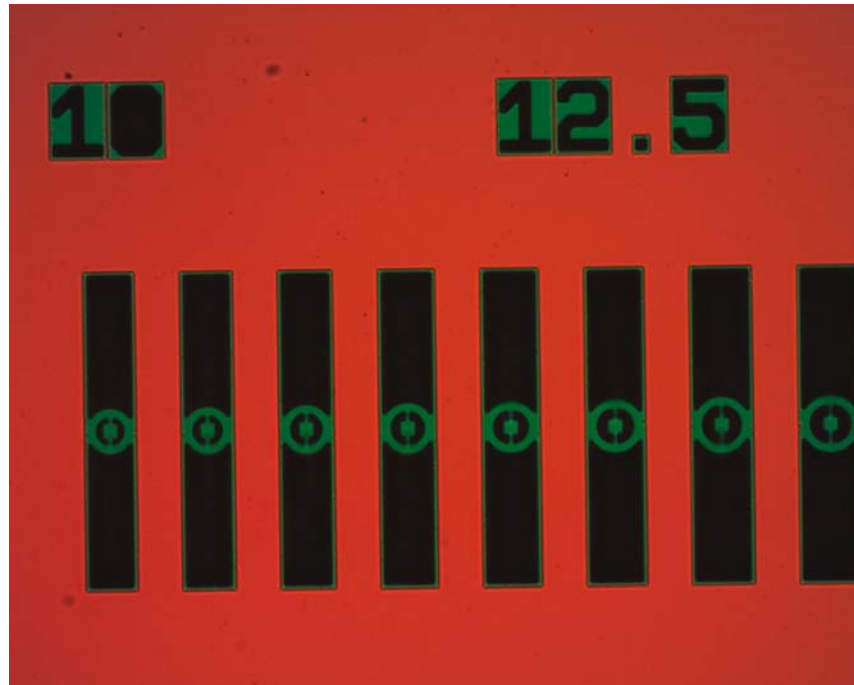


Figure 3.3: Some 10-13.5 μm SiN_x rings after fabrication. The black areas are where the silicon has been etched far deeper than the focal depth of the microscope, leaving the rings suspended.

residual film stress. As higher temperatures were applied by the peltier element, beam deflection out of the plane was observed using the depth measurement ability of the scope and its software.

For this particular experiment, 15 measurements were made at intervals of 5 degrees ranging from 35 to 100 C. This is the setpoint temperature measured at the copper plate xed to the peltier element, not the temperature measured on the die.

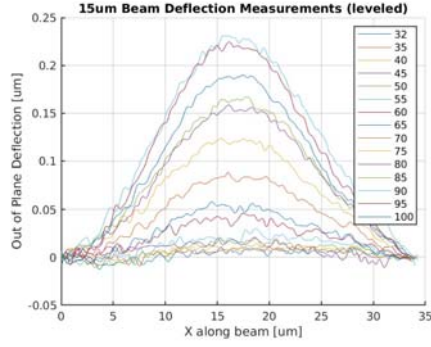
Each deflection measurement was made by drawing a profile line across the entire beam and to the outer edges of the ring. This introduced some variability in the consistency of measurements and introduced differences in leveling and offsets that needed to be compensated for in post processing. Figure 3.4 shows the data collected after processing in MATLAB.

Data Processing

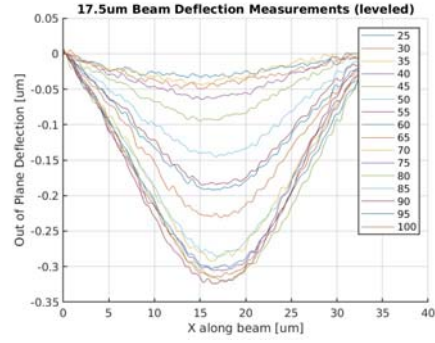
In order to arrive at a better estimate, MATLAB's curve fitting toolbox is used to fit the deflection curves to a sinusoid using nonlinear least squares. The sinusoidal fits for each temperature and both beams are shown in Figure 3.5.

Results

Over the full range of temperatures measured, a maximum deflection of approximately 220nm was observed for the 15 μ radius ring and approximately 320nm for the 17.5 μm radius ring. The maximum deflections of each beam at each temperature is measured by the absolute maximum

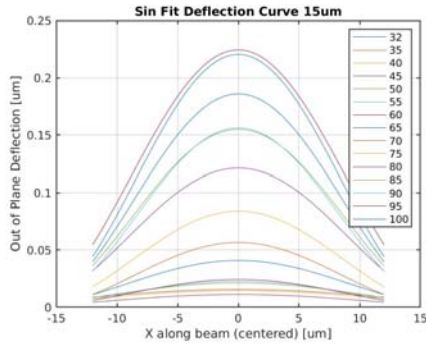


(a) 15 μm

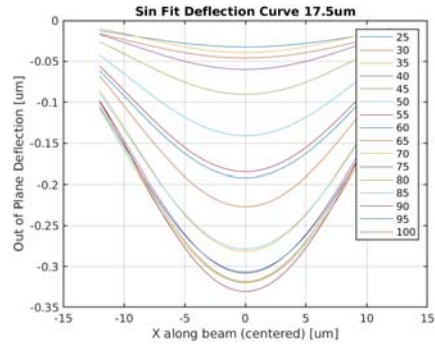


(b) 17.5 μm

Figure 3.4: Leveled and offset adjusted measurements of 15 and 17.5 μm radius rings over several temperatures.



(a) 15 μm



(b) 17.5 μm .

Figure 3.5: Sinusoidal non-linear least squares fit for ring deflection measurements of the measured data as shown in Figure 3.4 and by the maximum amplitude determined in The rings did appear to have a prebuckling, transition and postbuckling regions as depicted by Figure 1.2.

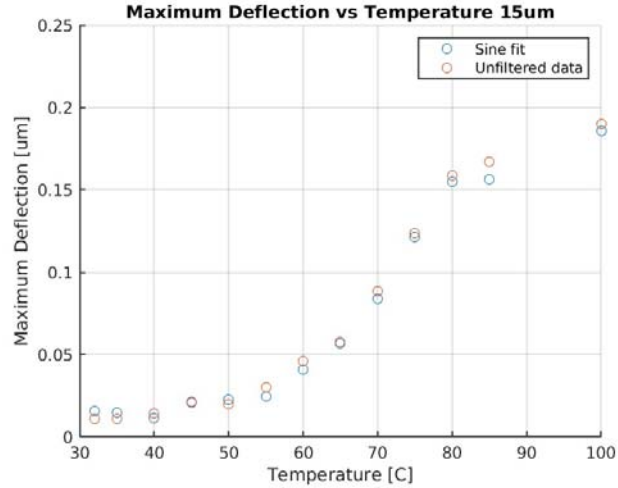


Figure 3.6: Maximum deflection over temperature of 15 μ m Guckel ring.

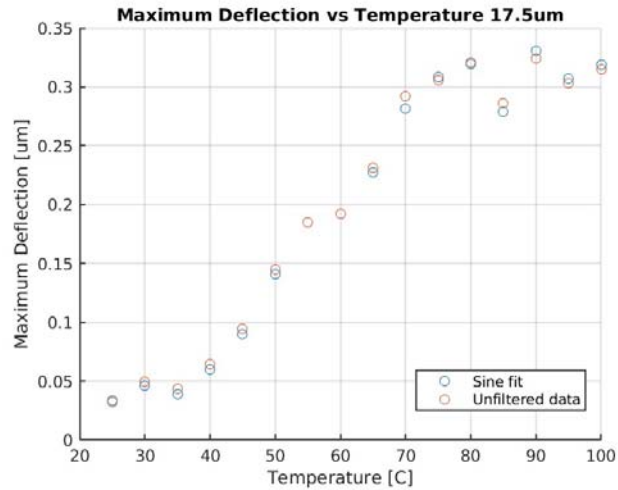


Figure 3.7: Maximum deflection over temperature of 17.5 μ m Guckel ring.

Conclusions

From the plots of Figures 3.6 and 3.7, we can see that about 10nm/ $^{\circ}$ C in deflection is achieved. While the results agree well with the Fang and Wickert model, the structure does not deflect enough for a high sensitivity thermal detector.

Ultimately, it is desired that a structure be created with the highest possible rate of change in deflection for the smallest change in temperature. As can be seen in Figure 1.2, the maximum rate of change increases as the net imperfection level (γ) decreases. While it is unclear what specifically contributes to the net imperfection, it follows that geometric imperfection is a key contributor. Overall tighter fabrication processes may decrease the imperfection level. For the case of the clamped beams, it would be advantageous to limit the undercut of the release around the beam pit as the strain around the edge of the SiO₂ is hard to predict if it is not supported by silicon underneath. Some other film and process may need to be used to arrive at a design that does not undercut.

Chapter 1 References

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- [3] Weileun Fang and JA Wickert. Post buckling of micromachined beams. Journal of Micromechanics and Microengineering, 4(3):116, 1994.
- [4] David William Burns, “Micromechanics of integrated sensors and the planar processed pressure transducer” Ph.D. Dissertation, University of Wisconsin, 1989.
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Design Analysis 2

Analysis of an Uncooled Infrared Detector Element with NETD ~ 1.5mK

This part of the report is an incomplete and preliminary design analysis by graduate student Avijit Das under the design and direction of Prof. Talghader. Recall from the proposal that we were originally studying a resonant cavity pyrometer pixel as our primary candidate for uncooled NETD near 1mK. Such a structure is conceptually shown in Figure 0.

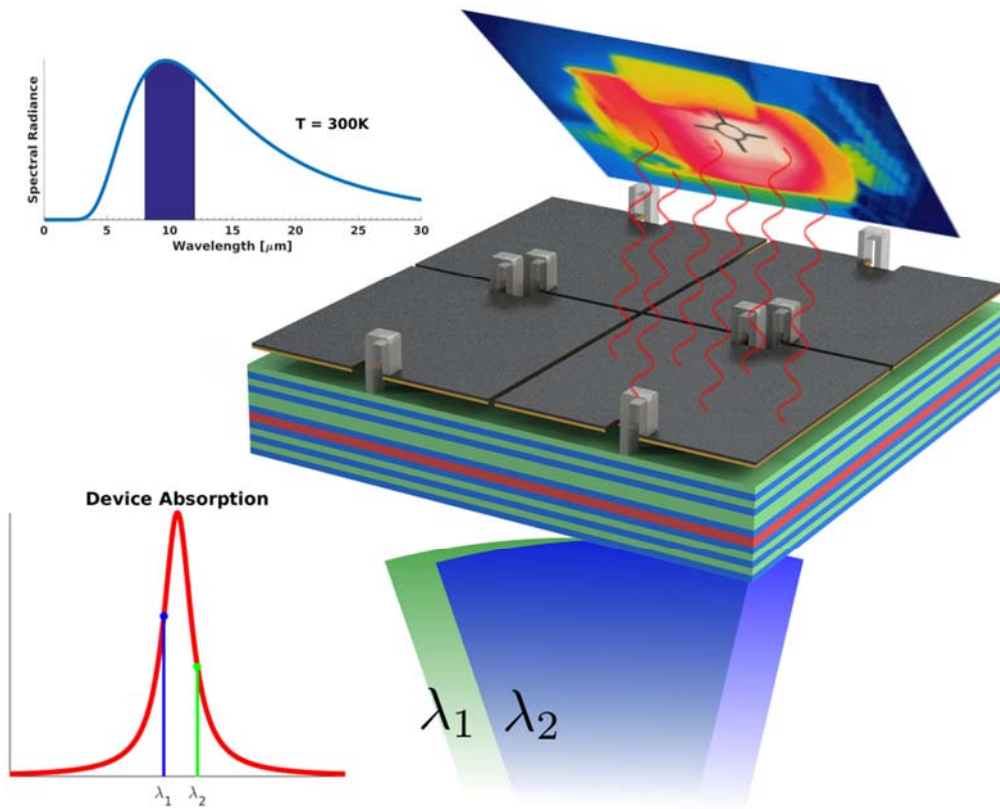


Figure 0 – Conceptual diagram of a resonant-cavity pyrometer device array. Long-wave infrared (LWIR) light from a target object is absorbed by the top surface of a thermal detector. The detector plate serves as part of the top mirror of an underlying optical cavity, and the plate deflects (for example via a thermal bimorph in this diagram) upon being heated by the absorbed LWIR light. The deflection shifts the resonance of the underlying cavity, and the resulting change in reflectivity can be read by short wavelength lasers.

In Fig.1, a mechanical model of such an infrared thermal detector is presented. A bimorph cantilever connected to a support contains a proof mass at its tip. The cantilever represents the infrared absorption area and the proof mass represents the top mirror of the resonant cavity. The cantilever is thermally actuated by long IR light (i.e., 8-10 μm). A visible or near IR laser (driving at 50 Hz) is used to readout the deflection due to thermal actuation.

The detailed schematic representation of the bimorph cantilever is showed in Fig. 2. Here length, width and thickness are denoted as L , W and t , respectively. Two different dielectric films are used in the bimorph structure. Layer 1 is taken as either Silicon nitride (Si_3N_4) or graphite and layer 2 is taken as polyamide. These materials are selected mainly due to their large difference in thermal expansion coefficients.

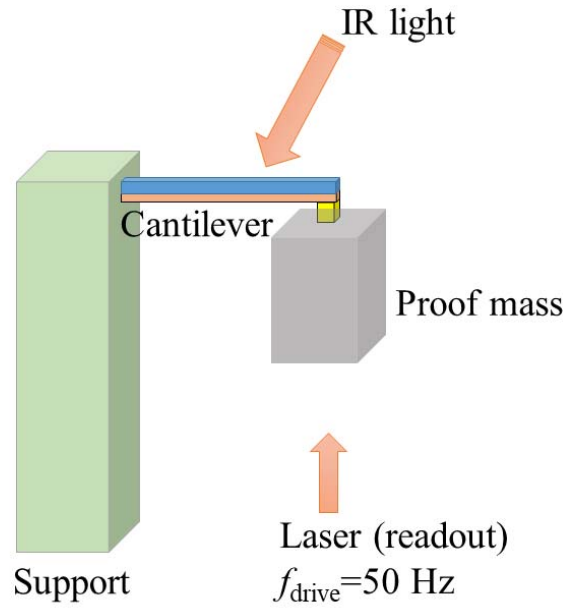


Figure 1: Simplified mechanical model of an infrared thermal detector. The bimorph cantilever structure represent the infrared absorption area and actuator while the proof mass represents the top mirror of the resonator. The Long IR ($\sim 8\text{-}10\text{ }\mu\text{m}$) light is used to thermally actuate the cantilever. A visible or near IR laser is used to readout the deflection as described in Figure 0.

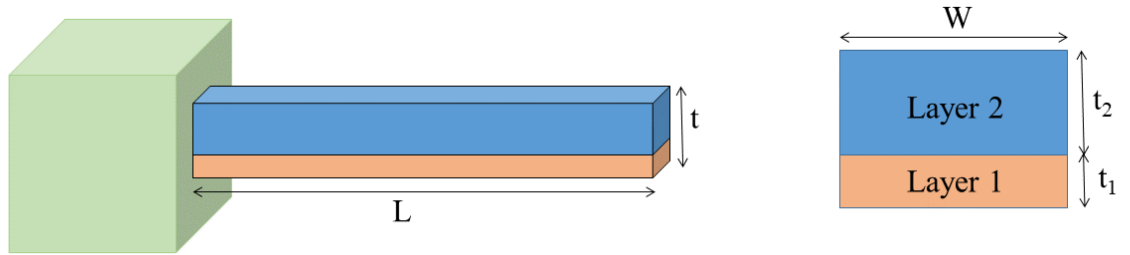


Figure 2: Schematic representation and cross-section of the bimorph cantilever structure. Length, width, and thickness are represented as L , W and T respectively

Calculation of deflections due to thermal actuation:

Improved Stoney's equation including higher-order terms of layer thicknesses to calculate thermal actuation as

$$x_{act} = \frac{6E_1E_2t_1t_2(t_1+t_2)(\alpha_2-\alpha_1)\Delta T}{E_1^2t_1^4+E_2^2t_2^4+2E_1E_2t_1t_2(2t_1^2+2t_2^2+3t_1t_2)} \frac{L^2}{2} \quad (1)$$

Where, L is the length of the cantilever, E is the Young's modulus, t is the thickness, α is the coefficient of thermal expansion, ΔT is the temperature increase, the subscripts 1 and 2 denote the graphite and polyamide layers, respectively.

The equivalent Young's modulus and density can be calculated as

$$E_{eff} = \frac{E_1^2\left(\frac{t_1}{t}\right)^4 + E_2^2\left(\frac{t_2}{t}\right)^4 + 2E_1E_2\left(\frac{t_1}{t}\right)\left(\frac{t_2}{t}\right)\left(2\left(\frac{t_1}{t}\right)^2 + 2\left(\frac{t_2}{t}\right)^2 + 3\left(\frac{t_1}{t}\right)\left(\frac{t_2}{t}\right)\right)}{E_1\left(\frac{t_1}{t}\right) + E_2\left(\frac{t_2}{t}\right)} \quad (2)$$

$$\rho_{eff} = \frac{\rho_1 \times t_1 + \rho_2 \times t_2}{t_1 + t_2} \quad (3)$$

where E_{eff} is equivalent Young's modulus, ρ_{eff} is equivalent density, ρ is the density of individual layer, and t is the total thickness of the bilayer cantilever (as $t=t_1+t_2$).

The dynamic behavior of the thermal actuation driven deflections can be represented by its dependence on the driving frequency, which can be expressed as

$$x_{act}(f) = x_{act} \frac{\exp(1/2\tau f) - 1}{\exp(1/2\tau f) + 1} \quad (4)$$

where x_{act} is the static deflection due to thermal actuation, f is the driving frequency of the thermal source (i.e., IR laser) and τ is the thermal time constant. The value of τ can be calculated from the following expression as

$$\tau = \frac{C_{cant}}{G_{rad}} \quad (5)$$

Here C_{cant} the total heat capacity of the detector and G_{rad} is the radiation limited thermal conductance (as the detection is optical). C_{cant} can be calculated as $C_{cant} = C_1\rho_1V_1 + C_2\rho_2V_2$, where V is the volume of individual layer and the subscripts 1 and 2 denote the graphite and polyamide layers, respectively. In addition, due to inclusion of the graphite layer (black body) in the cantilever, G_{rad} can be simplified and expressed as $G_{rad}=8A\sigma T^3$, where A is the surface area of the detector, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$) and T is the room temperature (300 K).

Calculation of deflections due to thermo-mechanical noise:

A crude frequency averaged thermal noise driven deflection at different resonance modes can be calculated as

$$x_{TM}(f_{rn}) = \frac{k_b T_m}{k_n} \quad (6)$$

Where k_b is the Boltzmann constant, T_m is the room temperature and k_n is the spring constant at the resonance mode. The amplitude of $x_{TM}(f_m)$ is dependent upon its resonant frequencies, which can be calculated as

$$f_{rn} = \frac{1}{2\pi} \sqrt{\frac{k_n}{m}} \quad (7)$$

with

$$k_n = \frac{\alpha_n^4 E_{eff} W t^3}{3 \cdot 4 L^3} \text{ and } m = \rho_{eff} L W t$$

Here, m is the mass of the bimorph cantilever and α_n is a constant corresponding to different resonant modes. For fundamental resonance ($n=1$), α_1 can be taken as 1.875. Other flexural modes can also be calculated as $\alpha_n=(n-1/2)*\pi$. Putting expression of k_n and m , Eq. (5) can be expressed as

$$f_{rn} = \frac{\alpha_n^2}{2\pi} \sqrt{\frac{E_{eff}}{12\rho_{eff}}} \frac{t}{L^2} \quad (8)$$

The deflection due to thermo-mechanical noise largely depends on frequency. Frequencies higher than resonant frequency (f_m) produces x_{TM} much smaller than $x_{TM}(f_m)$. Therefore, we decrease the resonant frequency f_m ($\sim 1-10$ Hz) and readout the thermally actuated deflection at a drive frequency (50 Hz) higher than f_m , where x_{act} would be larger than $x_{TM}(50 \text{ Hz})$. The inclusion of the proof mass at the tip of the cantilever serves the purpose of decreasing the resonant frequency. If the proof mass is M , the resultant shifted resonant frequency can be calculated as

$$f_{tn} = \sqrt{\frac{m}{M}} f_{rn} \quad (9)$$

Due to gravity, the proof mass would deflect the tip of the cantilever at $x_{mass}=Mg/k_n$, where g is the gravitational acceleration.

The magnitude of x_{TM}^2 at a particular frequency (say f_d) can be calculated by integrating the power spectrum density (PSD), $S_d(f)$ in a convenient frequency interval $2\Delta f$ around that particular frequency,

$$x_{TM}^2(f_d) = \int_{f_d-\Delta f}^{f_d+\Delta f} S_d(f) df \quad (10)$$

where,

$$S_d(f) = \frac{2k_b T_m}{k_n \pi f_{tn}} \frac{Q_n}{(1-u^2)^2 Q_n^2 + u^2} \quad (11)$$

Here, Q_n is the quality factor and $u=f/f_{tn}$ is the normalized frequency. The square root of x_{TM}^2 would provide the thermomechanical noise deflection for specific frequencies. If f_d is taken as f_m , the calculated thermomechanical noise deflection would be same as found from Eq. (5).

Calculation of radiation pressure driven deflection:

For readout laser, with visible or near IR wavelengths, the radiation pressure force can be calculated as

$$F_{\text{photon}} = \frac{2P_R + P_A}{c} \quad (12)$$

Where F_{photon} is the photon pressure force (N), P_R is the fraction of photon power (W) reflected from the proof mass surface, P_A is the fraction of photon power (W) absorbed, and c is the speed of light (m/s). In dynamic measurements, the RMS amplitude response of the cantilever due to photon pressure can be calculated as

(13)

$$x_{\text{photon}} = \frac{1}{2\sqrt{2}} \frac{(2P_R + P_A)(a^2 - 3a + 3)}{3ck_n a(a-2)^2}$$

Where a is the normalized measurement position ($a=x/L$ where x is the distance of measurement laser spot from the base of the cantilever and L is the length of the cantilever) and k_n is the spring constant. For convenience, we can assume $x=L$, so the value of a becomes 1.

Design of a thermal detector

(a) Serpentine struture

Fig. 3 shows a thermal detector design within $30 \mu\text{m} \times 30 \mu\text{m}$ lateral dimension. The detector consists of two serpentine shaped bimorph cantilevers. The lateral dimensions of each serpentine cantilever is shown in Fig. 4. The total thickness of the cantilever is taken as 100 nm (graphite layer 50 nm; polyamide layer 50 nm). Two serpentine structures are connected to a proof mass at their tips. The proof mass can be modeled as a multilayer SiO_2 - Si_3N_4 reflector, with lateral dimensions of $30 \mu\text{m} \times 30 \mu\text{m}$. This mass can be modeled as a top mirror of a Fabry Parot cavity. The bottom mirror will be another multilayer SiO_2 - Si_3N_4 structure. The thickness of individual SiO_2 and Si_3N_4 layers can be taken as 97.5 nm and 70.1 nm, respectively, which provides nearly 100% reflection in the wavelength range of 520-620 nm. Any wavelength in this range can be used as optical readout.

The total area by the cantilever is $770 \mu\text{m}^2$ (filling factor= 86%)

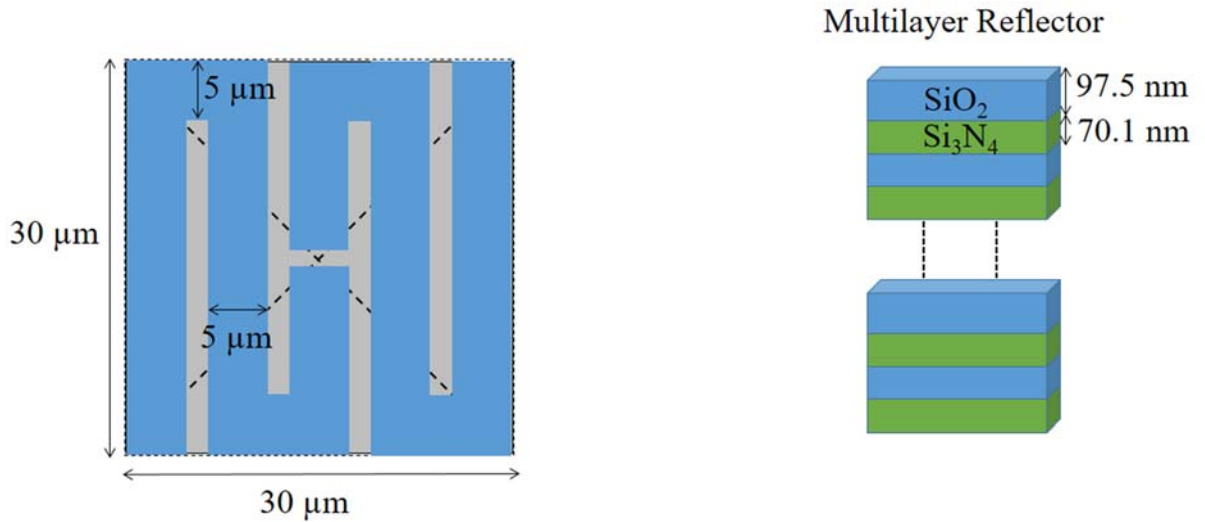


Figure 3: Schematic representation of an infrared thermal detector with bimorph cantilever and Fabry-Parot cavity. The total enclosed area is $30 \mu\text{m} \times 30 \mu\text{m}$.

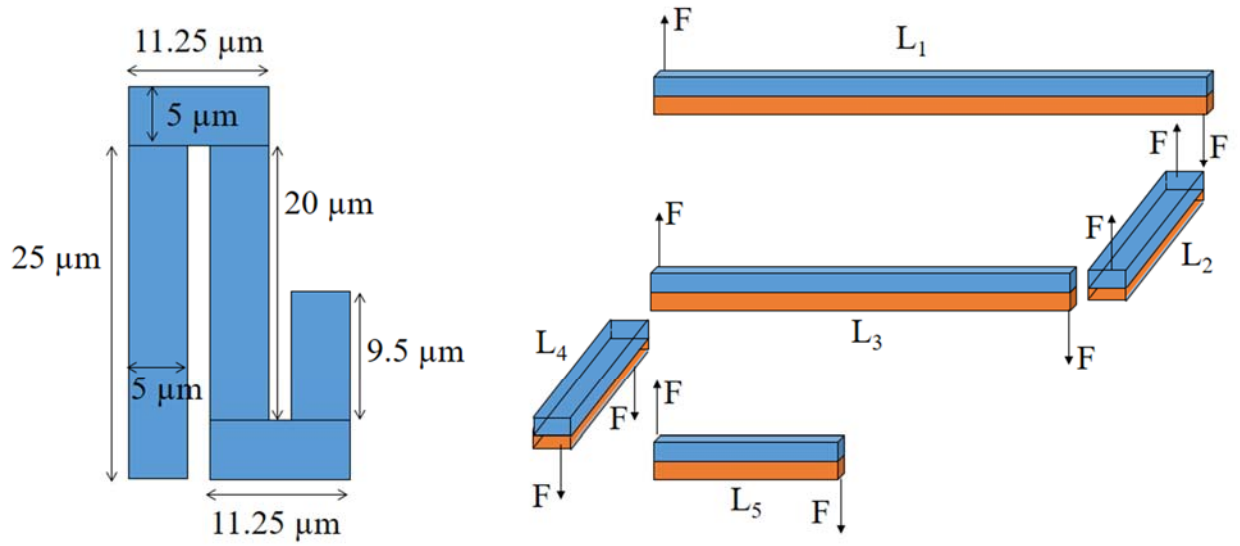


Figure 4: Lateral dimensions of the serpentine bimorph cantilever.

Cantilever Parts	Length, L	Width, W	Thickness, t	
			Graphite (t_1)	Polyamide (t_2)
Part 1	25 μm	5 μm	50 nm	50 nm
Part 2	11.25 μm	5 μm	50 nm	50 nm
Part 3	20 μm	5 μm	50 nm	50 nm
Part 4	11.25 μm	5 μm	50 nm	50 nm
Part 4	9.5 μm	5 μm	50 nm	50 nm

Stiffness Constant calculation for bending moment

For part 1, $k_{1c} = \frac{E_{eff}Wt^3}{4L_1^3} = 1.28 \times 10^{-3} \text{ Nm}^{-1}$;

For part 2, $k_{2c} = -\frac{E_{eff}Wt^3}{3L_1L_2^2} = -8.428 \times 10^{-3} \text{ Nm}^{-1}$

For part 3, $k_{3c} = \frac{E_{eff}Wt^3}{4L_3^3} = 2.5 \times 10^{-3} \text{ Nm}^{-1}$;

For part 4, $k_{4c} = -\frac{E_{eff}Wt^3}{3L_3L_4^2} = -10.5 \times 10^{-3} \text{ Nm}^{-1}$

For part 3, $k_{5c} = \frac{E_{eff}Wt^3}{4L_5^3} = 23.3 \times 10^{-3} \text{ Nm}^{-1}$

Total stiffness constant

$$\frac{1}{k_t} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \frac{1}{k_4} + \frac{1}{k_5}$$

$$k_t = 9.898 \times 10^{-4} \text{ Nm}^{-1}$$

There are two cantilevers in parallel, so $k_e = 2 \times k_t = 1.9796 \times 10^{-3} \text{ Nm}^{-1}$

According to Eq. (7) $k_n = \frac{\alpha_n^4}{3} k_e$; with fundamental mode ($n=1$, $\alpha_1=1.875$), $k_1 = 8,1559 \times 10^{-3} \text{ Nm}^{-1}$

Deflections due to thermal actuation (static) are presented in Fig. 5

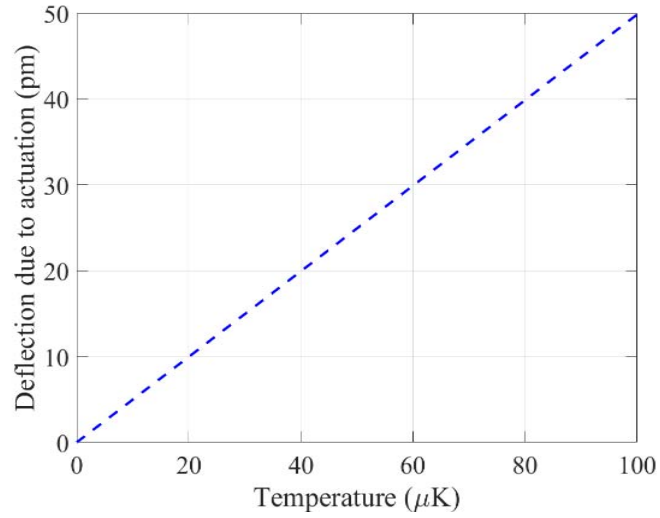


Figure 5: Deflections of the serpentine structure (showed in Fig. 3) due to thermal actuation.

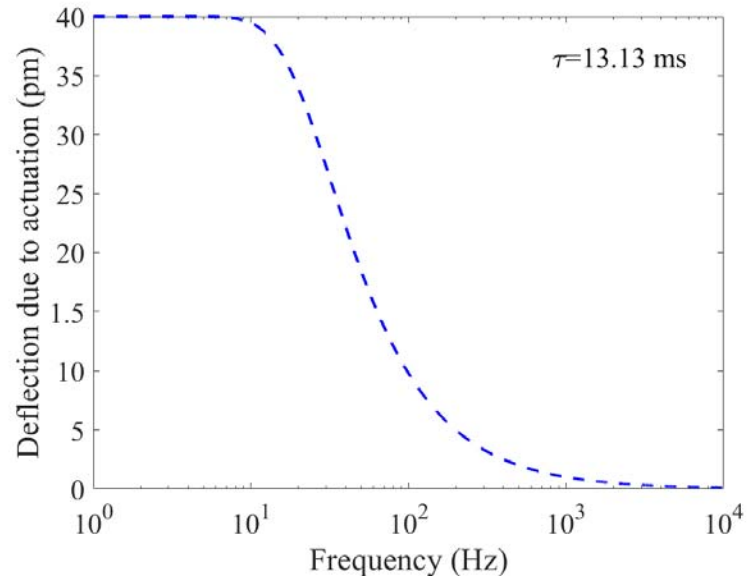


Figure 6: Frequency response of the thermally actuated deflections of the serpentine structure (showed in Fig. 3)

Spring constant, k (N/m)	Mass of the detector, m (kg)	Fundamental resonant frequency, f_{r1} (Hz)	Proof mass, M (kg)	Transformed resonant frequency, f_{t1} (Hz)	Deflection due to proof mass, x_{mass} (m)
$8.1559 \cdot 10^{-3}$	$1.128 \cdot 10^{-13}$	$2.1084 \cdot 10^4$	$8.0229 \cdot 10^{-12}$	$2.5 \cdot 10^3$	$9.36 \cdot 10^{-9}$

With the specified multilayer reflector (SiO_2 - Si_3N_4), the number of SiO_2 - Si_3N_4 layers needed for the proof mass will be 19 (18 pairs of SiO_2 - Si_3N_4 , with one single SiO_2 layer in the middle).

Power spectrum density (PSD) of thermal noise at shifted resonant frequency is plotted in Fig 7

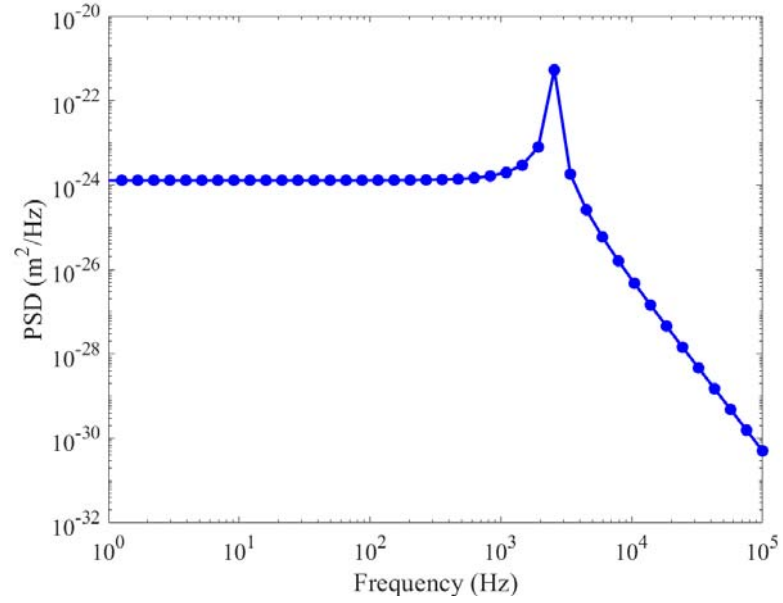


Figure 7: PSD of thermal noise induced deflection for the serpentine structure, with transformed resonance occurring at ~ 2500 Hz.

Reflection spectrum of the 19 layers of SiO_2 - Si_3N_4 dielectric mirror is shown in Fig. 8

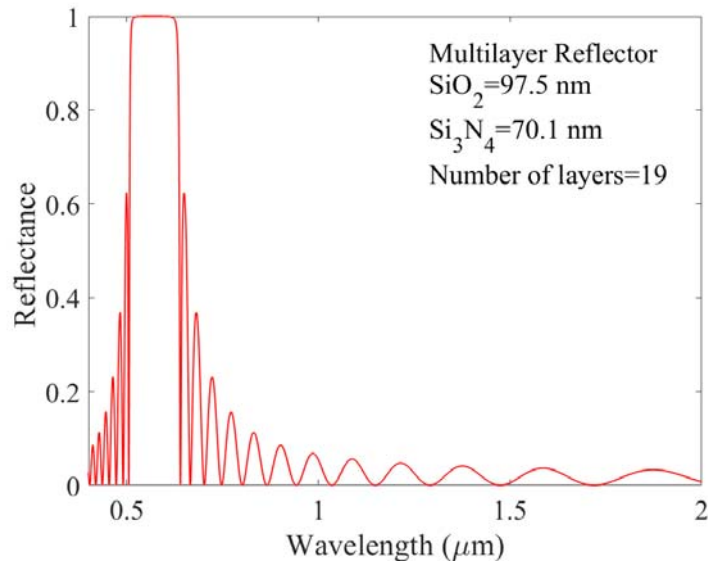


Figure 8: Reflection Spectrum of SiO_2 - Si_3N_4 multilayer structure. 9 layer of SiO_2 - Si_3N_4 ; 1 layer of SiO_2 ; 9 layer of Si_3N_4 - SiO_2 .

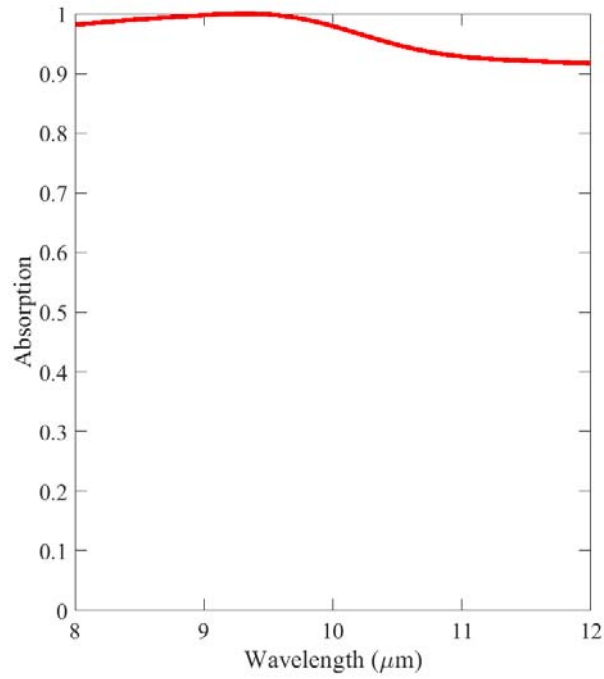


Figure 9: Absorption spectrum of the serpentine structure in the long IR range (8-12 μm)

x_{act} (static)	x_{act} (50 Hz)	x_{TM} (2500 Hz) (mode=1)	x_{TM} (50 Hz) (mode=1)	x_{photon} (due to radiation pressure)		
				$P_{\text{in}}=0.15$ mW	$P_{\text{in}}=0.2$ mW	$P_{\text{in}}=0.25$ mW
40 μm	19.13 μm	712 μm	5.0866 μm	14.49 μm	19.26 μm	24.08 μm

- Material properties:**

Material	Density (kg/m ³)	Specific Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)
graphite	1800	720	168
Polyamide	1130	1700	0.24

Heat capacity of the detector, $C_{\text{cant}} = 1.23852 \times 10^{-10}$ J/K

Thermal conductance, $G_{\text{rad}} = 8A\sigma T^3 = 9.4302 \times 10^{-9}$ W/K

Thermal time constant, $\tau = C_{\text{bimorph}} / G_{\text{rad}} = 13.13$ ms

$$NEP = G_{\text{rad}} \sqrt{\frac{k_B T^2}{C_{\text{cant}}}} = 9.4434 \times 10^{-13} \text{ W}$$

For NETD, we know

$$\frac{\delta T_d}{\delta T_0} = \frac{A\epsilon\pi}{4F^2 G_{\text{rad}}} \frac{dL}{dT_0}$$

If $\delta T_d = 80$ μK, then δT_0 reduces to 1.509 mK.

(b) Stripe structure

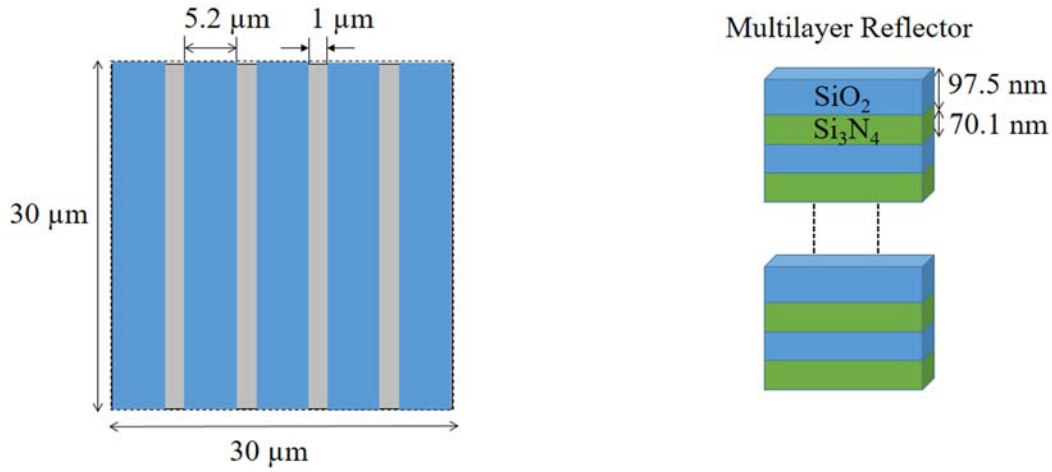


Figure 10: Schematic representation of an infrared thermal detector with bimorph cantilever and Fabry-Parot cavity. The total enclosed area is $30 \mu\text{m} \times 30 \mu\text{m}$.

Fig. 10 shows a thermal detector design within $30 \mu\text{m} \times 30 \mu\text{m}$ lateral dimension. The detector consists of five individual bimorph cantilevers. The dimensions of each cantilever are given in the following table. Five bimorph structures are connected to a proof mass at their tips. The proof mass can be modeled as a multilayer SiO_2 - Si_3N_4 reflector, with lateral dimensions of $30 \mu\text{m} \times 30 \mu\text{m}$. This mass can be modeled as a top mirror of a Fabry Parot cavity. The bottom mirror will be another multilayer SiO_2 - Si_3N_4 structure. The thickness of individual SiO_2 and Si_3N_4 layers can be taken as 97.5 nm and 70.1 nm, respectively, which provides nearly 100% reflection in the wavelength range of 520-620 nm. Any wavelength in this range can be used as optical readout.

The total area by the cantilever is $780 \mu\text{m}^2$ (filling factor= 87%)

Length, L	Width, W	Thickness, t	
		Graphite Layer (t_1)	Polyamide Layer (t_2)
$30 \mu\text{m}$	$5 \mu\text{m}$	50 nm	50 nm

Stiffness Constant calculation for bending moment

Stiffness constant for each bimorph structure $k_c = \frac{E_{eff} W t^3}{4L^3} = 7.7037 \times 10^{-4} \text{ Nm}^{-1}$;

There are five cantilevers in parallel, so $k_e = 5 \times k_c = 3.85185 \times 10^{-3} \text{ Nm}^{-1}$

According to Eq. (7) $k_n = \frac{\alpha_n^4}{3} k_e$; with fundamental mode ($n=1$, $\alpha_1=1.875$), $k_1=15.86 \times 10^{-3} \text{ Nm}^{-1}$

Deflections due to thermal actuation (static) are presented in Fig. 11

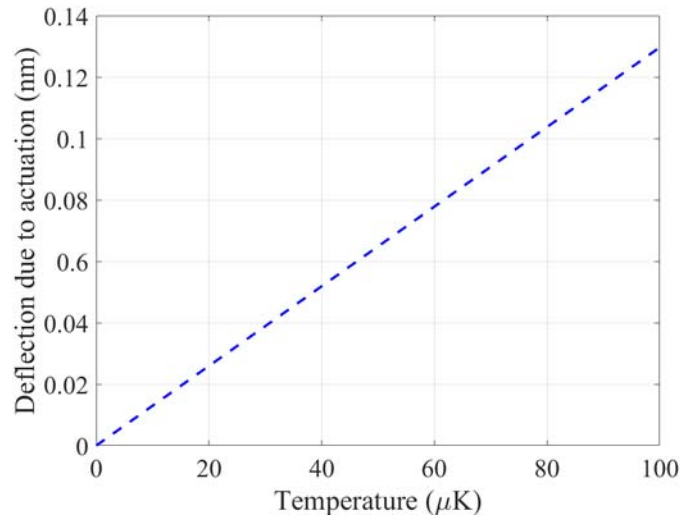


Figure 11: Deflections of the bimorph stripe structure (showed in Fig. 8) due to thermal actuation.

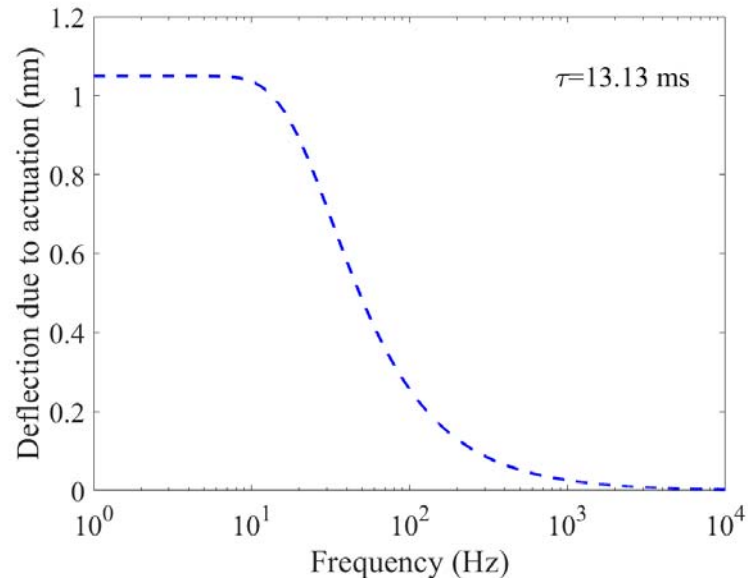


Figure 12: Frequency response of the thermally actuated deflections of the bimorph stripe structure (showed in Fig. 10)

Spring constant, k (N/m)	Mass of the detector, m (kg)	Fundamental resonant frequency, f_{r1} (Hz)	Proof mass, M (kg)	Transformed resonant frequency, f_{t1} (Hz)	Deflection due to proof mass, x_{mass} (m)
0.01586	$1.1427 \cdot 10^{-13}$	$5.9293 \cdot 10^4$	$9.5085 \cdot 10^{-12}$	$6.5 \cdot 10^3$	$5.875 \cdot 10^{-9}$

With the specified multilayer reflector (SiO_2 - Si_3N_4), the number of SiO_2 - Si_3N_4 layers needed for the proof mass will be 23 (22 pairs of SiO_2 - Si_3N_4 , with one single SiO_2 layer in the middle).

Power spectrum density (PSD) of thermal noise at shifted resonant frequency is plotted in Fig 13

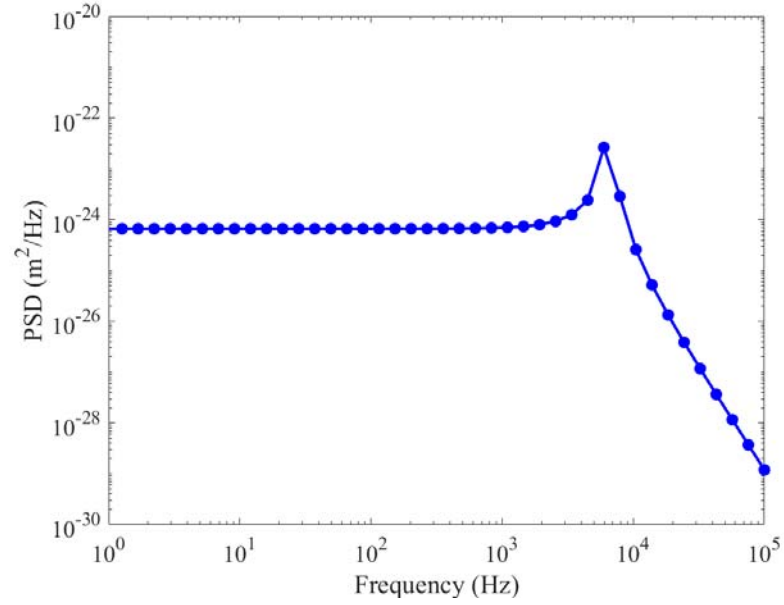


Figure 13: PSD of thermal noise induced deflection for the bimorph stripe structure, with transformed resonance occurring at ~ 6500 Hz.

Reflection spectrum of the 23 layers of SiO_2 - Si_3N_4 dielectric mirror is shown in Fig. 14

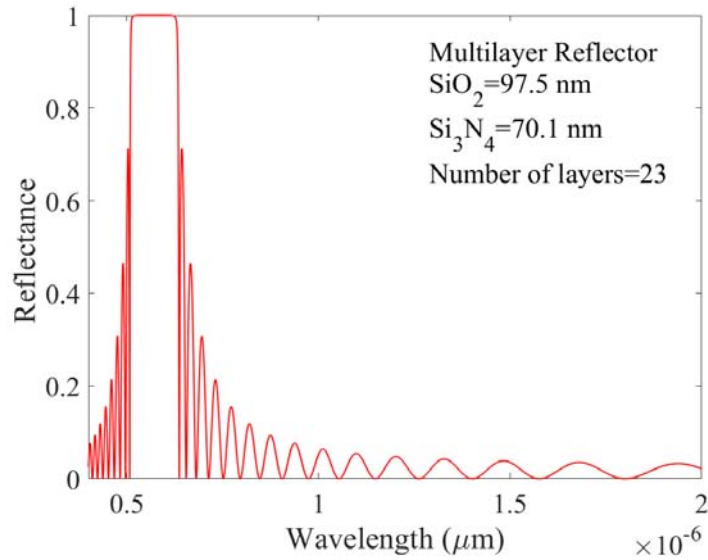


Figure 14: Reflection Spectrum of SiO_2 - Si_3N_4 multilayer structure. 11 layer of SiO_2 - Si_3N_4 ; 1 layer of SiO_2 ; 11 layer of Si_3N_4 - SiO_2 .

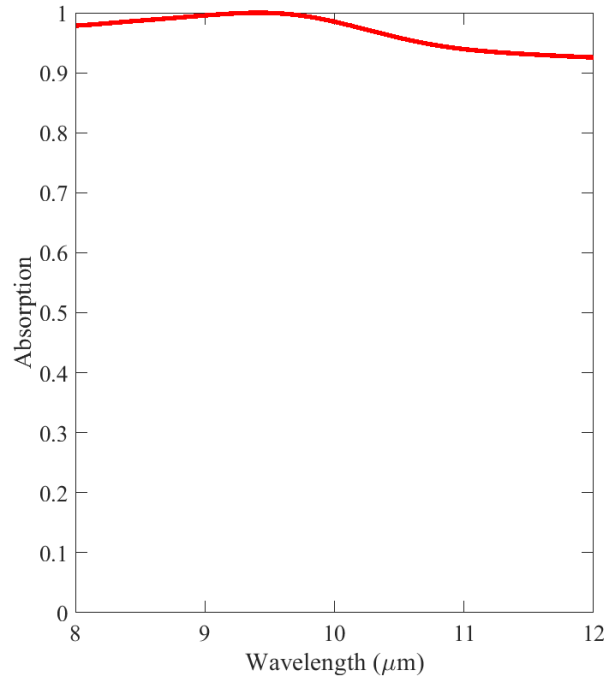


Figure 15: Absorption spectrum of the bimorph stripe structure in the long IR range (8-12 μm)

x_{act} (static)	x_{act} (50 Hz)	x_{TM} (2500 Hz) (mode=1)	x_{TM} (50 Hz) (mode=1)	x_{photon} (due to radiation pressure)		
				$P_{\text{in}}=0.8 \text{ mW}$	$P_{\text{in}}=1 \text{ mW}$	$P_{\text{in}}=1.2 \text{ mW}$
105 pm	51.12 pm	510.7 pm	2.2607 pm	39.6 pm	49.5 pm	59.44 pm

IV. Chapter 2: Optimizing Area per Unit Mass

Probably our most significant finding of the second year of the program was quantifying how much open space could be incorporated into a subwavelength infrared absorption structure yet still retain near 100% absorption levels. While such concepts have been known for antennas for decades, they have only recently been applied to other devices, and we may be the first to create a metric: absorption-per-unit-mass, that quantifies the performance improvement possible in uncooled LWIR detectors.

The first question we should pose is why do absorption and mass impact the performance of an uncooled detector? The first myth we need to reject is that one should design thermal detectors with the lowest possible mass to increase speed to its maximum possible value. While this design technique works for relatively low performance thermal detectors, such as would be seen in microbolometer cameras, it fails when one wishes to reach near radiation-limited performance for uncooled devices. Beyond a certain D^* (or NETD for a given architecture), the noise becomes limited by the temperature fluctuations of the detector itself, and these temperature fluctuations are inversely proportional to the square root of the thermal mass. If reducing the mass makes the temperature fluctuation noise greater than another noise source, then reducing the mass is harmful.

This means that the thermal mass of a high-performance detector is largely controlled by the radiation limit itself. The radiation-limit defines the minimum mass, and then one designs the detector to maximize the absorption area for that mass that still gives near-perfect absorption. These conditions maximize speed while still maintaining radiation-limited performance.

Introduction

Achieving near-perfect LWIR absorption with wide bandwidth has become a critical goal in the design and implementation of infrared thermal and imaging devices [1–4]. With the advent of science and technology, it has become possible to design LWIR broadband absorbers with ultra-thin sub-wavelength thicknesses [5–8]. Furthermore, nearly perfect absorbers have also been studied for their use in bio-sensing [9, 10], photodetection [11], and thermal emission based-cooling [12–15].

In recent years, relevant research has focused on the design and development of perfect LWIR absorbers with small amounts of material [16–18]. Maximizing absorption in a system with low thermal mass is crucial, for example, in microbolometers and other thermal detectors. In a traditional microbolometer, one attempts to reduce mass in order to achieve a lower thermal time constant (in other words, faster response) [3, 17, 19]. For high performance radiation-limited thermal detectors, the concept is a bit more subtle. The minimum mass of a detector is limited by the magnitude of intrinsic thermal fluctuations that can be tolerated on the device; therefore, any mass below this is counterproductive. With this given thermal mass, one then wishes to maximize the area of the detector so that the thermal conductance, which is dependent on the area for radiation-limited devices, can be maximized, reducing the time constant.

In order to achieve high LWIR absorption with low mass, a number of structures can be investigated, such as metamaterial absorbers [20–23] and plasmonic composites [24, 25]. Typically metamaterials are comprised of three distinct layers, (a) a bottom continuous metal layer, (b) an insulator spacing layer, and (c) a top subwavelength metal patch layer [5, 6]. In such a metal-insulator-metal (M-I-M) configuration, maximum light coupling is realized by perfect impedance matching with the incident medium, resulting in minimum (near zero) reflection. However, perfect impedance matching can only be obtained over a narrow frequency range, specifically with uniformly sized metal patches supporting a single resonant band [26, 27]. To broaden the bandwidth, one approach is to tailor the size of the planar metal patches in a single unit cell (i.e., multiple planar resonators in a unit cell), resulting in a superposition of multiple resonance bands [6]. In addition to increasing the absorption area, this approach has a couple of drawbacks: (1) larger volume of material in a period, resulting in smaller absorption per unit mass, and (2) the magnetic response may not be simultaneously tuned for all resonator patches in a single unit, resulting in an imperfect impedance matching and hence, imperfect optical absorption [26, 27]. Another convenient approach is to pattern the top layer with alternating metal-dielectric (i.e. metal-insulator, M-I) thin films vertically stacked in a graded fashion, resulting in anisotropic sawtooths [28] or trapezoidal pyramids [8, 29]. The vertically stacked films allow multiple resonant frequencies to be spaced adjacent to one another with smaller intervals among the resonance bands than the planar resonators, resulting in a reduction of the quality factor over a wide bandwidth. However, maximum absorption with low quality factor can only be achieved when a large number of metal-dielectric films can be stacked in a period,

eventually increasing the total volume and decreasing absorption per unit mass. For example, a graded trapezoidal pyramid requires a thickness of 6 μm to maintain perfect broadband absorption in the range of wavelengths from 10 μm to 30 μm [29]. Other metamaterial approaches for perfect broadband LWIR absorption include hyperbolic metamaterials (doped-undoped semiconductor stacks) [30, 31] and unpatterned metal-dielectric pairs [32], which require even larger amount of materials per pixel or period than M-I-M structures. In case of plasmonic structures, perfect LWIR absorption is typically observed over a narrow bandwidth, which can be attributed to their highly dispersive resonance characteristics [5, 9, 16]. A few works have reported broadband LWIR absorption through the superposition of multiple resonance bands at the cost of larger volumes of plasmonic structures [24, 25], yielding again larger amount of material. There is hardly, if any, work reported for broadband absorption over the LWIR transparency window that realizes near-perfect absorption with minimum material.

A broadband LWIR pixel array structure is described in this Interim Progress Report that maximizes absorption per unit mass by utilizing two-dimensional subwavelength gratings with guided mode resonance (GMR) in the pixel structure, and further designing the array so that gaps between pixels act as part of the absorption structure via evanescent field coupling. In recent years, GMRs have been exploited to design LWIR filters [33, 34] by virtue of their simple structures and nearly 100% diffraction efficiency. In our structure, we use lossy metal-dielectric (i.e., Ti-Si₃N₄) bilayer waveguide gratings with low fill factors (large hole fractions) that enable evanescent field coupling inside the open holes. Instead of the conventional M-I-M configuration used in many metamaterials, we design with only a metal-dielectric (two layer) grating, resulting in enhanced absorption per unit mass. We design and optimize a GMR pixel array (i.e., pixels surrounded by periodic air gaps), where each pixel is formed by the low fill factor Ti-Si₃N₄ grating (or grid unit) cells. We calculate the broadband LWIR absorption of the GMR pixels using the finite difference time domain technique (FDTD). Finally, we calculate and analyze the absorption per unit mass of the resulting pixel.

1. Theoretical design of the GMR pixel with subwavelength gratings

2.1 Metal-dielectric subwavelength grating cells

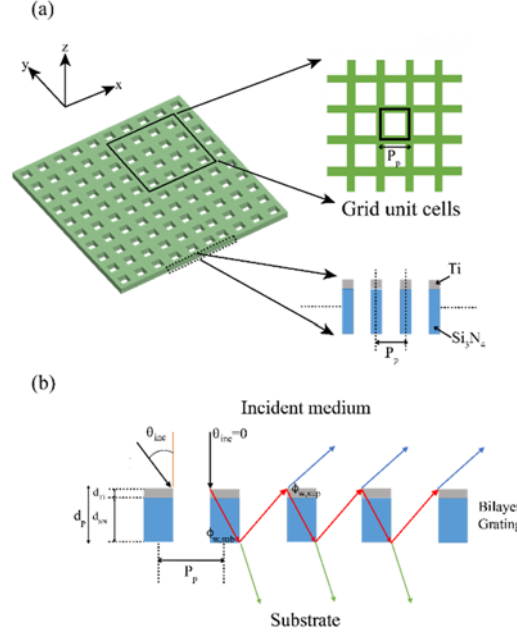


Fig. 1. (a) Schematic illustration of grid unit cells constructed from the metal-dielectric (Ti-Si₃N₄) waveguide gratings. Period of a grid unit cell (P_p) is highlighted, along with Ti and Si₃N₄ layers. (b) Incidence of light in the Ti-Si₃N₄ waveguide gratings; some portion will be reflected (blue arrows) and transmitted (green arrows), and the rest will propagate laterally inside the grating structure, resulting in trapping and absorption of light (red arrows). The thicknesses of the Ti and Si₃N₄ layers in the grating are presented as d_{Ti} and d_{SiN_4} , respectively. The total thickness is shown as d_p , i.e., $d_p = d_{Ti} + d_{SiN_4}$. $\phi_{w,sup}$ and $\phi_{w,sub}$ present phase shifts due to the total internal reflection at the waveguide-incident medium and waveguide-substrate interfaces.

Figure 1(a) shows the metal-dielectric (Ti-Si₃N₄) waveguide gratings in the form of grid unit cells. The period of the grid unit cells (P_p) is explicitly shown along with the metal and dielectric layers. Such optical gratings can support resonant waveguide modes depending on a number of parameters, including the complex dielectric permittivity, the thickness of the grating layers, and the hole fraction of the grating structure [35]. To ensure enhanced LWIR broadband absorption with small mass, lossy materials need to be chosen so that both refraction and extinction can contribute to the guided mode excitation. The mechanism of enhanced absorption due to lossy dielectrics has already been reported in previous articles [4, 36, 37]. Compatibility with common microfabrication technology makes SiO₂ and Si₃N₄ two of the simplest choices for lossy dielectrics in the LWIR. SiO₂ has a very sharp absorption peak at $\sim 9.22 \mu\text{m}$, resulting in highly dispersive characteristics in the LWIR [38]. Si₃N₄ has multiple vibrational phonon peaks in between $8\text{--}12 \mu\text{m}$, which correspond to a comparatively moderate dispersion and broader absorption profile in the LWIR [39]. For this reason, we choose Si₃N₄ as the lossy dielectric. The addition of a thin metal layer (absorbing in the LWIR) on top of the dielectric layer can significantly reduce the quality factor and broaden the entire absorption band [40]. A number of metal films e.g., Ti, Cr and Ni have already been used for this purpose due to their similar optical properties [41–43]. However, Cr and Ni have densities approximately two times larger than Ti [44], which would increase the overall amount of mass. Therefore, we choose Ti as the lossy thin metal film to ensure enhanced absorption with smaller amount of mass. At this point, we should note that for some applications, such as thermal detectors, the optimal

performance metric is absorbance per unit thermal mass per unit volume instead of absorbance per unit mass. In these cases, the product of the density and specific heat for Ti, Cr, and Ni would be technically more accurate than density alone. In any case, Ti is also the best choice by this metric: the density-specific heat products of Cr and Ni are 40.3% and 65.8% higher than that of Ti, respectively.

Figure 1(b) shows 1D illustration of the bilayer waveguide gratings with incidence of light (θ_{inc}). Some portion of the light will reflect (blue arrows) or transmit (green arrows), and the rest will propagate inside the waveguide grating (red arrows), resulting in total internal reflection at the waveguide-incident medium and waveguide-substrate interfaces. At the guided mode resonant condition, the penetration of the light in the substrate or incident medium can be greatly reduced by forcing the diffracted light to propagate laterally and thus increasing the optical path inside the waveguide grating, resulting in maximum absorption. To ensure guided mode excitation, the grating thickness needs to be optimized with different hole fractions (i.e. duty cycles or fill factors). This requires an effective medium approximation in the waveguide grid unit cells. It should be noted that the dimensions of our subwavelength grating cells are well below the wavelength of the light in consideration, therefore effective medium approximation can be applied for the subwavelength domain. Fig. 2(a) presents the schematic of a grid unit period with the complex dielectric permittivities:

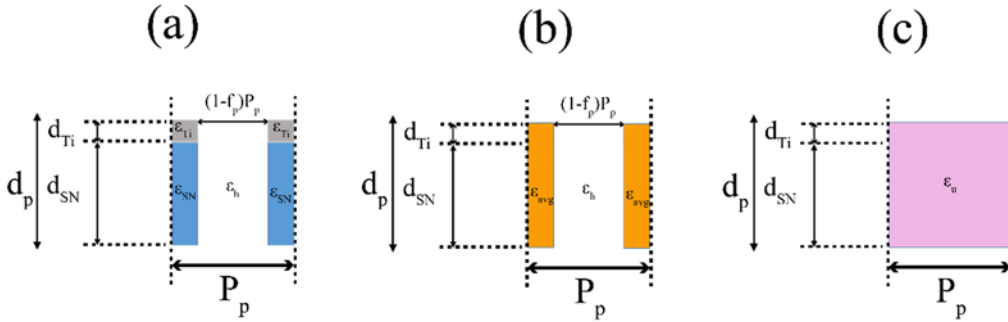


Fig. 2. Equivalent permittivity approximation of a grid unit cell. (a) Schematic illustration of a grid unit period with the complex dielectric parameters; ϵ_{Ti} , ϵ_{SN} , and ϵ_h for Ti, Si_3N_4 , and the hole (open) area, respectively. f_p and P_p correspond to the duty cycle and period of the unit cell, respectively. (b) As in part (a) but with an average permittivity ϵ_{avg} of the Ti- Si_3N_4 bilayer. (c) As in parts (a) and (b) but with an equivalent homogeneous permittivity ϵ_u of the grid unit period.

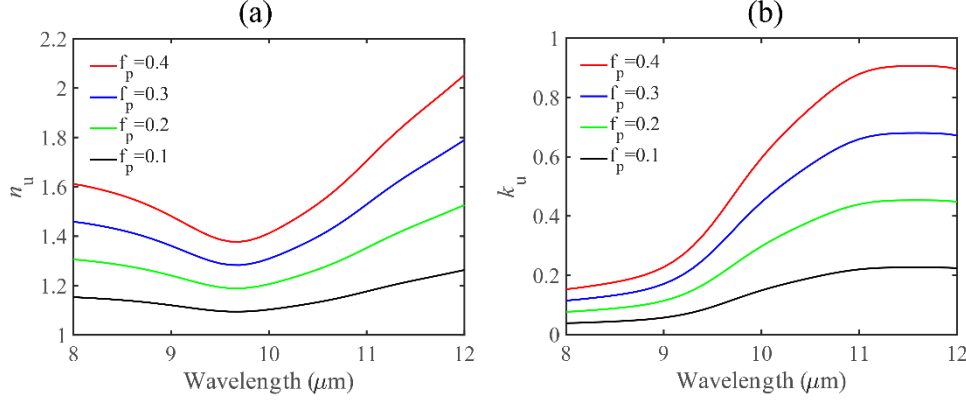


Fig. 3. Refractive index (n_u) and extinction coefficient (k_u) of the equivalent homogeneous grid unit cell. The thicknesses are assumed as $d_{Ti}=0.2d_p$ and $d_{SN}=0.8d_p$. f_p corresponds to the linear duty cycle of the unit cell, which in turn defines the fill factor (fractional area filled by solid material) and hole fraction.

ϵ_{Ti} , ϵ_{SN} , and ϵ_h for Ti, Si_3N_4 , and hole (open) area, respectively. f_p corresponds to the linear duty cycle of the unit cell, which in turn defines the fill factor (fractional area filled by solid material) and hole fraction. The thicknesses of Ti and Si_3N_4 layers in the unit cell are presented as d_{Ti} and d_{SN} , respectively. The total thickness is shown as d_p , i.e., $d_p = d_{Ti} + d_{SN}$. Let us assume $d_{Ti}=0.2d_p$ and $d_{SN}=0.8d_p$, considering maximum light coupling inside the dielectric layer (i.e., absorption dominated by dielectric loss) to avoid any unnecessary thermal heating due to metals [45]. The metal-dielectric bilayer grating can be approximated as a single layer with an average permittivity calculated as [46–50],

$$\epsilon_{avg} = \left(\frac{d_{Ti}}{d_p} \frac{1}{\epsilon_{Ti}} + \frac{d_{SN}}{d_p} \frac{1}{\epsilon_{SN}} \right)^{-1} \quad (1)$$

Fig. 2(b) shows the metal-dielectric bilayers approximated by a single effective layer with permittivity ϵ_{avg} . After single layer approximation, the hole ratio can be incorporated in the grid unit period to form an equivalent medium by the effective medium approximation as [47, 51–53],

$$\epsilon_u = f_p \epsilon_{avg} + (1 - f_p) \epsilon_h \quad (2)$$

where ϵ_u is the equivalent homogeneous permittivity of the grid unit cell (in Fig. 2(c)). Note that for air, $\epsilon_h = 1$. Fig. 3 shows the refractive index n_u and extinction coefficient k_u calculated from ϵ_u (i.e., $n_u + ik_u = \sqrt{\epsilon_u}$) with different values of f_p . Please note that we focus on investigating enhanced absorption with a minimum amount of material, therefore lower values of f_p have been considered in our analysis. From Fig. 3, it is quite evident that a lower f_p would decrease both n_u and k_u values due to a larger hole ratio. Since the silicon nitride layers are much thicker than those of Ti, n_u and k_u profiles of the homogeneous grid cell are much dominated by those of silicon nitride [54]. As a result, dielectric losses become prominent over much of the spectral range. Please note that the effective medium

approximation has been previously reported in analyzing the optical absorption of the grating and periodic array

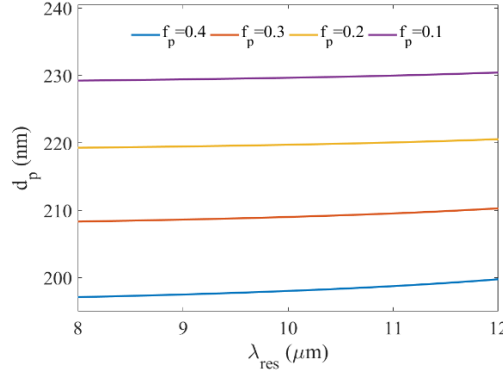


Fig. 4. Based on guided mode resonance theory, the thickness of the grid unit cell is optimized for diffraction efficiency with different duty cycles f_p . The x-axis shows the guided resonant wavelengths in the LWIR. Normal incidence of light ($\theta_{\text{inc}}=0^\circ$) and $P_p=1 \mu\text{m}$ are considered with first order diffraction ($m=\pm 1$).

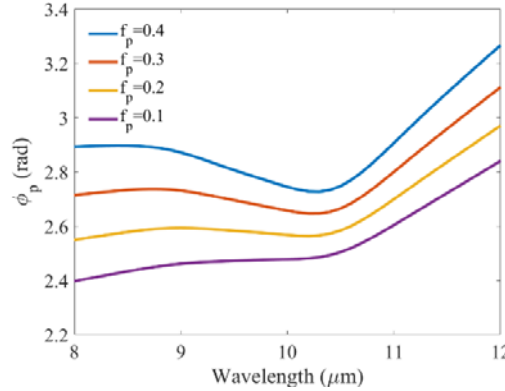


Fig. 5. Phase shifts of the grid unit cell with different duty cycles f_p . At a resonant wavelength (e.g., $\lambda_{\text{res}}=10.5 \mu\text{m}$), the optimum thickness d_p for different duty cycle f_p are taken from Fig. 4. Normal incidence of light ($\theta_{\text{inc}}=0^\circ$) and $P_p=1 \mu\text{m}$ are considered with first order diffraction ($m=\pm 1$).

structures [4, 55–57]. The effective medium cells show optical absorption nearly close to those of the actual structures (For example, an average relative error of $\sim 3\%$ found while analyzing in between $0.35\text{--}0.9 \mu\text{m}$ [55] and $\sim 8.5\%$ found while analyzing in between $7\text{--}14 \mu\text{m}$ [4]).

To optimize the diffraction efficiency based on GMR, the propagation waveguide modes in the grid unit cells with homogeneous permittivity ϵ_u can be coupled with the diffraction grating equation as [35, 58],

$$\tan(\kappa_i d_p) = \frac{\epsilon_u \kappa_i (\epsilon_{\text{sub}} \gamma_i + \epsilon_{\text{sup}} \delta_i)}{\epsilon_{\text{sub}} \epsilon_{\text{sup}} \kappa_i^2 - \epsilon_u^2 \gamma_i \delta_i} \quad (3)$$

where

$$\left\{ \begin{array}{l} \kappa_i = \sqrt{\varepsilon_u k_0^2 - \beta_i^2} \\ \gamma_i = \sqrt{\beta_i^2 - \varepsilon_{\text{sup}} k_0^2} \\ \delta_i = \sqrt{\beta_i^2 - \varepsilon_{\text{sub}} k_0^2} \\ \beta_i = k_0 \left(\sqrt{\varepsilon_{\text{sup}}} \sin \theta_{\text{inc}} + m \frac{\lambda}{P_p} \right) \\ k_0 = \frac{2\pi}{\lambda} \end{array} \right. \quad (4)$$

where λ is the wavelength, θ_{inc} is the angle of incidence (at normal incidence, $\theta_{\text{inc}}=0^\circ$), m is the diffraction order, ε_{sup} and ε_{sub} are the permittivity of the incident medium and substrate, respectively (for air, $\varepsilon_{\text{sup}} = \varepsilon_{\text{sub}} = 1$). Using this model, it is possible to evaluate the grid unit cell thickness d_p optimized for diffraction efficiency (based on GMR theory) across the LWIR (i.e., 8–12 μm) with different duty cycles f_p . Fig. 4 presents the optimum thicknesses d_p of the grid unit gratings for different duty cycles f_p , with the assumption of $\theta_{\text{inc}}=0^\circ$ (normal incidence), $m=\pm 1$ (first-order diffraction), and $P_p=1 \mu\text{m}$. The x -axis corresponds to the guided resonant wavelengths in the LWIR. Please note that only the transverse magnetic (TM) polarization is calculated since 2D symmetric grating structures (shown in Fig. 1(a)) at normal incidence are polarization independent [59–61], and can be analyzed by 1D gratings with only TM (or only TE) polarized light [60–62]. From Fig. 4, it is evident that for each duty cycle, the optimum thickness values are almost same over the whole LWIR range, which can ensure resonant absorption with a wide bandwidth. In addition, a lower duty cycle corresponds to a larger grating thickness for guided mode excitation, which has been observed in previously reported waveguide gratings [63].

At a particular optimum thickness, we can calculate the phase shifts of the diffracted light inside the grid unit cells to study the resonance quality (high-Q or low-Q) of the guided modes. As seen in Fig. 1(b), light traveling inside the waveguide grating encounters phase shifts that are characteristic of the various propagation modes, as well as, total internal reflections at the substrate-waveguide and incident medium-waveguide interfaces. Therefore, the total phase shift of the diffracted light inside the grid cell can be approximated as [64, 65],

$$\phi_p = 2k_0 \left| \sqrt{\varepsilon_u - \varepsilon_{\text{eff}}} \right| d_p + \phi_{w,\text{sup}} + \phi_{w,\text{sub}} \quad (5)$$

where

$$\left\{ \begin{array}{l} \sqrt{\varepsilon_{\text{eff}}} = \frac{\beta_i}{k_0} = \sqrt{\varepsilon_{\text{sup}}} \sin \theta_{\text{inc}} + m \frac{\lambda}{P_p} \\ \phi_{w,\text{sup}} = -2 \tan^{-1} \left| \frac{\varepsilon_u}{\varepsilon_{\text{sup}}} \frac{\sqrt{\varepsilon_{\text{sup}} - \varepsilon_{\text{eff}}}}{\varepsilon_u - \varepsilon_{\text{eff}}} \right| \\ \phi_{w,\text{sub}} = -2 \tan^{-1} \left| \frac{\varepsilon_u}{\varepsilon_{\text{sub}}} \frac{\sqrt{\varepsilon_{\text{sub}} - \varepsilon_{\text{eff}}}}{\varepsilon_u - \varepsilon_{\text{eff}}} \right| \end{array} \right. \quad (6)$$

where ε_{eff} is the effective permittivity of the guided mode propagating through the waveguide gratings (obtained from Eq. (4)). In order to demonstrate the first order diffracted phase shifts in between 8–12 μm , the permittivity ε_u for different duty cycles f_p

can be approximated from Eq. (2). In addition, a central resonant wavelength (e.g., $10.5\ \mu\text{m}$) can be considered for choosing the optimum grating thickness d_p with different values of f_p . From Fig. 4, we took $d_p=230, 220, 210$ and $198\ \text{nm}$ for $f_p=0.1, 0.2, 0.3$ and 0.4 , respectively. Fig. 5 shows the phase shifts of the grid unit calculated at different f_p values. Apart from a slight notch at the resonant wavelength, the phase curve shows a gradual change throughout the LWIR region. Please note that the amount of phase shift is very sharp and abrupt if the resonance band is small (i.e., high-Q resonance) [65, 66], whereas the phase changes slowly and gradually if the resonance band is large (i.e., low-Q resonance) [67]. Therefore, the phase curves in Fig. 5 clearly suggest a low-Q resonance in the optimized grid units.

2.2 Metal-dielectric grating pixel

Using the optimized Ti-Si₃N₄ grid unit cells, we can design the grating pixel array with enhanced absorption per unit mass. Fig. 6 shows the metal-dielectric grating pixel array (period P_t) formed by the grid unit cells (period P_p) and air gaps (g_t) between adjacent pixels. Guided mode excitation in the pixel structure can be properly optimized when analyzed with an

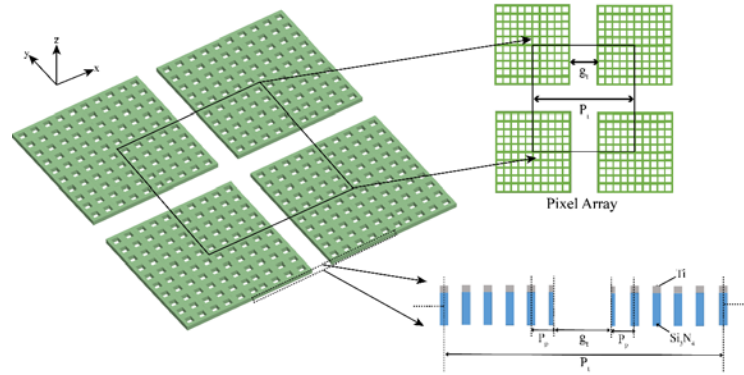


Fig. 6. Schematic illustration of pixel array structure constructed from the grid unit cells. Period of a grating pixel (P_t) is highlighted, along with the grid unit cells and air gap (g_t) between adjacent pixels.

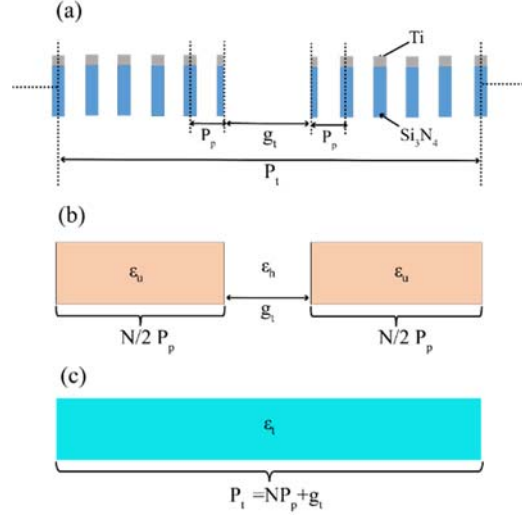


Fig. 7. Analysis of effective permittivity of a periodic pixel with subwavelength gratings. (a) Schematic illustration of a pixel period (P_t) with grid unit cells (period P_p) and air gap (g_t) between adjacent pixels. (b) Equivalent permittivity ϵ_u of the grid unit cells is shown along with the air gap permittivity ϵ_h . A total of N grid unit cells are present in the pixel period. (c) Pixel period with an effective permittivity ϵ_t

effective optical permittivity. Fig. 7 presents the effective permittivity analysis of the 1D grating pixel. In Fig. 7(a), N bilayer grid unit cells are symmetrically arranged on both sides of the air gap g_t to form the pixel period. In Fig. 7(b), the bilayer unit cells are replaced by the equivalent homogeneous cells with permittivity ϵ_u (from Fig. 2). Therefore, the grating pixel takes the form of a periodic structure, with homogenous medium ϵ_u (filling portion) and air gap medium ϵ_h (hole portion). Based on this form, the pixel period P_t can be defined as $P_t = NP_p + g_t$. In Fig. 7(c), the pixel period is approximated by an effective permittivity ϵ_t , which can be calculated as [47, 68, 69],

$$\begin{aligned} \epsilon_t &= \epsilon_h + \Delta\epsilon f_t \\ \begin{cases} \Delta\epsilon = \epsilon_u - \epsilon_h \\ f_t = \frac{NP_p}{NP_p + g_t} \end{cases} \end{aligned} \quad (7)$$

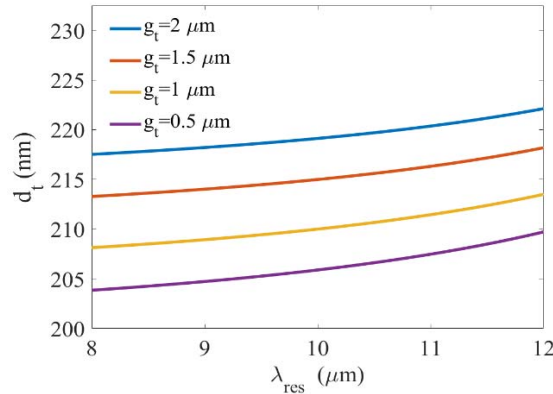


Fig. 8 Based on guided mode resonance theory, the thickness of the grating pixel is optimized for diffraction efficiency with different air gap distances g_t . The x-axis shows guided mode resonant

wavelengths in the LWIR. Normal incidence of light ($\theta_{\text{inc}}=0^\circ$), $P_p=1\ \mu\text{m}$, $f_p=0.2$, and $N=10$ are considered with first order diffraction ($m=\pm 1$).

where f_t is the linear duty cycle of the pixel period. It should be noted that Eq. (7) is validated by the effective grating theory [68–70], which applies for gratings with subwavelength thickness and period less than or comparable to the illumination wavelength.

In order to obtain enhanced absorption per unit mass, the grating pixel needs to be designed with low fill factor grid units (i.e., small amounts of material) forming a large period (i.e., large absorption area). Therefore, in Eq. (7), the permittivity ε_u of the grid unit cells must be calculated using a low duty cycle f_p . Considering good optical properties from Fig. 3 (e.g. effective refractive index close to unity, resulting in minimum reflection) and a requirement of minimum material, we use grid unit cells with $f_p=0.2$ and $P_p=1\ \mu\text{m}$ in our analysis. Please note that although $f_p=0.1$ (and other lower values) would require less material, free-standing periodic grid units with $f_p=0.1$ and $P_p=1\ \mu\text{m}$ have significant fabrication limitations [17]. To form a large pixel, we consider 10 grid units inside the pixel period P_t (i.e., $N=10$). By increasing the periodic air gap g_t , the pixel period can be further increased, which, in turn, requires proper optimization of the pixel thickness based on GMR theory. To ensure maximum evanescent field coupling inside the air gaps, pixel thickness d_t can be optimized for diffraction efficiency across the LWIR (i.e., 8–12 μm) when the grid unit permittivity ε_u and period P_p are replaced with pixel permittivity ε_t and period P_t in Eqns. (3) and (4), respectively. Fig. 8 shows the optimum pixel thicknesses d_t for different air gaps g_t , with the assumptions of $\theta_{\text{inc}}=0^\circ$ (normal incidence), $m=\pm 1$ (first-order diffraction), $P_p=1\ \mu\text{m}$, $f_p=0.2$, and $N=10$. The x -axis indicates guided mode resonant wavelengths in the LWIR. It can be clearly observed that an increase in gap g_t (i.e., decrease in f_t) would require a larger pixel thickness d_t to compensate for the overall amount of material required for the resonant coupling. This is similar to the case seen in Fig. 4. Moreover, for a particular g_t , the optimum thicknesses are close to one another over the LWIR range (with a deviation of only $\sim 3\%$).

Similarly to the grid units, the resonance quality (high-Q or low-Q) of the guided modes inside the pixel can be studied by calculating the phase shifts of the light diffraction. By replacing permittivity ε_u with ε_t , and period P_p with P_t in Eqns (5) and (6), the phase information of the pixel structure can be extracted. Note that at the resonant wavelength (e.g., 10.5 μm), the optimum pixel thicknesses d_t for different air gaps g_t are used to calculate the phase shifts. The values of d_t are taken from Fig. 8. The other specifications are kept fixed ($\theta_{\text{inc}}=0^\circ$, $P_p=1\ \mu\text{m}$, $f_p=0.2$, and $N=10$), and the phase calculations of the pixel structure for different air gaps are presented in Fig. 9. The relatively smooth and small change in slope across the LWIR resonance implies a very low-Q system [67].

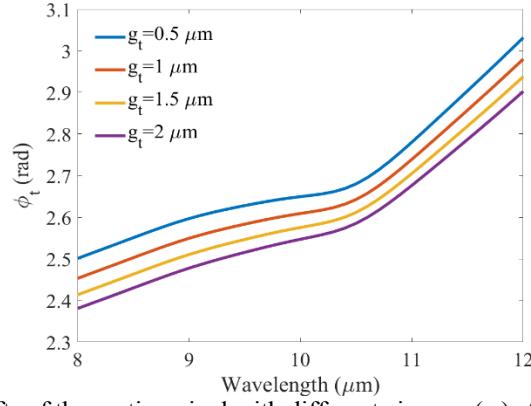


Fig. 9. Phase shifts of the grating pixel with different air gaps (g_t). At a given resonant wavelength (e.g., $\lambda_{\text{res}} = 10.5 \mu\text{m}$), the optimum thickness d_t corresponding to different g_t are taken from Fig. 8 for calculating the phase shifts. The simulated conditions are: normal incidence ($\theta_{\text{inc}} = 0^\circ$), $P_p = 1 \mu\text{m}$, $f_p = 0.2$, and $N = 10$ with first order diffraction ($m = \pm 1$).

2. Analysis of optical absorption

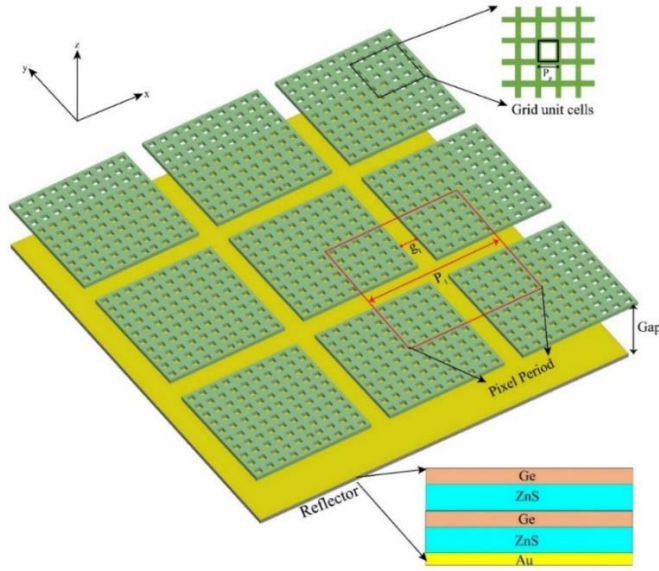


Fig. 10 Schematic representation of the Ti-Si₃N₄ grating pixel array with a bottom reflector placed at a gap distance of 2.5 μm . The reflector is made of two pairs of Ge-ZnS layers and a thin 100 nm Au film. The layers are arranged to approximate Bragg mirrors [71], and the thicknesses of the Ge and ZnS layers are taken to be 0.625 μm and 1.136 μm , respectively. With the Au film underneath, the reflector ensures nearly 100% reflection of the LWIR, and therefore, maximum light coupling within the grating pixel.

Figure 10 presents a schematic illustration of our Ti-Si₃N₄ grating pixel used as a broadband absorber. The pixels are arranged in a periodic fashion along the x and y directions. A bottom reflector is placed underneath the pixel structure at a gap distance of 2.5 μm , which is a quarter of the wavelength of 10 μm [17]. The reflector is made of two pairs of Ge-ZnS layers and a thin 100 nm Au film. According to the Bragg mirror approximation [71], the thickness of Ge and ZnS layers are taken as 0.625 μm and 1.136 μm , respectively. With the Au film underneath, the reflector ensures nearly 100% reflection of the LWIR, and therefore, maximum light coupling within the grating pixel. Such backside reflectors have already been demonstrated for increasing the GMR absorption in previous studies [72, 73].

To calculate the optical absorption, we solve Maxwell's electromagnetic equations using a finite difference time domain (FDTD) technique in Lumerical Solutions [74]. Assuming a full 3D model, we analyze a pixel period and/or grid unit period with periodic boundary conditions along the horizontal directions (i.e., x- and y- axis) and with perfectly matched layer (PML) conditions (i.e., no reflection of light at the boundaries) along the vertical direction (i.e., z- axis). We assume the incident light is a plane wave directed normally to the surface (i.e., $\theta_{\text{inc}}=0^\circ$) and with wavelengths ranging from 8 μm to 12 μm . We take the frequency-dependent optical properties (n and k) of Ti, Si₃N₄, Ge, ZnS, and Au from previous experimental studies [54, 75–78]. In the simulations, we employ a mesh size of 20 nm along the x- and y- axis (grating plane), and a mesh size of 5 nm along the

z- axis (thickness). The absorption in the simulations is defined as $A(\lambda) = 1 - R(\lambda) - T(\lambda)$, where $R(\lambda)$ and $T(\lambda)$ present the reflection and transmission, respectively.

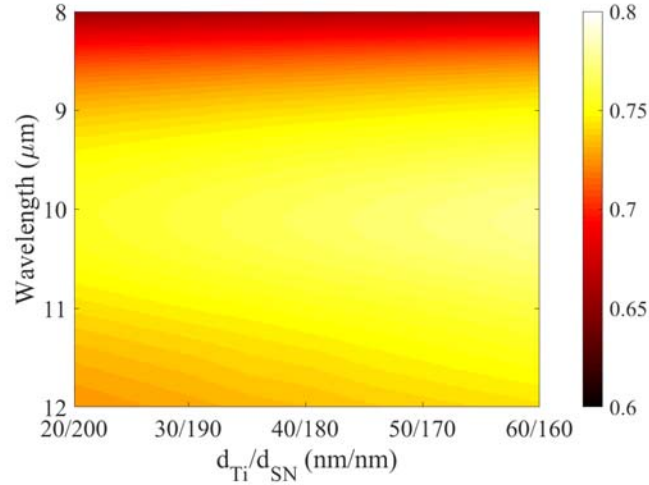


Fig. 12 Absorption profile of periodic grid unit cells with different thickness combinations of Ti (d_{Ti}) and Si_3N_4 (d_{SN}). The duty cycle f_p and period P_p are taken as $0.2 \mu m$ and $1 \mu m$, respectively. The total thickness is kept as 220 nm to maintain the GMR condition (from Eq. (3)).

Initially we analyze an optimized grid unit cell with duty cycle $f_p=0.2$ and period $P_p=1 \mu m$. This would correspond to a fill area factor of 36% (hole area of 64%). From our prior theoretical analysis (Fig. 4), we take the grid unit thickness as 220 nm . While keeping the resonance condition approximately constant with a total thickness of 220 nm , we vary the thicknesses of Ti and Si_3N_4 layers to study the effect on the optical absorption. Fig. 11 shows the optical absorption for the grid unit period with different thickness combinations of Ti and Si_3N_4 layers (i.e., d_{Ti}/d_{SN}). It can be observed that larger Ti thickness gradually broadens the optical absorption, while keeping the resonance in between $9-11 \mu m$. This can be attributed to the large extinction coefficient of Ti causing a decrease in the quality factor since $Q \propto \frac{1}{k}$ [40]. In addition, larger Ti layer does not enormously increase the absorption profile (only $\sim 6\%$ increase in maximum absorption), which is indicative of a primarily dielectric-loss-based absorption. Such absorption characteristics (dominated by dielectric loss) in metal-dielectric films have been previously reported, in which metals layers are found to contribute $\sim 5-8\%$ to the total absorption in the LWIR [4, 36]. We choose 50 nm Ti and 170 nm Si_3N_4 for our grating pixel to obtain a uniformly high absorption profile across the LWIR. It should be noted that these thicknesses correspond to $d_{Ti}=0.22d_p$ and $d_{Ti}=0.78d_p$, which are almost same as our theoretical analysis (i.e., $d_{Ti}=0.2d_p$ and $d_{SN}=0.8d_p$).

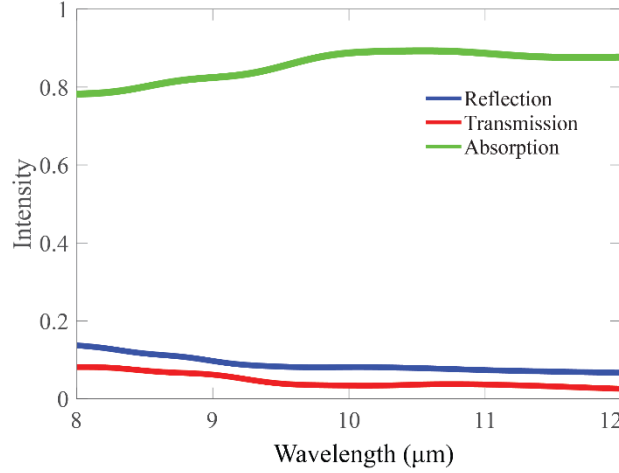


Fig. 12 - Reflection (R), transmission (T), and absorption (A) spectra of a metal-dielectric grating pixel structure, with 10 subwavelength grid unit cells (i.e., $N=10$) inside a linear period and a 2 μm gap (g_i) between adjacent pixels. For each grid unit cell, grid unit period $P_p=1 \mu\text{m}$, duty cycle $f_p=0.2$, $d_{Ti}=50 \text{ nm}$, and $d_{SN}=170 \text{ nm}$ are used.

Fig. 12 shows the simulated reflection (R), transmission (T), and absorption (A) of the grating pixel period with normally incident light and grid unit parameters specified as: $f_p=0.2$, $P_p=1 \mu\text{m}$, $d_{Ti}=50 \text{ nm}$, and $d_{SN}=170 \text{ nm}$. From our theoretical analysis, 10 grid unit cells ($N=10$) are considered inside the 1D pixel period (i.e., 100 cells inside the pixel area), with a periodic air gap g_i of 2 μm . With these parameters, the pixel structure corresponds to a total area of $144 \mu\text{m}^2$ with a filled area of $36 \mu\text{m}^2$, i.e., a fill factor of 25%. From Fig. 12, it is evident that the grating pixel realizes excellent broadband absorption in between 8–12 μm , yielding an average absorption of $\sim 86\%$ with maximum absorption of $\sim 90\%$.

3. Optimization of absorption in grating pixel

In general, guided mode excitation largely depends on the proper optimization of materials present in the grating structure [35, 58, 62]. In order to study optimum absorption in our pixel, we can consider the duty cycle $f_p=0.2$ (keeping minimum materials) and vary the grid unit period P_p . Fig. 13 shows the LWIR absorption profile with constant duty cycle $f_p=0.2$, and with

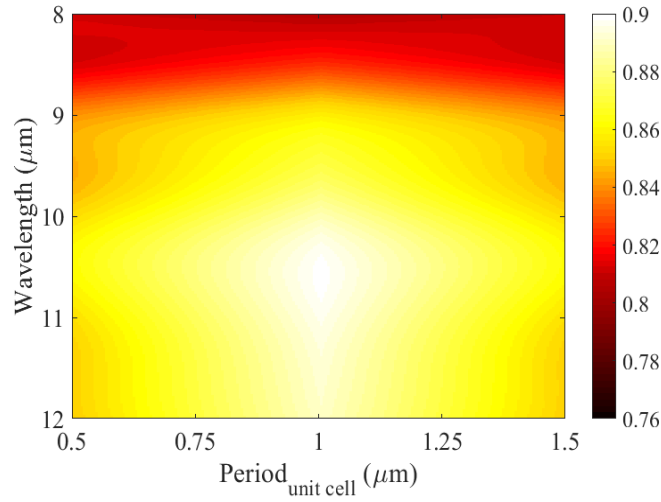


Fig 13: Absorption profile of a grating pixel structure with different periods of the grid unit cells. The duty cycle of the unit cells (f_p) is fixed at 0.2. The other specifications are: $N=10$ and $g_i=2 \mu\text{m}$.

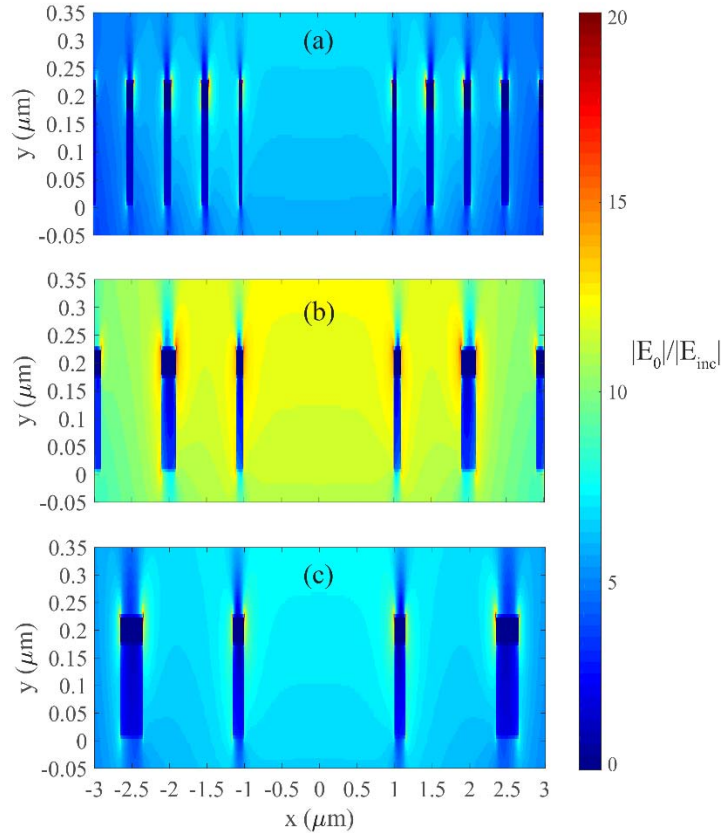


Fig 14: Spatial electric field distribution for the periodic grating pixel at $\lambda=10.5 \mu\text{m}$ with different grid unit cell periods: (a) $P_p=0.5 \mu\text{m}$, (b) $P_p=1 \mu\text{m}$, and (c) $P_p=1.5 \mu\text{m}$. The duty cycle of the unit cells (f_p) is fixed at 0.2. The other specifications are: $N=10$ and $g_i=2 \mu\text{m}$.

varying grid unit periods ranging from $0.5 \mu\text{m}$ to $1.5 \mu\text{m}$. The other parameters (i.e., $N=10$ and $g_i=2 \mu\text{m}$) are kept fixed as before. From Fig. 13, it can be observed that maximum

absorption occurs when grid unit period P_p is $1\ \mu\text{m}$. This can be attributed to the maximum coupling efficiency associated with the optimum pixel thickness. Our calculations indicate that a pixel thickness of $220\ \text{nm}$ can realize guided mode coupling with air gap $g_t=2\ \mu\text{m}$ (Fig. 8), when grid unit parameters are: $f_p=0.2$ and $P_p=1\ \mu\text{m}$. Therefore, P_p larger or smaller than $1\ \mu\text{m}$ cannot provide optimum absorption, which validates the theoretical analysis. To further illustrate this, Fig. 14 presents the spatial electric field distribution of pixel structure with grid unit periods of $0.5\ \mu\text{m}$, $1\ \mu\text{m}$ and $1.5\ \mu\text{m}$. With the same parameters as Fig. 13, it can be observed that the evanescent field is coupled within the air gaps and maximum coupling occurs for period $P_p=1\ \mu\text{m}$, realizing enhanced broadband absorption in the bilayer pixel by effectively extending the pixel size (absorption area) to encompass the open gaps between and around the pixels.

4. Performance Analysis with absorption per unit mass

To understand optimum coupling with a minimum amount of material, we perform a comparative analysis of our pixel structure with the previously reported LWIR broadband absorbers. It should be noted that when an absorber period (e.g., pixel or periodic structure) is much larger than the operating wavelength (i.e., $\text{period} \gg \lambda$), the total amount of material proportionately increases with the area, while the total absorption may not increase significantly [79, 80]. Therefore, to analyze the overall quality of the absorber, the absorption may need to be normalized to both mass and area. However, in case of an absorber period comparable to or smaller than the operating wavelength (i.e., $\text{period} \leq \lambda$), the absorption per unit mass (absorption/mass) of the pixel or periodic structure would better define the absorber performance. Our proposed absorber, as well as the previously reported LWIR absorbers (analyzed in this section), have pixels or periodic structures smaller or comparable to the LWIR wavelengths (i.e., $8\text{--}12\ \mu\text{m}$) [4, 17, 24–26]. Therefore, we consider the absorption per unit mass as our performance metric.

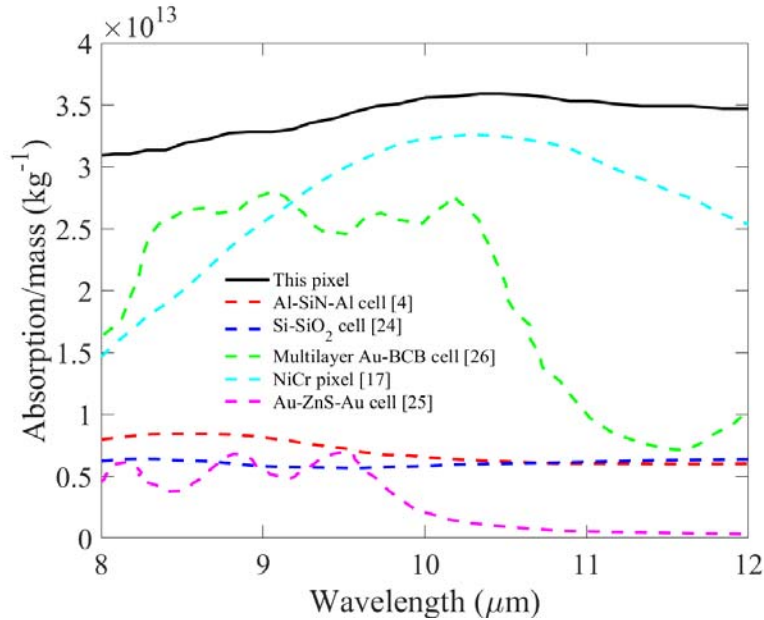


Fig. 15 Comparative analysis of absorption/mass per period of our pixel structure with the state-of-the-art LWIR broadband absorbers, including metamaterials, metasurface and plasmonic structures.

Table 1 - Average absorption in the LWIR (8–12 μm) and total amount of mass of the absorber periods (pixels or periodic cells) from this and several previously reported works.

Absorber	Average Absorption	Mass (kg)	Reference
This pixel	86%	2.5225×10^{-14}	
Al-SiN-Al cell	85%	1.1858×10^{-13}	[4]
Si-SiO ₂ cell	90%	1.4862×10^{-13}	[24]
Multilayer Au-BCB cell	71%	3.1178×10^{-14}	[26]
NiCr pixel	78%	2.996×10^{-14}	[17]
Au-ZnS-Au cell	65%	1.3818×10^{-13}	[25]

To compare the previously reported works, we consider all kind of structures, including metamaterials, metasurfaces and plasmonic structures. For example, Bouchon et al. [25] reported a wideband omnidirectional infrared absorber using an Au-ZnS-Au (M-I-M) structure, which includes four different sized resonators in a single period and realizes absorption through coupling multiple resonance bands. Later on, Adomanis et al. [26] proposed a fully functional bilayer metamaterial nearly perfect absorber, which consists of two pairs of Au-benzocyclobutene (BCB) films along with an Au substrate (i.e., Au-BCB-Au-BCB-Au, double M-I-M configuration). Gorgulu et al. [24] reported an ultra-broadband plasmonic infrared absorber, which considers symmetric 2D Si gratings on top of a SiO₂ layer. Jung et al. [17] presented the non-resonant broadband LWIR absorption in a metasurface pixel, formed by a NiCr film with periodic air holes. Moreover, Ustun et al. [4] reported broadband absorption in an Al-SiN-Al periodic structure (M-I-M) through a rigorous numerical analysis. To illustrate the amount of materials required for the broadband absorption, Table 1 shows the average absorption in the LWIR (i.e., 8–12 μm) and total amount of mass utilized in each of the absorber periods. Note that most LWIR broadband absorbers, specifically metamaterials and plasmonic composites, do not report pixel size or array geometry but rather focus on the details of the periodic cell structures. Therefore, in those cases we consider the reported periodic cells as the absorber periods for our analysis. From the table, it can be observed that the design methodology of this paper realizes an average absorption of $\sim 86\%$ with a mass amount of 2.5225×10^{-14} kg for the pixel. This mass is at least $\sim 18.77\%$ smaller than the previously reported absorber periods. The use of only two layers (Ti and Si₃N₄) instead of tri- or multilayers and the use of optimum pixel design to increase evanescent field coupling within the gaps (due to GMR), within and around the pixel yield the enhanced broadband absorption with the minimum amount of materials. To further illustrate this, we calculate the absorption/mass per period (pixel or periodic cell) of the absorber structures in between 8–12 μm , which is shown in Fig. 15. From the figure, it can be observed that metamaterial with an M-I-M configuration, e.g., Al-SiN-Al, plasmonic structure e.g., Si-SiO₂, and plasmonic metamaterial e.g., Au-ZnS-Au show uniform absorption/mass (below 1×10^{13} kg⁻¹) throughout the LWIR region. Due to having double M-I-M stacks, multilayer Au-BCB cell shows higher absorption/mass ($\sim 2.5 \times 10^{13}$ kg⁻¹) in a smaller window (i.e., 8.3–10.2 μm). Comparatively higher but significantly nonuniform absorption/mass profile is observed for the NiCr pixel, which has a maximum value of 3.2×10^{13} kg⁻¹. Our pixel structure shows a

high and uniform absorption/mass profile with a maximum value of $\sim 3.6 \times 10^{13} \text{ kg}^{-1}$ near at $\sim 10.5 \text{ }\mu\text{m}$ (resonance) and with a standard deviation of only 4.2% across the entire LWIR. An average absorption/mass of $3.45 \times 10^{13} \text{ kg}^{-1}$ is found for our pixel, which is $\sim 1.33\text{--}7.33$ times larger than the previously reported LWIR absorbers.

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V. Chapter 3: Uncooled Optomechanical Detector Performance in Air

Infrared detectors are transducers producing a measurable electrical/optical output in response to long wavelength radiation intercepted by the sensing element. The highest

theoretically possible performance is achieved at the background-limit, a state where photons emitted from the target dominate the total noise. In the long-wave infrared (LWIR, $\lambda \sim 8\text{--}12\text{ }\mu\text{m}$), this limit is usually achieved by cooling a focal plane array (FPA) to cryogenic temperatures so that other noise sources, which depend on the detector temperature, can be minimized. At higher temperatures, particularly room temperature, uncooled thermal detectors are used but are usually packaged in vacuum to ensure that low NETD can be achieved at video frame rates [1, 2].

Uncooled LWIR thermal detector technology is dominated primarily by microbolometer arrays [3–5] but with a smaller contingent of alternative technologies such as thermopiles [6, 7]. Microbolometers consist of highly thermally-isolated resistors that absorb LWIR light, heat the device, alter device resistance, and allow a bias current to produce a signal-dependent potential difference. Thermopiles produce a temperature dependent voltage (based on the Seebeck effect) upon LWIR absorption. Both of these devices possess electrical noise sources (e.g., Johnson or $1/f$), which are not fundamental to thermal detection and degrade the minimum measurable signal, often measured using a parameter called the noise-equivalent temperature difference (NETD). Optical readouts, such as used for cantilever detectors [8–10] and thermo optic cavity detectors [11], can eliminate electrical noise, but they have often been plagued by large thermal mass, resulting in reduced performance even in vacuum.

Optimum performance can be achieved if the thermal mass is at exactly the level necessary to prevent temperature fluctuations from dominating the noise. Once this level is reached, a device should have the largest possible absorption area for its mass. One method to maximize the area of a minimum-mass infrared detector is to create a perforated metastructure whose subwavelength periodicity allows it to absorb LWIR light even outside the dimensions of the physical detector. Further optimization using the effective medium theory and guided mode resonance techniques will allow it to absorb at high levels throughout the broadband LWIR spectrum [12]. In this work, we demonstrate a nano thermo-optic

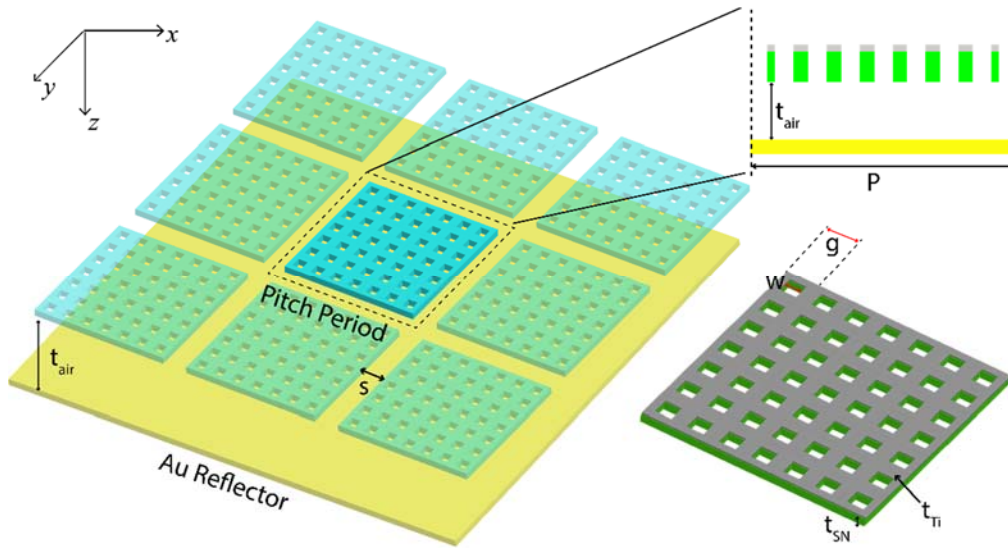


Fig. 1. Schematic illustration of the Ti-SiN_x grating metastructure. Absorber pitch period P , grid unit period g , and perforation size w are highlighted along with the Ti and SiN_x layers. A bottom Au reflector is placed underneath at the quarter-wave anti resonant ($m\lambda/4$) position.

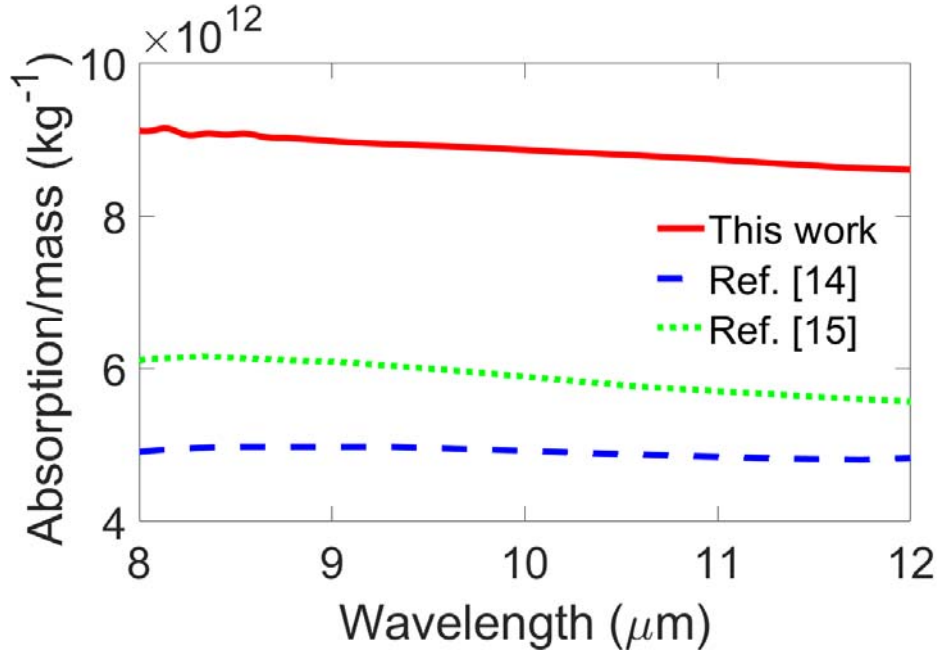


Fig. 2. Comparative analysis of the absorption-per-unit-mass of our structure with recently reported broadband metastructures for infrared detectors.

infrared detector using this pixel technology. The thermal detector achieves enhanced absorption per unit mass through sub-wavelength perforations or gratings. Lossy Ti and SiN_x films are used to form a metal-dielectric hybrid metastructure. The device is read using a Mach-Zehnder interferometer (optical readout), a technology chosen because of its ease of integration, as shown in fiber optic communications, and its potential to read an entire array simultaneously. The detector shows a thermal time constant of 2 ms, and we obtain a record noise equivalent temperature difference (NETD) of 23 mK in air and a detectivity in air of $0.92 \times 10^9 \text{ cm}\sqrt{\text{Hz}}/\text{W}$. These results indicate that further performance gains could be achieved in vacuum as with commercial microbolometer arrays and pave the way for scalable nano thermo-optics based infrared sensing for different military and civilian applications.

Figure 1 presents a schematic illustration of our Ti-SiN_x broadband absorber. The structure consists of pixels with an array of square gratings (i.e., pitches) with a periodicity, P of 8 μm. Each array contains 49 nano-scale grid units, with each grid having a period, g of 1 μm, and a perforation size, w , of 0.8 μm (i. e., perforation ratio, $w/g=0.8$). Thicknesses of the Ti (t_{Ti}) and SiN_x (t_{SiN}) layers are taken as 20 nm and 200 nm, respectively. An air gap,

s of 1 μm is utilized around the solid absorbers designed to couple evanescent LWIR light in the gaps as part of the pixel absorption. The metastructure is placed above an Au reflector at a gap distance, t_{air} of $\sim 2.7 \mu\text{m}$, ensuring a quarter-wave anti-resonance ($m\lambda/4$) condition that boosts the optical absorption across the 8–12 μm region. Such backside reflectors have been used in previously reported infrared absorbers [13, 14].

Figure 2 presents the absorption-to-mass ratio of our absorber compared to recently published infrared metastructures by Cetin et. al. [14] and Varpula et. al. [15]. The perforations in these works are much smaller than LWIR wavelengths (i.e., $w \ll \lambda$), therefore the performance of the absorbers can be well-analyzed by the absorption/mass ratio [12]. Cetin et al. [14] proposed a NiCr (19 nm) on SiN_x (230 nm) broadband metasurface, with a pitch period of 25 μm , grid unit of 3 μm , and perforation ratio of 0.77. Later on, Varpula et al. [15] reported a TiN (50 nm) on poly-Si (70 nm) thermoelectric infrared bolometer, with an absorber area of 24.6 μm , a grid unit of 3 μm , and a perforation ratio of 0.8. To provide a comparative analysis, we consider an absorption area of 24 $\mu\text{m} \times 24 \mu\text{m}$ for our structure (i.e., 3×3 pitch periods or array). From Fig. 2, it can be observed that the NiCr on SiN_x metastructure shows nearly uniform absorption/mass, with an average value of $4.9 \times 10^{12} \text{ kg}^{-1}$. Due to having a smaller thickness of poly Si, the thermoelectric TiN on poly-Si structure shows a comparatively higher absorption/mass, with an average value of $5.89 \times 10^{12} \text{ kg}^{-1}$. Our designed structure shows an average absorption/mass of $8.89 \times 10^{12} \text{ kg}^{-1}$, which is $\sim 81\%$ higher than the NiCr on SiN_x metastructure and $\sim 50\%$ higher than the TiN on poly-Si bolometer. It should be noted that the absorption profiles presented in this analysis are calculated by numerical methods. We and Cetin et al. [14] use finite difference time domain techniques, whereas Varpula et al. [15] uses a finite element method.

Figure 3 shows an optical microscopic image of our infrared metastructure, after it is successfully fabricated and released in air. It consists of an array of 25 grating absorber periods (5×5 array), comprising a total absorption area of 40 $\mu\text{m} \times 40 \mu\text{m}$. Fabrication of the metastructure is realized through a three mask electron beam (e-beam) lithography process. Fig. 4 presents the flow chart of our fabrication process. Initially, an Au film of 150 nm is deposited and patterned on an Si wafer using the first mask, which works as the bottom mirror. Then a sacrificial polyimide layer (PI 2611, from HD Microsystems) is spin-coated (6500 rpm for 30 s) on top of the Au mirror to form the quarter-wave anti-resonant cavity. The polyimide is gradually hard baked from 100°C to 350°C with a total time of ~ 60 minutes, which results in a $\sim 2.7 \mu\text{m}$ thick sacrificial layer that is resistant to any resist remover, e.g., Acetone or 1165 lift-off solutions. Using high density plasma chemical vapor deposition (HDPCVD), a 150 nm SiN_x film is coated over the hard baked polyimide. This is followed by the deposition of a 20 nm Ti film with e-beam evaporation, which is patterned into nano-scale grids using the second mask. Please note that sputtering can be another option for Ti

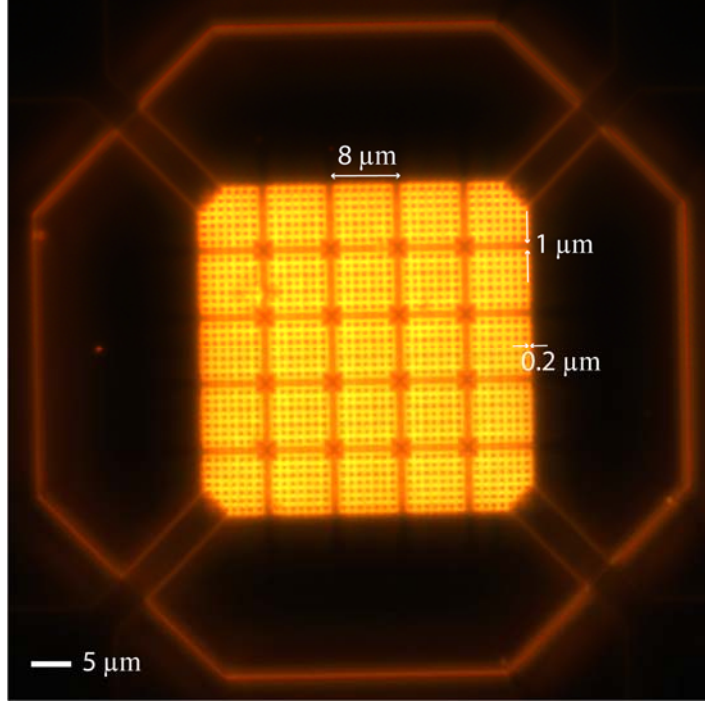


Fig. 3. Optical microscope image of the successfully released perforated Ti-SiN_x metastructure, with an absorption area of 40 μm×40 μm (i. e., 5×5 grating pixel array). Pitch period, air gap between adjacent absorber pitches and linewidth of the grids are highlighted, along with the scale bar of 5 μm in the inset.

deposition, however, it suffers from shadowing effects resulting in non-conformal coatings especially in nano-scale patterns [16]. Moreover, note that e-beam evaporation provides better fabrication tolerance, with a thickness of 20 ± 0.6 nm (deviation of ~3%) for our Ti film. In the next step, a thin SiN_x film of 50 nm is coated on top of metal grids as a passivation layer, which protects the Ti from being oxidized (i.e., forming thin TiO₂). The third mask is used to define the perforations and hole patterns. The etch release of the structure starts with removal of SiN_x through perforations and holes using reactive ion etching (RIE). The etch recipe uses CHF₃ and SF₆ gases with a 10 mtorr chamber pressure. The passivation SiN_x layer of the grids doesn't get etched as it is protected by the e-beam resist PMMA (polymethyl methacrylate). Finally, the metastructure is successfully suspended by removal of sacrificial polyimide using an oxygen plasma etch.

The fabricated device is read using a Mach-Zehnder interferometer (optical readout), as shown with a schematic illustration in Fig. 5. A He-Ne laser source ($\lambda \sim 632.8$ nm) with a power of 10 mW is used for our experiment. The laser beam is divided into two orthogonal linearly polarized beams by a polarizing beam splitter (PBS). One of the beams is incident on the fabricated sample along the pixel gratings, and called the observation beam. A micro-scale pinhole (~ 50 μm) is used to focus the beam on to the detector gratings, and thus minimize unnecessary background reflection. The other orthogonally polarized beam (called the reference beam) travels to an Au mirror through a similar pinhole, and then becomes parallel to the observation beam through a half wave plate. The reflected light

from the metastructure interferes with the reference beam through another beam splitter (non-polarizing) generating interference fringes, which are recorded by a CMOS camera. A polarizer is used before the polarizing beam splitter to control and equalize the intensity of the reference & observation beams to maximize the contrast of fringe pattern on the CMOS

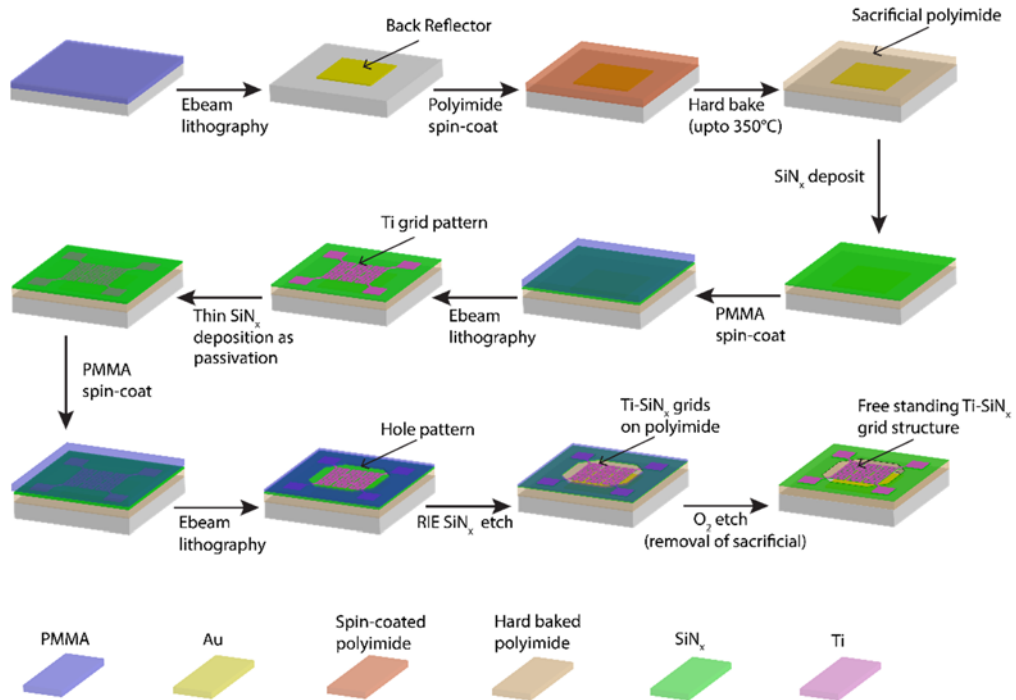


Fig. 4. Fabrication process flow of the infrared detector.

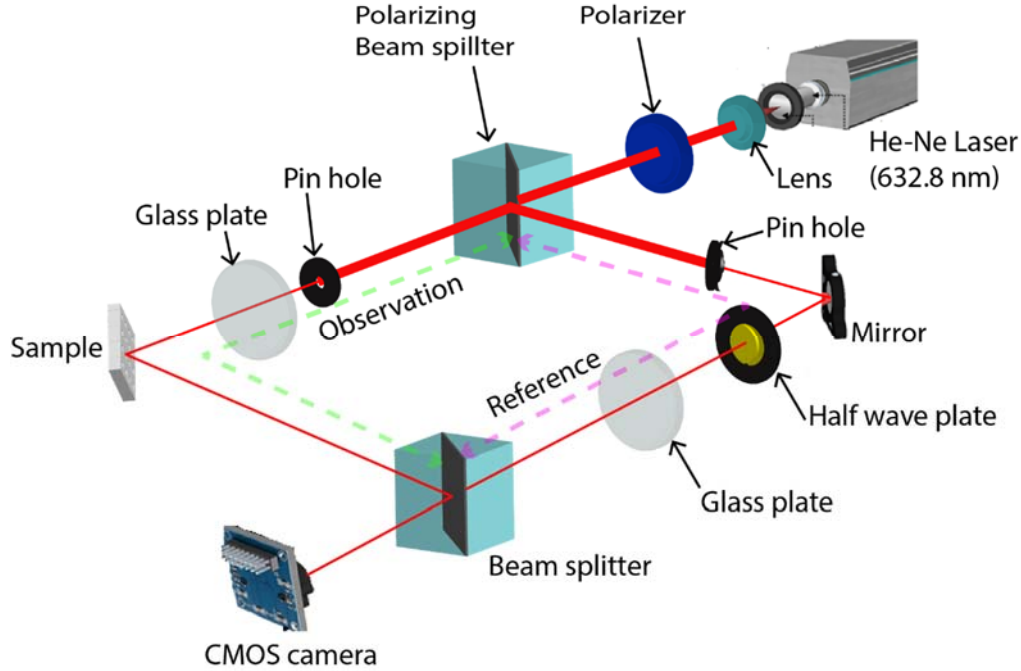


Fig. 5. Schematic diagram of the Mach-Zehnder interferometer with infrared detector (sample).

camera. Moreover, note that glass plates ($\sim 500 \mu\text{m}$) are used along the two beam paths to assess the stability of the interference fringes, meaning that whether the fringe shifts with a slight rotation (e.g., 0.5°) of any of the plates, i.e., slight change in optical path differences.

For analyzing the thermal sensitivity, a highly emissive ($\varepsilon \sim 0.95$) IR source, e.g., electric resistor is placed near our metastructure without blocking the interference light path. The source causes IR absorption and heats the structure, resulting in slight deformations in the shape of the perforated membrane. This produces optical path differences between the observation and reference beams, and hence distinct phase shifts of the interference fringes. As an example, Fig. 6(a) shows a phase shift of 0.9π of the fringes due to heating, as recorded by our CMOS camera. The heating in this example image corresponds to a source temperature change of $\sim 300 \text{ mK}$ stabilized over 1 full second, as calibrated by a commercial microbolometer camera (Jenoptik IR-TCM 384). The fringe images are further processed with bright and dark colors (in Fig. 6(a)), converted into a 0–255 data scale, and fitted with sinusoidal curves. For our NETD (thermal sensitivity) analysis, fringe fluctuations without an IR source (i.e., a sine peak position) are recorded and analyzed for ~ 3154 frames. Fig. 6(b) shows the overall distribution of the sine peak at different positions. It is found that the standard deviation of the peak fluctuations is $\sim 3.5\%$ of the fringe period, which corresponds to a temperature difference (NETD) of $\sim 23 \text{ mK}$ in air at room temperature ($\sim 310 \text{ K}$). This NETD is approximately 30% lower than the excellent state-of-the-art thermal detector (recently reported) operating in air [17].

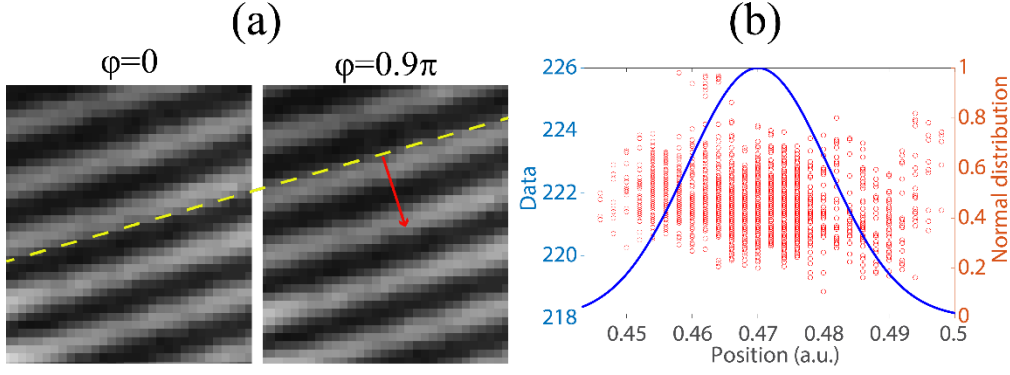


Fig. 6. (a) Fringe images recorded on a CMOS camera. A yellow line is shown as a reference to highlight the phase shift of the fringes. The fringe movement is indicated by a red arrow. The fringe shift corresponds to a temperature change of ~ 300 mK, as measured by a commercial microbolometer camera. (b) A plot of the normal distribution of fluctuations in the position of an interference fringe without external IR absorption. This distribution is used to determine our noise. The standard deviation of this distribution is compared to the interference fringe shift created by known source temperature changes. Using this method we find that our NETD is 23 mK in air.

The thermal capacitance of the infrared device can be defined as [17, 18],

$$C = C_{\text{Ti}} \rho_{\text{Ti}} V_{\text{Ti}} + C_{\text{SN}} \rho_{\text{SN}} V_{\text{SN}} \quad (1)$$

where C , ρ and V correspond to the specific heat, density, and volume of the material of interest, i.e., SiN_x or Ti. Considering both grating structures and support cross-legs, the total capacitance of our device is calculated as $\sim 3.3 \times 10^{-10}$ J/K.

In order to find out the thermal conductance, we can use its relationship with NETD [19–21],

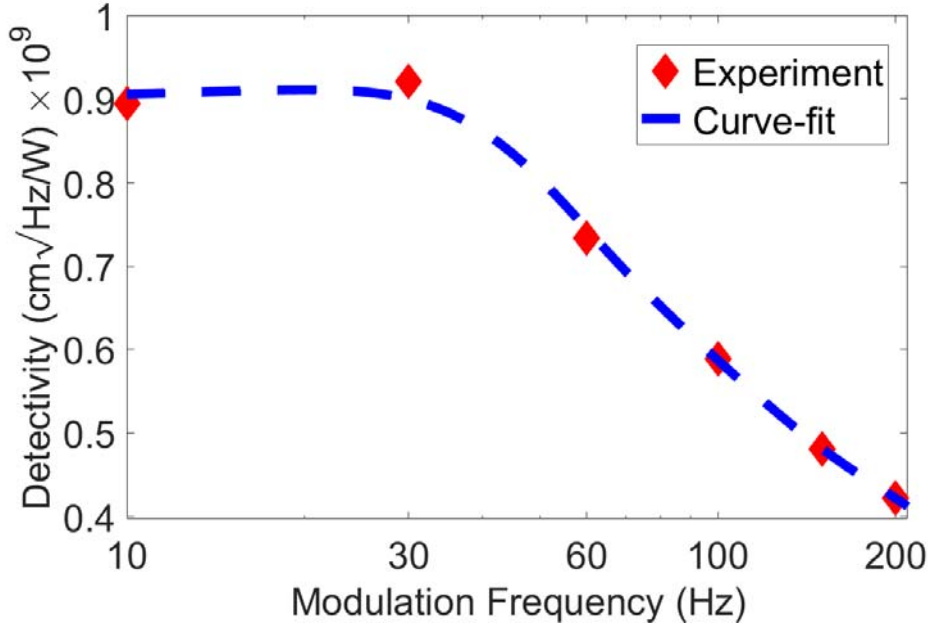


Fig. 7. Detectivity analyzed at different modulation frequencies. Red dots are measured data points, which are curve-fit through a blue line. From this data, thermal time constant is measured as ~ 2 ms.

$$NETD = \frac{4F^2GT}{\frac{\Delta L}{\Delta T} A_d \varepsilon \pi} \sqrt{\frac{k_B}{C}} \quad (2)$$

where F is $f/\#$ of the system optics, $\Delta L/\Delta T$ is the change in luminescence, A_d is the effective area of IR absorption, k_B is the Boltzmann constant, ε is emissivity, and G is the thermal conductance of the device (in air). For parameters in the $\lambda \sim 8-12 \mu\text{m}$ range and the measured NETD, the thermal conductance is found as $\sim 2.665 \times 10^{-7} \text{ W/K}$, which includes both contributions from heat radiation and conduction in the solid state and air [18].

Detectivity is often used to describe the performance of an infrared detector and is related to the noise-equivalent power (NEP) by $D^* = \sqrt{A_d \Delta f} / NEP$ [22], where Δf is the measurement bandwidth. Unlike typical thermoelectric devices and bolometers, our device is free from electrical noise. In addition, other noises e.g., mechanical fluctuations and photon pressure are quite negligible ($< 0.01\%$) with our optical readout (see Supplemental Document). Therefore, the NEP of our device can be calculated from thermal conductance noise as [22],

$$NEP = G \sqrt{\frac{k_B T^2}{C}} \quad (3)$$

With our values of C and G , NEP is found as 16.9 pW , which gives a detectivity D^* of $\sim 0.92 \times 10^9 \text{ cm}\sqrt{\text{Hz/W}}$. This is a nearly 60% increase in detectivity over other excellent

state-of-the-art work (thermal detector in air) in a field usually typified by incremental performance advances over decades [17].

The thermal time constant is measured by characterizing our device at different modulation frequencies. The NETD and detectivity are measured by chopping the IR signal. Fig. 7 shows the analyzed detectivity as a function of modulation frequency. From the figure, the thermal time constant is found as ~ 2 ms, which is significantly faster than video frame rates.

Optical characterization techniques using Mach Zehnder interferometry have been fully integrated in microelectromechanical systems (MEMS) [23, 24], with promising possibilities in a number of applications, such as fiber optics communication [25-27] and optical sensing [28-30]. Mach Zehnder interferometers require very low power consumption and are easily integrated. Most relevant to this paper are the extremely small volumes of the interferometers, which indicate that an imaging Mach-Zehnder is easily compatible with commonly used camera form factors. A focal plane array of pixels can be optically sensed by mapping phase images obtained with an imaging MEMS Mach Zehnder interferometer.

Just recently, we have completed our vacuum measurement set-up in our lab and have measured these devices in vacuum. tested $40\mu\text{m} \times 40\mu\text{m}$ devices in vacuum and have achieved an NETD of 4.88mK at a frame rate of 10Hz, which corresponds to a detectivity of $3.1 \times 10^9 \text{ cmHz}^{1/2}/\text{W}$. This is the lowest by a significant margin slightly higher than the highest detectivities ever reported for uncooled devices in 2013 [7].

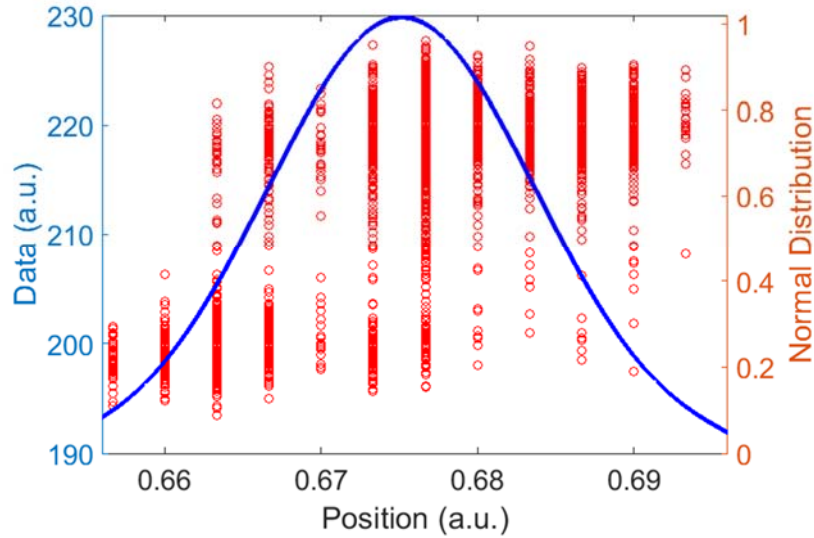


Fig. 8. A plot of the normal distribution of fluctuations in the position of an interference fringe without external IR absorption. This distribution is used to determine our noise. The standard deviation of this distribution is compared to the interference fringe shift created by known source temperature changes. Using this method we find that our NETD is 4.88 mK in air.

Chapter 4 References

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VI. Chapter 4: Thermodynamically Limited Uncooled Optomechanical Detector Performance

In the final year of the program, we achieved the program goal of uncooled detection reaching near 1mK NETD. Indeed the detector had such a high detectivity that its noise was dominated (98%) by fundamental thermodynamic phonon and photon fluctuations rather than read-out noise. This work was recently published in *Optica*, the top journal of Optica (Optical Society of America). Primary Source of Report: A. Das, M. L. Mah, J. Hunt, and J. J. Talghader, “Thermodynamically limited uncooled infrared detector using an ultra-low mass perforated subwavelength absorber,” *Optica*, vol. 10, no. 8, pp. 1018-1028, August 2023. doi.org/10.1364/OPTICA.489761

The detector performed with a detectivity of $3.8 \times 10^9 \text{ cmHz}^{1/2}/\text{W}$, which is the highest reported for any room temperature device operating in the long-wave infrared ($\lambda \sim 8\text{-}12\mu\text{m}$). The device has shown a noise-equivalent temperature difference of 4.5mK and a time constant of 7.4 ms. The detector contains a subwavelength perforated absorber with an absorption-per-unit-thermal-mass-per-unit-area of $1.54 \times 10^{22} \text{ kg}^{-1} \text{ m}^{-2}$. The perforated absorber membrane is mostly open space, and the solid portion consists of Ti, SiNx, and Ni layers with an overall fill factor of 28%, where subwavelength interference, cavity coupling, and evanescent field absorption among units induce the high absorption-per-unit-thermal mass-per-area. Readout of the detector occurs via infrared-absorption-induced deformation using Mach–Zehnder interferometry, with a specific implementation chosen for its long-term compatibility with array reads using a single integrated transceiver.

Infrared detectors [1-5] are transducers producing a measurable electrical/optical output in response to long wavelength radiation intercepted by the sensing element. The highest theoretically possible performance is achieved at the background-limit, a state where photons emitted from the target dominate the total noise. In the long-wave infrared (LWIR, $\lambda \sim 8\text{-}12 \mu\text{m}$), this limit is usually achieved by cooling a focal plane array (FPA) to cryogenic temperatures so that other noise sources, which depend on the detector temperature, can be minimized.

Uncooled detector technology is dominated primarily by microbolometer arrays [6–10] but with a smaller contingent of alternative technologies such as thermopiles [11–13]. Originally developed in the 1970’s and 80’s [14–17], microbolometers consist of highly thermally isolated resistors that absorb LWIR light, heat the device, alter device resistance, and allow a bias current to produce a signal-dependent potential difference. Thermopiles have some similarities in structure and operation to a microbolometer, but differ in the electrical readout, which uses thermocouples to produce a temperature dependent voltage based on the Seebeck effect. In recent years, diode- and transistor-based detectors [18–20] have emerged, which have many similarities to bolometers with semiconductor resistors. Considering high IR absorption, all these detectors can be

designed with metal-insulator-metal (MIM) [21–25] and frequency selective surface (FSS)-based absorbers [26–28]. Typically, three distinct layers, i.e., (i) a bottom metal layer, (ii) an insulator spacer, and (c) a top thin film, are used to form a MIM based detector absorber. In such a configuration, enhanced light coupling is realized by effective impedance matching of the top metal to free space, resulting in a minimum (nearly zero) IR reflection. Often the top surface is composed of sub-wavelength periodic metal patches, which absorb essentially perfectly at selective frequencies. This type of surface is also known as frequency selective surface (FSS) [28]. Typically, metal patches with uniform sizes support a single resonant band, resulting in a narrowband LWIR absorption. However, broadband absorption can be achieved by tailoring the metal patches to different sizes in a unit cell, causing superposition of multiple resonance bands [29, 30]. In recent years, uncooled microbolometers have been integrated with both narrowband and broadband IR FSS absorbers [28].

It should be noted that both microbolometers and thermopiles possess electrical noise sources

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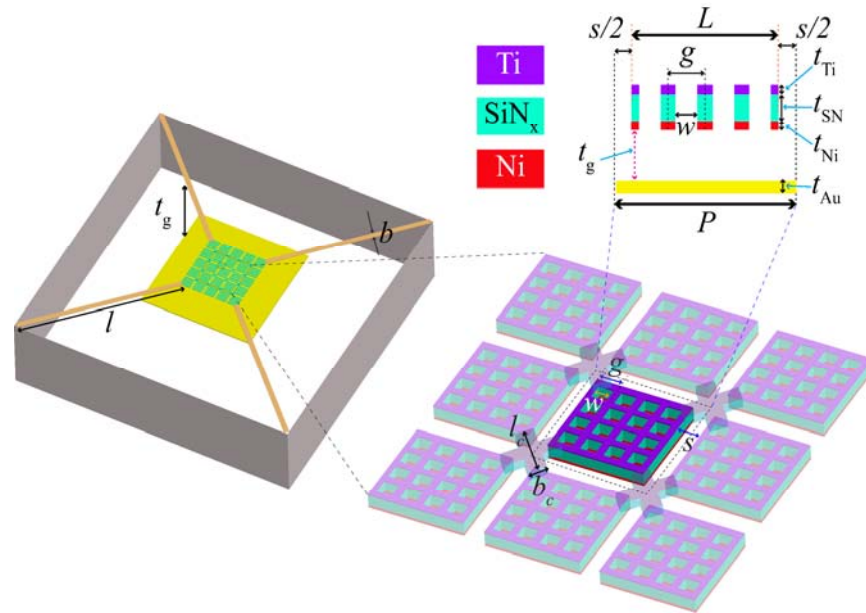


Figure 1. Schematic illustration of a long-wave infrared thermal detector with a subwavelength perforated absorber suspended by four straight tethers. All the absorber design parameters are highlighted along with the Ti, SiN_x, and Ni films. A bottom Au reflector is placed underneath at an air gap to satisfy quarter-wave anti-resonance ($m\lambda/4$) condition.

fundamental to thermal detection and degrade the minimum measurable signal, often measured using a parameter called the noise-equivalent temperature difference (NETD). Thermo-mechanical detectors, such as cantilever detectors [31–35]; and thermo-optic detectors [36, 37] can reduce or eliminate electrical noises, but they have often been plagued by large thermal mass, resulting in degraded performance even in vacuum.

Enhanced performance can be achieved when the thermal mass of the detector is low such that the thermal fluctuations from radiation dominate other noise sources. With such a reduced thermal mass, the detector can be fast, but to collect sufficient light to overcome thermal fluctuations, its area must be large enough that the radiation becomes significant in the heat transfer. One method to maximize the area of a minimum-mass infrared detector is to create a perforated device whose subwavelength periodicity allows it to absorb the

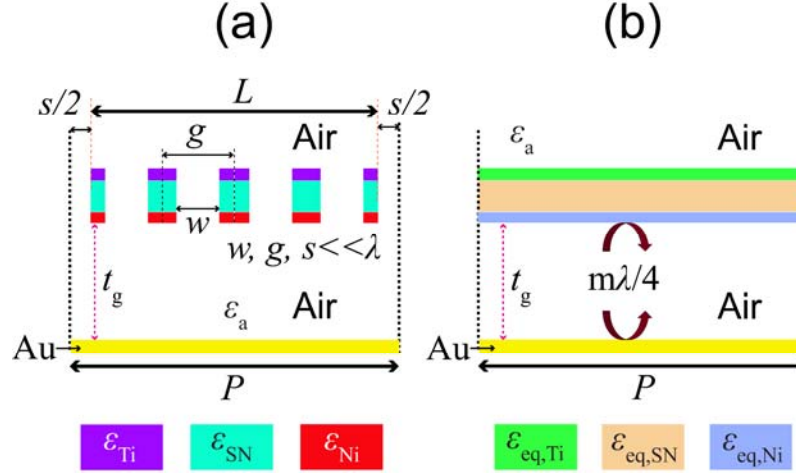


Figure 2. (a) Schematic illustration of a pitch period of the Ti-SiN_x-Ni perforated absorber. All the necessary parameters are highlighted along with optical permittivity ϵ_{Ti} , ϵ_{SN} , ϵ_{Ni} , and ϵ_a for Ti, SiN_x, Ni, and free space, respectively. (b) Equivalent multilayer model where Ti, SiN_x, and Ni layers are presented with effective homogeneous layers.

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demonstrated a subwavelength perforated detector with record room temperature performance across key detector metrics, coming within about a factor of 4 of the background radiation limits for detectivity. Lossy Ti, SiN_x, and Ni films were used to form the perforated structure. Using effective medium analysis and Fabry Perot cavity coupling, the infrared detector achieved enhanced absorption-per-unit-thermal mass-per-area of $1.54 \times 10^{22} \text{ kg}^{-1} \text{ m}^{-2}$, which is approximately 1.6–32.1 times greater than the state-of-the-art infrared absorbers reported till date. For the optical readout of the detector, we chose Mach Zehnder interferometry because of its ease of integration, as shown in fiber optic communications, and its long-term potential to read an entire array simultaneously with a single transceiver. With a thermal time constant of $\sim 7.4 \text{ ms}$, we measured a noise equivalent temperature difference (NETD) of 4.5 mK and a record detectivity of $3.8 \times 10^9 \text{ cm} \sqrt{\text{Hz}}/\text{W}$. Compared to other state-of-the-art uncooled detectors, our device records the highest detectivity reported till date, as seen with a listing of 70+ selected other works shown in Fig. 12. In addition, the detector is almost entirely limited by the temperature fluctuation noise, i.e., thermodynamic noise, which consists of about 98% of the overall noise. Our work would pave the way for scalable thermo-optics based infrared sensing for different military [38–42], biomedical [43–46], and industrial [47] applications.

5. Detector design

Figure 1 presents a schematic illustration of the uncooled long-wave infrared (LWIR) thermal detector with a subwavelength perforated absorber freely suspended by four straight tethers, with length l of 100 μm and width b of 2 μm . The absorber consists of an array of square pitches with a periodicity, P of 7.5 μm . Each pitch contains 16 nano-scale grid units, with each grid having a period, g of 1.5 μm and a perforation size, w of 1.2 μm (i. e., perforation ratio, $w/g=0.8$). The subwavelength grids consist of Ti, SiN_x, and Ni films in a perforated metal-insulator-metal (MIM) configuration, whose thicknesses, i.e., t_{Ti} , t_{SN} , and t_{Ni} are taken as 10 nm, 200 nm, and 10 nm, respectively. A free space gap s of 1.5 μm is utilized around the solid absorber pitches designed to couple evanescent LWIR light in the gaps as part of the detector absorption. The absorber pitches are connected with small

supporting legs with length l_c of 3 μm and width b_c of 1 μm . The whole detector is situated above a gold (Au) reflector (thickness t_{Au} of 120 nm) at a gap distance t_g of ~ 2.3 μm , ensuring quarter-wave anti-resonance ($m\lambda/4$) condition to boost up the LWIR ($\lambda \sim 8\text{--}12$ μm) absorption [48].

6. Effective medium analysis

To better understand the underlying mechanism for optical absorption in the perforated Ti-SiN_x-Ni absorber, we need to perform an effective permittivity analysis. The grid unit period g , perforation length w , and air space s are well below the wavelengths of light in consideration; therefore, an effective medium approximation can be applied for the subwavelength grids [49]. The effective medium approximation has been previously reported in analyzing the optical absorption of periodic grating structures [50–52]. Figure 2(a) presents the schematic of a pitch period with optical permittivity ϵ_{Ti} , ϵ_{SiN_x} , ϵ_{Ni} , and ϵ_a for Ti, SiN_x, Ni, and free space, respectively. All necessary parameters are highlighted as in Figure 1. Figure 2(b) shows the equivalent homogeneous films of the subwavelength grids, whose optical permittivity can be calculated from the effective medium approximation [53–55] and effective grating analysis [56, 57] as (details in Supplementary Material),

$$\epsilon_{\text{eq},x} = f_p \epsilon_x + (1 - f_p) \epsilon_a \quad (1)$$

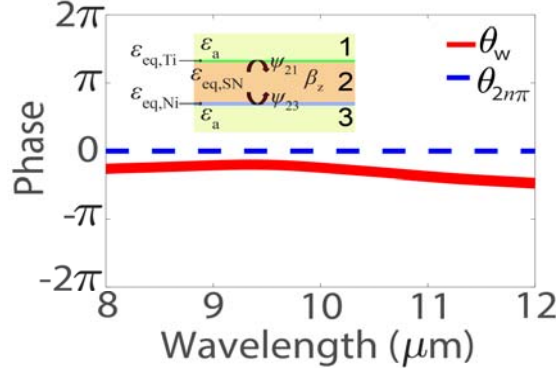


Figure 3. Round-trip phase θ_w of LWIR light inside detector using the effective medium model of the Ti-SiN_x-Ni detector absorber. The inset depicts the phases of reflections Ψ_{21} and Ψ_{23} , and the propagation constant β_z inside the absorber.

where $\epsilon_{eq,x}$ is the effective permittivity of the films, with x =Ti, SiN_x, or Ni and $\epsilon_a=1$. f_p corresponds to the linear duty cycle of the pitch, as if $f_p = \frac{L}{P} \left(1 - \frac{w}{g}\right)$, where L can be defined as $L = P - s$. Due to the higher permittivity of the metals compared to the dielectric, the homogeneous Ti and Ni layers can be conceptually understood as “mirrors” that would trap the incoming light inside the equivalent SiN_x layer. Upon incidence, the LWIR light would reflect multiple times from the two metal films, forming a Fabry-Perot-like cavity. Maximum coupling can be achieved when the round-trip phase θ_w of this light fulfills as follows [58, 59],

$$\theta_w = \psi_{21} + \psi_{23} + 2\beta_z t_{SN} = 2n\pi, \quad n = 0, 1, 2, \dots \quad (2)$$

where Ψ_{21} and Ψ_{23} are the phases of reflection at the interfaces of Ti/air and Ni/air, respectively. Considering t_{Ti} , $t_{Ni} \ll t_{SN}$ and effective light coupling within the dielectric, $\beta_z = \frac{2\pi}{\lambda} \sqrt{\epsilon_{eq,SN}}$ is the propagating phase in the SiN_x layer, where $\epsilon_{eq,SN}$ is the effective homogeneous permittivity of SiN_x and λ is the wavelength of light. When θ_w approaches $2n\pi$, the waves that encounter multiple reflections inside the absorber waveguide get closer

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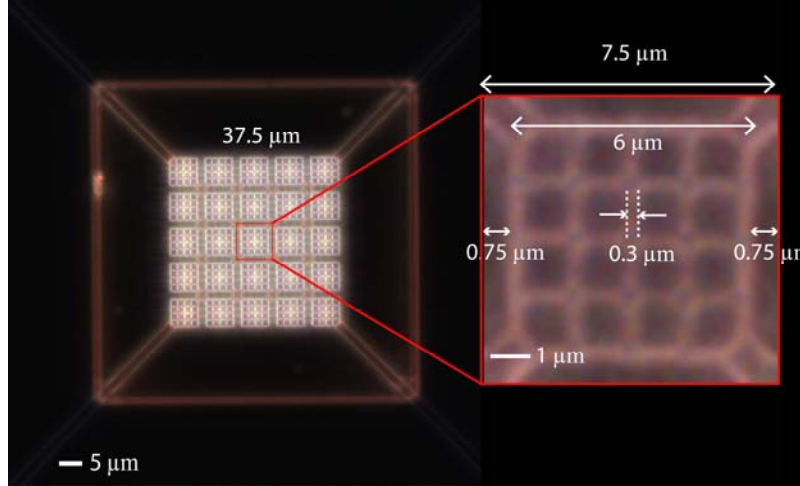


Figure 4. Optical microscopic image of the successfully released perforated Ti-Si_x-Ni infrared detector, with an absorption area of 37.5 μm × 37.5 μm (i.e., a 5×5 grating pixel). The inset shows the pitch period, solid pitch length, air space between adjacent pitches, and linewidth of the nano-grids.

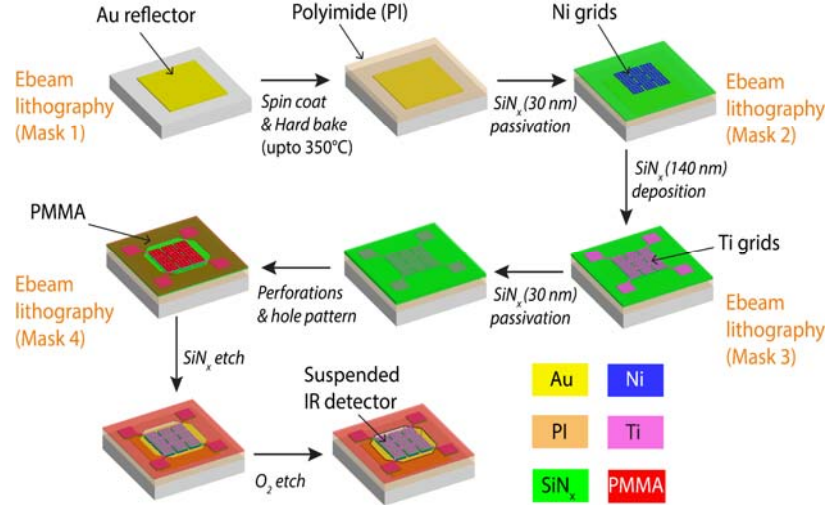


Figure 5. Fabrication process of the Ti-Si_x-Ni infrared thermal detector.

constructive interference and hence, lead to resonant cavity modes. Figure 3 presents the round-trip phase θ_w calculated across the LWIR region ($\lambda \sim 8-12 \mu\text{m}$). It can be observed that the phase gets closer to 0 (i.e., $n=0$) around 8–9 μm, and moves away from the $2n\pi$ line in longer wavelengths. Therefore, higher absorption should be observed in shorter wavelengths. In addition, the wide bandwidth of the round-trip phase implies broadband optical absorption across the LWIR.

7. Fabrication process

Figure 4 shows an optical microscopic image of our infrared structure, after it was successfully fabricated and released in air/vacuum. It consists of an array of 25 grating absorber periods (5×5 array), comprising a total absorption area of 37.5 μm × 37.5 μm. Fabrication of the structure was performed through a four-mask electron beam (e-beam) lithography process. Fig. 5 presents the flow chart of our fabrication process. Initially, an

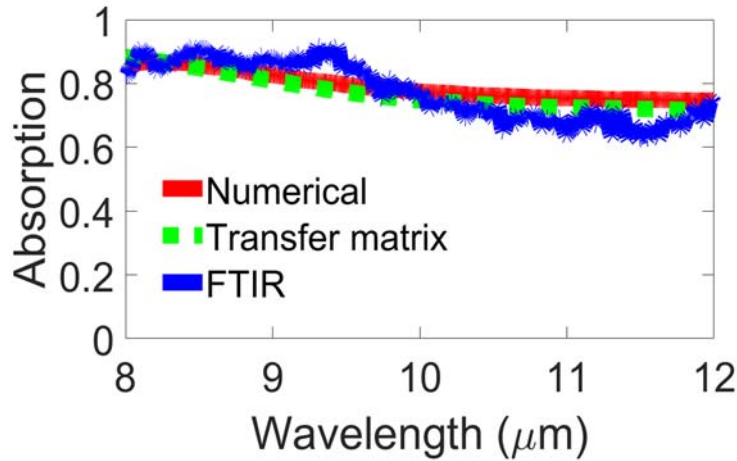


Figure 6. Spectral LWIR absorption measurements (FTIR) and simulations (numerical FDTD technique and multilayer transfer matrix method) of the detector.

film of 120 nm was deposited and patterned on a Si wafer using the first mask. The Au works as a bottom mirror. Then a sacrificial polyimide layer (PI 2611, from HD Micro Systems) was spin-coated (6500 rpm for 30 s) on top of the Au mirror to form the quarter-wave anti-resonant cavity. A tube furnace was used to bake the polyimide film gradually from room temperature to $\sim 350^{\circ}\text{C}$ with a time span of ~ 2 hours. Note that the tube furnace was equipped with an N_2 gas supply to protect the sacrificial layer from oxidation. After the baking was complete, the resultant polyimide film was quite uniform with a thickness of $\sim 2.3\ \mu\text{m}$, which was resistant to any resist remover (e.g., Acetone or 1165 stripper).

Using high density plasma chemical vapor deposition (HDPCVD), 20 nm of SiN_x was initially deposited on the hard-baked polyimide to protect the metal grids from erosion and contamination. Then, 10 nm of Ni (without the supporting tethers) were evaporated and patterned into perforated grids using the second mask of the e-beam lithography. This was followed by the deposition of 160 nm of SiN_x using HDPCVD. In the next step, 10 nm of Ti (with the supporting tethers) were evaporated and patterned into identical perforated grids using the third mask of the e-beam lithography. Sputtering can be another option for Ni/Ti deposition; however, it would produce more conformal coatings, especially in nanoscale grids, resulting in poor patterns during lift-off [60]. In addition, e-beam evaporation provides better fabrication tolerance, with a thickness of $10 \pm 0.3\ \text{nm}$ (deviation of $\sim 3\%$) for the Ni/Ti film deposition.

A thin SiN_x film of 20 nm was coated on top of the Ti grids as a passivation layer, which would protect Ti from getting oxidized (i.e., forming thin TiO_2). The fourth mask of the e-beam lithography was used to remove dielectric material in the metal perforation patterns. Extreme care was taken while aligning the fourth mask on top of the Ti grids, as a slight rotation of the substrate ($>0.2^{\circ}$) could result in misregistration. The etch release of the detector began with the removal of SiN_x through the grid openings using reactive ion etching (RIE). We used an etch recipe of 10 sccm of CHF_3 and 10 sccm of SF_6 , with an RF power of 50 W. The chamber pressure was kept at 5 mTorr to ensure an anisotropic etch. The passivation SiN_x film on top of the Ti gridlines themselves was not removed as it was protected by the PMMA resist. Finally, the perforated detector was successfully suspended

in air by removing the sacrificial polyimide using an O₂ isotropic etch. The etch release recipe used 30 sccm of O₂, with 100 W of RF power and 30–50 mTorr of chamber pressure. If a high pressure, such as 300–500

Table 1. Average absorption, thermal mass, and absorption-per-unit-mass-per-area (Abs/mass-area) of our detector membrane with state-of-the-art infrared absorbers

Absorber	Average Absorption (%)	Thermal mass (kg)	Average Abs/mass-area (kg ⁻¹ m ⁻²)	$\frac{\text{Abs/mass-area}_{\text{TiSiN}_x\text{-Ni}}}{\text{Abs/mass-area}_{\text{other works}}}$	References
Ti-SiN _x -Ni	78	1×10^{-13}	1.54×10^2	1	This work
Al-Si-Al	93	2.38×10^{-12}	6.8×10^{20}	22.6	[61]
Si-SiO ₂ -Si	90	1.34×10^{-12}	1.2×10^{21}	12.8	[62]
Ti-Ge-Ti	93	1.77×10^{-12}	9.3×10^{20}	16.6	[63]
NiCr (Ge spacer)	79	2.86×10^{-12}	4.8×10^{20}	32.1	[64]

mTorr were used, the O₂ gas would have removed polyimide more isotopically. As a result, the base support for the tethers/legs and the detector membrane might be compromised and collapse.

8. Optical absorption and absorption-per-unit-thermal mass-per-area

Both theoretical calculations and experimental measurements were utilized to analyze the optical absorption of the Ti-SiN_x-Ni detector. For theoretical analysis, we used a finite difference time domain (FDTD) technique and a transfer matrix method. For experimental verification, we used Fourier-transform infrared spectroscopy (FTIR). Details of the absorption simulations and measurements are presented in the Supplementary Material. Figure 6 shows the absorption spectrum of the detector across the LWIR. Both simulations and measurements show broadband absorption throughout the 8–12 μm wavelength range and are in close proximity to one another. The absorption is found to be higher (>80%) at shorter wavelengths (e.g., 8–9 μm), and gradually gets lower (<80%) in longer wavelengths. This can be attributed to the round-trip phase calculations analyzed for Fabry

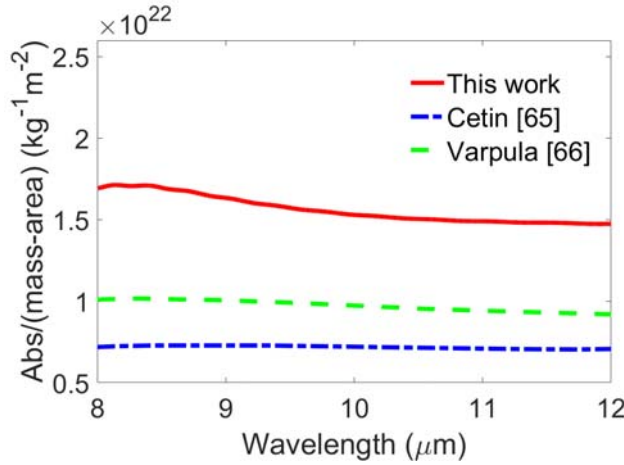


Figure 7. Comparative analysis of the absorption-per-unit-thermal mass-per-area (Abs/mass-area) of our structure with very recently reported metal-dielectric broadband metastructures by Cetin *et al.* [65] and Varpula *et al.* [66].

Perot cavity, as shown in Figure 3. The slight discrepancy between simulations and measurements may originate from the scattering losses in the back mirror [12].

To understand optimum coupling with a minimum amount of material, a comparative analysis of our detector absorber is required with the state-of-the-art LWIR broadband absorbers. When an absorber area (i.e., $L_{\text{abs}} \times L_{\text{abs}}$) is formed consisting of arrays of periodic pixels or pitches, the lateral length of the area (i.e., L_{abs}) is typically larger than the operating wavelengths of the absorber. The total amount of thermal mass proportionately increases with the absorber area, although the total absorption may not increase significantly. To ensure optimum performance, we can reduce the thermal mass of the absorber such that the detector would be limited only by thermodynamic temperature fluctuation. With this reduced mass, we can tend to enlarge the absorber area such that the radiation-limited thermal conductance, which depends on the detector area, can be increased, reducing the thermal time constant (i.e., faster response). In this work, we attempted to design the absorber area comparable to the state-of-the-art broadband

absorbers and detectors but with thermodynamically limited thermal mass. Therefore, to realize better performance (i.e., lower time constant) of the detector, the absorption may need to be normalized to both thermal mass and area. In other words, performance metric can be defined as ‘absorption-per-unit-thermal mass-per-area’ (Abs/mass-area) for a comparative analysis of the absorbers, when a common (or approximately same) absorption area can be considered for all structures. To compare with state-of-the-art works, we considered different types of structures, including metamaterials, metasurfaces, and plasmonic absorbers. Table 1 shows the average LWIR ($\lambda \sim 8\text{--}12\ \mu\text{m}$) absorption, amount of thermal mass, and average Abs/mass-area of the broadband infrared absorbers. We considered a fixed absorption area of $24\ \mu\text{m} \times 24\ \mu\text{m}$ for all these structures. For comparison, we took a 3×3 grating pixel for our Ti-SiN_x-Ni structure, which corresponds to an absorption area of $22.5\ \mu\text{m} \times 22.5\ \mu\text{m}$. It can be observed that all the reported works show an average absorption in between 80–93% but require a total mass of $\sim 10^{-12}$ kg. Our Ti-SiN_x-Ni detector absorber is designed with a mass of 1.00×10^{-13} kg while maintaining an average absorption near 80%. As a result, our absorber shows an average Abs/mass-area of $1.54 \times 10^{22}\ \text{kg}^{-1}\text{m}^{-2}$, which is 1 or 2 orders of magnitude larger than other state-of-the-art broadband absorbers.

Recently, metal-dielectric perforated metastructures have been reported with an $m\lambda/4$ air spacer, which utilizes effective sheet resistance matching for broadband absorption. Cetin *et al.* [65] proposed a NiCr (19 nm) on SiN_x (230 nm) broadband metasurface, with a pitch period of $25\ \mu\text{m}$, grid unit of $3\ \mu\text{m}$, and perforation ratio of 0.77. Later, Varpula *et al.* [66] reported a TiN (50 nm) on poly-Si (70 nm) thermoelectric infrared bolometer, with a pitch period of $24.6\ \mu\text{m}$, a grid unit of $3\ \mu\text{m}$, and a perforation ratio of 0.8. To provide a comparative analysis, Fig. 7 presents the spectral absorption-per-unit-thermal mass-per-area (Abs/mass-area) of our structure in the LWIR range, along with the works of Cetin *et al.* and Varpula *et al.* It can be observed that the NiCr on SiN_x metastructure shows nearly uniform Abs/mass-area with an average value of $\sim 7.2 \times 10^{21}\ \text{kg}^{-1}\text{m}^{-2}$. Due to having a smaller thickness of polysilicon, the thermoelectric TiN on polysilicon absorber shows comparatively higher Abs/mass-area, with an average value of $\sim 9.8 \times 10^{21}\ \text{kg}^{-1}\text{m}^{-2}$. With $\sim 1.54 \times 10^{22}\ \text{kg}^{-1}\text{m}^{-2}$, our designed absorber shows average Abs/mass-area ~ 2.1 times higher than that of the NiCr on SiN_x metastructure and ~ 1.6 times higher than that of the TiN on poly-Si bolometer. Note that the absorption profiles used in Fig. 7 are taken from numerical methods, as experimental measurements of absorption were not available for all cases. We and Cetin *et al.* used an FDTD technique, whereas Varpula *et al.* used a finite element method.

9. Detector characterization

9.1 Interferometry setup

The fabricated detector was read optically using a Mach Zehnder interferometer, as shown with a schematic illustration in Fig. 8. A He-Ne laser source ($\lambda=632.8$ nm) with a power of 10 mW was used for our experiment. The laser beam was divided into two orthogonal linearly polarized beams by a polarizing beam splitter (PBS). One of the beams,

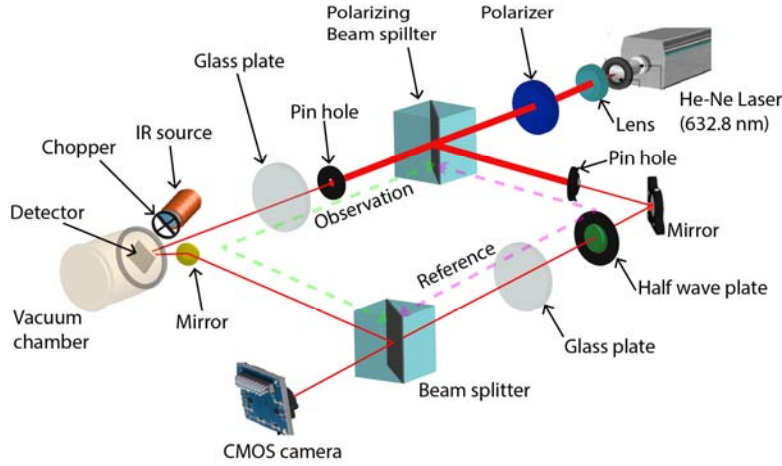


Figure 8. Schematic illustration of the Mach Zehnder interferometer and infrared detector.

mentioned as the “observation” beam, was incident on the pixel gratings of the fabricated detector placed inside a vacuum chamber (pressure $\sim 1.6 \times 10^{-4}$ torr). A micro-scale pinhole (~ 50 μm) was used to limit the beam to the detector gratings, and therefore, minimize unnecessary background reflection. Being reflected from the detector, the observation beam was guided towards a non-polarizing beam splitter (NPBS) by a small Au mirror. The other orthogonal polarized beam, mentioned as the “reference” beam, was reflected by another Au mirror and traveled to a half-wave plate to become parallel to the polarization state of the observation beam. A similar micro-scale pinhole was used to limit the reference beam. The observation and reference beams interfered with each other at the non-polarizing beam splitter (NPBS), generating interference fringes which were recorded by a CMOS camera. A polarizer was used before the polarizing beam splitter (PBS) to control and equalize the intensity of the reference and observation beams to maximize the contrast of the fringe patterns on the CMOS camera. Glass (SiO_2) plates, with a thickness of ~ 500 μm , were used along the two beam paths to assess the stability of the interference fringes. This means they were used to test whether the fringes shifted with a slight rotation (e.g., 0.5°) of any of the plates. To analyze the thermal sensitivity, an IR source (with a chopper) was placed near the vacuum chamber window (i.e., our detector).

It should be noted that at equilibrium, the observation beam travels a slightly larger optical path than the reference beam (in Fig. 8), resulting in an optical path difference of ΔL_{OR} in the absence of any IR excitation. To keep the interference fringes visible, the path difference ΔL_{OR} must be smaller than the coherence length L_c of the He-Ne laser beam, which means [67, 68],

$$\Delta L_{\text{OR}} < \frac{c}{\pi \Delta \nu} \quad (3)$$

where $\Delta \nu$ is the spectral linewidth of the laser (in Hz) and c is the speed of light. With $\Delta \nu \sim 0.95$ GHz and $\Delta L_{\text{OR}} \sim 40$ mm for our experiment, Eq. (3) was satisfied to ensure visible interference fringes.

9.2 Measurement of thermal response

When the detector is excited by an IR source, the incident optical power is absorbed and heats the detector. As the outer layers of the detector, i.e., Ti and Ni have thermal expansion mismatch (details in Supplementary Material), the heating produces thermal stress and hence, slight deformations in the shape of the perforated membrane, leading to additional path differences between the observation and reference beams beyond that of equilibrium, and therefore, distinct phase shifts develop in the interference fringes. As an example, Fig. 9 shows a phase shift of $\sim 2.2\pi$ of the fringes due to a chopped ($f_c = 10$ Hz) IR excitation, as recorded by our CMOS camera at room temperature (~ 310 K). The frame rate of the camera was 30 Hz during this measurement, which could be varied further with chopper frequencies to maintain the Nyquist condition [69]. The heating in this example image corresponds to a source temperature change ΔT of ~ 101 mK stabilized over a 1 second duration, as calibrated by a commercial microbolometer camera (Jenoptik IR-TCM 384).

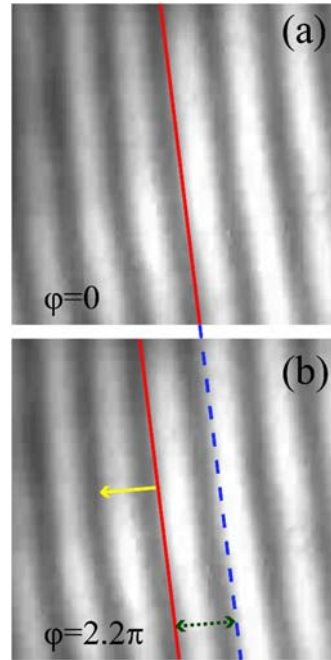


Figure 9. Fringe images recorded on a CMOS camera. A solid red and a dashed blue line are used to highlight the distinct phase shift of the fringes. The fringe movement is indicated by a yellow arrow. The fringe shift corresponds to a temperature change ΔT of 101 mK, as measured by a commercial microbolometer camera.

The fringe images were further processed with bright and dark colors, converted into a 0–255 data scale, and fitted with sinusoidal curves to measure the amount of phase shift.

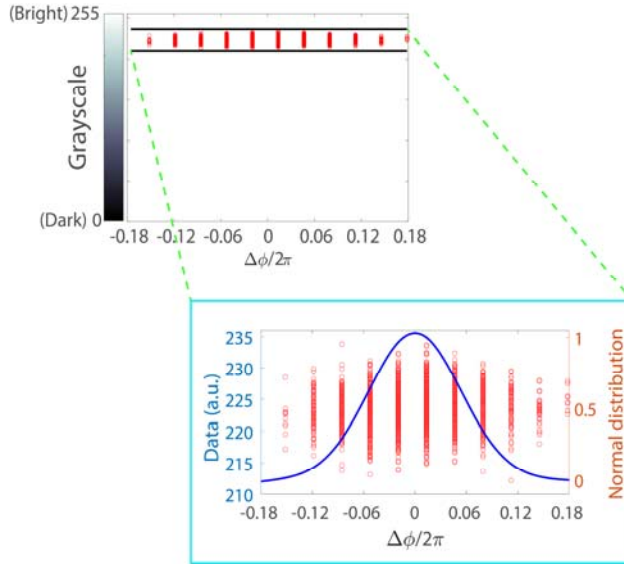


Figure 10. Fluctuations of an interference fringe (sine peak position) without external IR absorption presented in terms of normalized phase shifts $\Delta\phi/2\pi$, where mean equilibrium is presented as 0. The inset shows a zoomed version of the grayscale data points with normal distribution, which is used to determine our noise. The standard deviation σ of this distribution (i.e., $\Delta\phi/2\pi \sim 0.05$) is compared to the fringe shift created by known source temperature. Using this method, we found a minimum NETD of ~ 4.5 mK for our detector.

Details of the fringe analysis and source calibration have been discussed in the Supplementary Material. For NETD (noise-equivalent temperature difference) analysis, the fringe fluctuations (changes in a sine peak position) without IR excitation were recorded repeatedly over a duration of ~ 126 s and analyzed for ~ 3800 frames. The IR source could be turned off or shuttered during this measurement. Fig. 10 presents the grayscale data points of the fringe fluctuation (changes in sine peak position) with normalized phase shifts $\Delta\phi/2\pi$, where the mean equilibrium is shown as 0. The inset presents a zoomed version of the data with a normal distribution, which is used to determine our noise. We found that the standard deviation of this distribution is $\sim 5\%$ of the fringe period (i.e., $\Delta\phi/2\pi \sim 0.05$), which corresponds to a temperature difference (NETD) of ~ 4.5 mK when compared to the average fringe shift of 2.24π (i.e., $\Delta\phi/2\pi \sim 1.12$) created by the source excited temperature change ΔT of 101 mK. Three sets of measurements were analyzed to calculate the source-excited average shift of 2.24π . The measured NETD is an order of magnitude lower than that of standard uncooled commercial thermal cameras (~ 50 mK) [70].

10. Results and discussion

10.1 Calculation of thermal properties

The material properties of Ti, SiN_x, and Ni are presented in tabular format in the Supplementary Material. To analyze the heat transfer using thermodynamics, the thermal capacitance of the infrared detector can be defined as [71, 72],

$$C = C_{\text{Ti}}\rho_{\text{Ti}}V_{\text{Ti}} + C_{\text{SN}}\rho_{\text{SN}}V_{\text{SN}} + C_{\text{Ni}}\rho_{\text{Ni}}V_{\text{Ni}} \quad (4)$$

where, C , ρ , and V correspond to the specific heat, density, and volume of the material of interest, respectively. Considering solid pitch area and material thicknesses, the thermal capacitance of the grating pitches C_p (i.e., 5×5 array) is $\sim 3.2 \times 10^{-10} \text{ JK}^{-1}$. Moreover, the contribution of support cross-legs (length l_c and width b_c) among the pitches correspond to a thermal capacitance C_s of $\sim 8 \times 10^{-11} \text{ JK}^{-1}$. Therefore, the total thermal capacitance of the detector $C_T = C_p + C_s$ is found to be $\sim 4 \times 10^{-10} \text{ JK}^{-1}$.

The total thermal conductance G_T of the detector can be expressed with the following equation [73, 74],

$$G_T = G_{\text{leg}} + G_{\text{rad}} + G_{\text{air}} \quad (5)$$

where, G_{leg} , G_{rad} , and G_{air} are the heat conduction through the four tether legs (length l and width b), the heat radiation of the detector absorber, and the heat exchange by air flow, respectively. During fabrication, the tether legs were made of Ti and SiN_x films, and the Ni film was only deposited as a part of the infrared absorber. Therefore, from Deng *et al.* [72], we can calculate the thermal conductance of the support tether legs G_{leg} as,

$$G_{\text{leg}} = 4 \times \left(\eta_{\text{Ti}} \frac{b \times t_{\text{Ti}}}{l} + \eta_{\text{SN}} \frac{b \times t_{\text{SN}}}{l} \right) \quad (6)$$

where, η_{Ti} and η_{SN} are thermal conductivities of Ti and SiN_x , respectively. With $l=100 \text{ }\mu\text{m}$ and $b=2 \text{ }\mu\text{m}$, G_{leg} would be found to be $\sim 3.9 \times 10^{-8} \text{ WK}^{-1}$. In addition, the radiation-limited thermal conductance G_{rad} can be given by the derivative of the radiation power with temperature as [75],

$$G_{\text{rad}} = \frac{2h^2c^3A_d}{k_B T^2} \int_{\lambda, \Omega} \frac{\varepsilon_d(\lambda) \exp(hc / \lambda k_B T) d\lambda d\Omega}{\lambda^6 [\exp(hc / \lambda k_B T) - 1]^2} \quad (7)$$

with spherical radiation around the detector over the LWIR wavelengths (i.e., $8\text{--}12 \text{ }\mu\text{m}$), G_{rad} would be calculated to be $\sim 1.4 \times 10^{-8} \text{ WK}^{-1}$. For the heat transfer through air flow, the thermal conductance G_{air} depends on the chamber pressure P_{ch} as [73],

$$G_{\text{air}} = \left(\frac{1}{\kappa_{\text{hp}}} \frac{t_g}{A_d} + \frac{1}{\gamma_{\text{lp}}} \frac{1}{P_{\text{ch}}} \frac{1}{A_d} \right)^{-1} \quad (8)$$

where, κ_{hp} is the thermal conductivity coefficient of air in the classical theory, which has been reported as $0.0263 \text{ Wm}^{-1}\text{K}^{-1}$ [73] and γ_{lp} is a correction factor when the air molecules are confined between the detector and bottom Au reflector and the mean free path is much larger than the air gap t_g of $2.3 \text{ }\mu\text{m}$. With a specific heat of air C_{air} (i.e., 1005

$\text{Jkg}^{-1}\text{K}^{-1}$) and mass of a single molecule m_{air} (i.e., $4.65 \times 10^{-26} \text{ kg}$), $\gamma_{\text{lp}} = \frac{C_{\text{air}}}{3} \sqrt{\frac{8m_{\text{air}}}{\pi k_B T}}$ [73] at $T \sim 310 \text{ K}$ can be calculated to be $\sim 1.8 \text{ ms}^{-1}\text{K}^{-1}$. Note that Eq. (8) indicates an increase in G_{air} when the chamber pressure P_{ch} rises. During the experiment, we achieved a moderately

high vacuum (i.e., $P_{\text{ch}} \sim 1.6 \times 10^{-4}$ torr) using a turbomolecular pump. Therefore, using Eq. (8), G_{air} for our system should be $\sim 5.5 \times 10^{-11} \text{ WK}^{-1}$, which is quite negligible compared to G_{leg} and G_{rad} . With all three parts, the total thermal conductance G_{T} of our detector would be $\sim 5.3 \times 10^{-8} \text{ WK}^{-1}$. The thermal response time constant (τ) is one of the most important

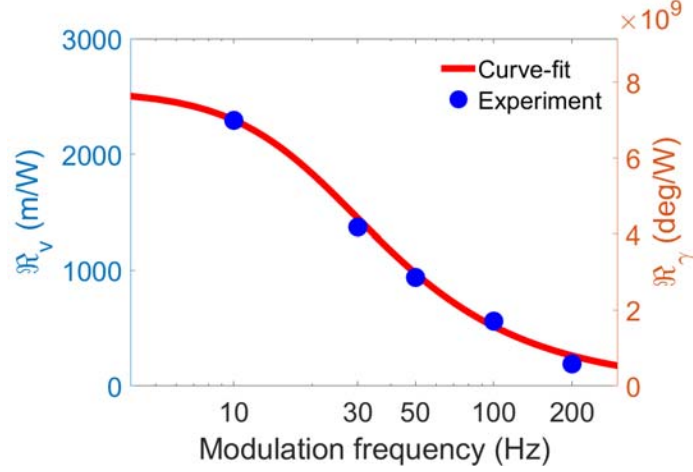


Figure 11. Linear and angular responsivities of the detector with different modulation frequencies.

parameters of the infrared detector. More information can be captured by a quicker response speed, i.e., a smaller time constant. The typical values of (τ) in an infrared detector may vary from 0.5 ms to ~ 1 s [71]. From C_{T} and G_{T} , we can calculate our thermal time constant as $\tau = C_{\text{T}}/G_{\text{T}}$, which would give a value of ~ 7.5 ms.

10.2 Responsivity and detectivity

Typically, thermal detectors with electrical readouts, such as microbolometers or thermopile detectors, report the thermal responsivity in terms of output voltage per unit of optical power (V/W). However, in detectors with optical readouts, the responsivity can be described as the deflection per unit power, either linear (m/W) or angular (deg/W) [76]. With experimental measurements of the fringe shifts and corresponding detector membrane deflections, we analyzed the linear responsivity $\mathfrak{R}_v$ and angular responsivity $\mathfrak{R}_\gamma$ with different modulation frequencies when the source excited temperature increment ΔT was ~ 101 mK. Details of the deflection analysis with temperature increment are discussed in the Supplementary Material. Fig. 11 shows the responsivities $\mathfrak{R}_v$ and $\mathfrak{R}_\gamma$ as functions of the modulation frequencies. With increasing frequencies, the gradual decrease in $\mathfrak{R}_v$ and $\mathfrak{R}_\gamma$ are plotted with the experimental points and fitted to a

theoretical curve $\mathfrak{R} = \frac{\mathfrak{R}_0}{\sqrt{1 + \omega^2 \tau^2}}$, where $\mathfrak{R}_0$ is the dc responsivity and $\omega = 2\pi f$. From -3dB cutoff, the time constant τ of the detector can be found to be ~ 7.4 ms, which is almost the same as observed in the theoretical calculations.

Detectivity is often used to describe the performance of an infrared detector and is related to the noise-equivalent power (NEP) by [71, 75],

$$D^* = \frac{\sqrt{A_d \Delta f}}{NEP} \quad (9)$$

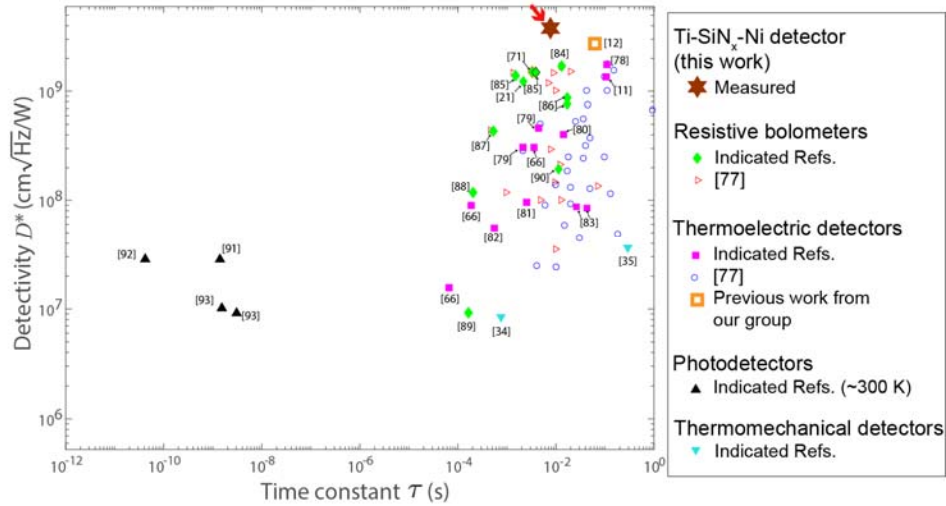


Figure 12. Comparative analysis of detectivity D^* and thermal time constant τ of the Ti-SiNx-Ni infrared detector presented in this work with other state-of-the-art resistive microbolometers, thermoelectric detectors, thermomechanical detectors, and photodetectors. Only uncooled (i.e., room temperature) detectors are considered in this plot.

where Δf is the measurement bandwidth. Unlike typical thermoelectric devices and resistive bolometers, our detector is free from electrical noise (i.e., Johnson or flicker $1/f$). The only noise that limits the performance is the thermodynamic temperature fluctuations. The details of the noise calculations will be discussed in the following section. The NEP of the detector can be calculated from the measurement of NETD as [3],

$$NETD = \frac{4F_{no}^2}{A_d \varepsilon_d \pi (\Delta L / \Delta T)} NEP \quad (10)$$

where F_{no} is the F-number of the system optics (here, $F_{no}=1$) and $\Delta L/\Delta T$ is the change in the radiance with temperature. With our measured NETD from Fig. 10 and other parameters calculated for $\lambda \sim 8\text{--}12 \text{ }\mu\text{m}$; i.e., $A_d=37.5 \text{ }\mu\text{m} \times 37.5 \text{ }\mu\text{m}$, $\varepsilon_d=0.78$ (averaged from measurements), and $\Delta f=10 \text{ Hz}$, a detectivity D^* of $3.8 \times 10^9 \text{ cm}\sqrt{\text{Hz}}/\text{W}$ was found from the experiment. This is the highest D^* for any room temperature infrared detector reported to date. To better understand this statement, Fig 12 presents a comprehensive analysis of the uncooled infrared detector technology in terms of detectivity and thermal time constant. In this analysis, we have included all types of detectors, i.e., thermoelectric detectors [11, 12, 66, 77–83], resistive microbolometers [71, 77, 84–90], thermomechanical detectors [34, 35] and photodetectors (uncooled) [91–93]. It can be clearly observed that our fabricated detector shows the highest detectivity over nearly 70 reported works, with a time constant ($\sim 7.4 \text{ ms}$) relatively faster than that of video frame rates.

10.3 Limiting noise and detector improvement

Table 2: Noise-equivalent power (NEP) for different noise sources

Noise source	NEP (pW)
Temperature fluctuation	3.05
Mechanical fluctuation	0.38
CMOS readout noise	0.013
Laser pressure noise	0.007
Diffraction induced noise	6.8×10^{-5}
Total noise	3.07

Being free from electrical noise, e.g., Johnson and $1/f$ (flicker) noise, our thermal detector is still vulnerable to other sources of noise, e.g., temperature fluctuations (i.e., thermodynamic noise), mechanical fluctuations (i.e., thermomechanical noise), laser pressure induced deflections (i.e., photon pressure noise), noise from the CMOS camera (readout noise), and the diffraction of the probe beam. Details of these noise calculations are presented in the Supplemental Information. Table 2 presents the noise-equivalent

power (NEP), i.e, the amount of radiation power yielding a signal-to-noise ratio (SNR) of unity, analyzed from different noise sources and the total NEP calculated as,

$$NEP = \sqrt{\sum_i NEP_i^2} \quad (11)$$

It can be clearly observed that temperature fluctuation noise, i.e., thermodynamic noise dominates over all other noise sources. Note that using Eq. (9), the NEP of 3.05 pW from thermodynamic noise would result in a D^* of $3.9 \times 10^9 \text{ cm}\sqrt{\text{Hz}}/\text{W}$, which is almost the same as our experimental measurement shown in Fig. 12. Therefore, our Ti-SiN_x-Ni detector is limited by the thermodynamic noise. The thermodynamic noise arises primarily from the thermal conductance of the tethers, i.e., phonons absorbed and emitted from the detector grid but is small enough that a substantial contribution arises from photon fluctuations. This device is not far from the fundamental performance limit. Using the heat conduction of the four straight tethers (G_{leg}) and radiation from the absorber (G_{rad}) into temperature fluctuation noise calculation (please see Supplemental Information); it can be found that, out of 3.05 pW, ~2.24 pW noise originates from phonons and the rest, 0.81 pW, comes from photons.

The thermal conductance noise could be greatly reduced if we would have used SiO₂ instead of SiN_x in the support tethers, as the thermal conductivity of SiO₂ is lower than that of SiN_x [94]. With a length l of 100 μm and width w of 2 μm for Ti-SiO₂ tether, the support leg thermal conductance G_{leg} can be calculated as $\sim 1.8 \times 10^{-8} \text{ WK}^{-1}$, which gives a total thermal conductance G_{T} of $\sim 3.3 \times 10^{-8} \text{ WK}^{-1}$. This is about 37% lower than that of our fabricated structure. With the same absorber design (Ti-SiN_x-Ni perforated absorber), the detector with Ti-SiO₂ tethers would show a total NEP of ~2 pW and a detectivity D^* of $\sim 6 \times 10^9 \text{ cm}\sqrt{\text{Hz}}/\text{W}$, which would be an 58% increase compared to our present design.

It should be noted that recent works often report NEP as their performance metric instead of detectivity. For example, Blaikie *et al.* [95] recently reported a room-temperature graphene nanomechanical bolometer, with an NEP (normalized to bandwidth) of $2 \text{ pW}/\sqrt{\text{Hz}}$. When normalized to bandwidth, the NEP of our detector is found to be somewhat less than $1 \text{ pW}/\sqrt{\text{Hz}}$, which implies a ~50% improvement in sensitivity over that of Blaikie *et al.* [95].

It should be noted that optical characterization techniques using Mach Zehnder interferometry have been fully integrated in microelectromechanical systems (MEMS) [96, 97], with promising possibilities in a number of applications, such as fiber optics communication [98–100] and optical sensing [101–103]. Mach Zehnder interferometers require very low power consumption and are easily integrated. Most relevant to this paper are the extremely small volumes of the interferometers, which indicate that an imaging Mach-Zehnder is easily compatible with commonly used camera form factors. A focal plane array of pixels can be optically sensed by mapping phase images obtained with an imaging MEMS Mach Zehnder interferometer.

Chapter 5 References

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