AFRL-RX-WP-TR-2020-0043

ATOMIC CALLIGRAPHY TO BUILD TUNABLE OPTICAL

David J. Bishop
Trustees of Boston University

12 FEBRUARY 2020
Final Report

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

This report is the result of contracted fundamental research deemed exempt from public affairs security and policy review in accordance with SAF/AQR memorandum dated 10 Dec 08 and AFRL/CA policy clarification memorandum dated 16 Jan 09. This report is available to the general public, including foreign nationals.

Copies may be obtained from the Defense Technical Information Center (DTIC) (http://www.dtic.mil).

AFRL-RX-WP-TR-2020-0043 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//SIGNATURE//______________________	//SIGNATURE//______________________
JOHN JONES	MARK SCHMITT
Work Unit Manager	Branch Chief
Nanoelectronic Materials Branch	Nanoelectronic Materials Branch
Functional Materials Division	Functional Materials Division
Materials and Manufacturing Directorate	Materials and Manufacturing Directorate

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*
12 February 2020

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
04 June 2015 – 12 January 2020

4. TITLE AND SUBTITLE
Atomic Calligraphy to Build Tunable Optical Metamaterials

5a. CONTRACT NUMBER
FA8650-15-C-7545

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
65502e

6. AUTHOR(S)
David J. Bishop

5d. PROJECT NUMBER
DARPA

5e. TASK NUMBER

5f. WORK UNIT NUMBER
X0ZX

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Trustees of Boston University
1 Silber Way
Boston, MA 02015-1390

8. PERFORMING ORGANIZATION REPORT NUMBER
DARPA

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Materials and Manufacturing Directorate
WPAFB, OH 45433-7750
Air Force Materiel Command
United States Air Force

Defense Advanced Research
Projects Agency (DARPA)
3701 North Fairfax Drive
Arlington VA 22203-1714

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RXAN

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RX-WP-TR-2020-0043

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Report contains color.

14. ABSTRACT *(Maximum 200 words)*

Developed under DARPA-BAA-14-56. In this program we have leveraged the power and flexibility inherent in our recently developed atomic calligraphy technology and used it to create low cost, *tunable* optical metamaterials for use in the visible and IR. In the battlefield of the future, optical radiation will be used for both locating a platform as well as destroying it and that radiation will be multi-frequency and/or dynamically tunable. The optical properties of any platform that one wishes to survive in such an environment will need to be dynamic as well. Our metamaterials allow the system designer to build platforms whose optical properties can be tuned in real time, responding to rapidly changing threats in its environment.

15. SUBJECT TERMS
DARPA report, optical meta-material, IR, tunable, nano-manufacturing, atomic calligraphy, nanotechnology

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES
Unclassified	Unclassified	Unclassified	SAR	28

19a. NAME OF RESPONSIBLE PERSON (Monitor)
John Jones

19b. TELEPHONE NUMBER *(Include Area Code)*
(937) 255-9106

TABLE OF CONTENTS

Section **Page**

LIST OF FIGURES

Figure: **Page**

BOSTON UNIVERSITY POINT OF CONTACTS

BU Technical Contact:

Dr. David J. Bishop
Professor of Physics, ECE, ME, BME and MSE
Department of Electrical and Computer Engineering
Boston University
Boston, MA 02215

Mailing Address: 8 Saint Mary's Street, Boston, MA 02215
Email: djb1@bu.edu
Phone: (617) 990 4037

BU Financial Contact:

Mr. Michael Trieu
Research Administrator
Post Award Financial Operations
Boston University
Boston, MA 02215

Mailing Address: 25 Buick Street, Boston, MA 02215
Email: mhtrieu@bu.edu
Phone: (617) 358 5255

BU Contracting Contact:

Mr. Paul Murphy
Associate Director, Pre-Award Services
Sponsored Programs
Boston University
Boston, MA 02215

Mailing Address: 25 Buick Street, Boston, MA 02215
Email: pemurphy@bu.edu
Phone: (617) 358 1458

1. SUMMARY

In the research funded here, the goal was to create tunable optical metamaterials using atomic calligraphy. Atomic calligraphy is a technique of atomic scale 3D printing developed at Boston University. As shown in this report, we have been quite successful and achieved all of our research goals. Our work has been published in 18 archival publications with 4 more currently in preparation.

In atomic calligraphy, one essentially spray paints atoms unto any material surface one wishes. In this work we have been able to spray paint atoms upon a wide range of surfaces including semiconductors and polymer substrates patterned using a direct laser write 3D printer (Nanoscribe). We have produced both static and dynamic optical metamaterials and written upon both 2D and 3D structures. We have developed the technical tools to write upon these structures, built them and then created tunable optical metamaterials. We have then optically characterized them, seen the desired tuning effect in their optical response and published the results.

In addition to our technical accomplishments, in our education program, three Post Docs (Matthias Imboden, Jeremy Reeves and Pablo del Corro) and eight graduate students (Thomas Stark, Han Han, Richard Lally, Lawrence Barrett, Josh Javor, Alexander Stange, Corey Pollock and Rachael Jayne) have been trained by working on various aspects of this project. Matthias works at Swatch R&D, Jeremy and Thomas currently work at BAE, Han works at Google, Pablo and Alex work at Analog Devices, Rachael works at St. Gobain, Corey works at Draper Labs and Richard and Josh are still completing their thesis work and Lawrence has just defended his dissertation this week and will be graduating soon. We have also hosted a number of high school students, undergraduates and local high school teachers during the summers who have worked on various aspects of this program.

2. INTRODUCTION

In this program we proposed to leverage the power and flexibility inherent in our recently developed atomic calligraphy technology and use it to create low cost, *tunable* optical metamaterials for use in the visible and IR regions. In the battlefield of the future, optical radiation will be used for both locating a platform as well as destroying it and that radiation will be multi-frequency and/or dynamically tunable. The optical properties of any platform that one wishes to survive in such an environment need to be dynamic as well. Our metamaterials allow the system designer to build platforms whose optical properties can be tuned in real time, responding to rapidly changing threats in its environment. In our program we used atomic calligraphy and dynamic stencils to build flexible scaffolds whose spacing, density and symmetry can be tuned over a wide range, allowing one to rapidly tailor the optical properties of the material in real time. Our approach used low cost materials and techniques allowing for modest cost subsystems at the end of the program but subsystems that leverage performance advantages uniquely enabled by the nanoscale features in the metamaterial. This is essentially a nanomanufacturing challenge which we believe we have solved.

Nanomanufacturing typically converges from two opposite approaches, top-down and bottom-up. Bottom-up manufacturing is how chickens are manufactured. Over billions of years, nature has evolved a set of processes whereby information encoded in DNA is used to control, via chemical and biological processes we are only just beginning to understand, the construction of complex biological systems with extraordinary functionality. The human brain is the quintessential example of what bottom-up engineering can do. Some extraordinary examples of bottom-up engineering exist today where resourceful scientists are beginning to replace billions of years of trial and error with deductive reasoning. The top-down approach is the march along a trajectory as defined by Moore's Law. Most nanotechnologists believe this is likely to be the direction that will produce microprocessors and memory chips for the next 10-20 years. This top-down approach is what we have done here, using atomic calligraphy.

Atomic calligraphy is a technique for directly writing with atoms at the nanoscale. The basic idea is to take a plate with one or more nanoscale apertures, and move it while spraying atoms onto the substrate. In Fig. 5, for example, there are shown four tethers that are attached to linear MEMS drives that move the plate while writing. The honeycomb structure above the plate is a shutter that can be used to start and stop the writing. Devices, both electrical and mechanical, with dimensions well into the sub-100nm regime can be written. Advantages of atomic calligraphy are 1) parallel processing giving one the opportunity to create many devices at the same time, 2) high resolution in the 10's of nm regime, 3) the deposition is the last step in the process meaning a wide range of materials can be used including both metallic and insulating materials, 4) no photoresist is used and so devices can be directly written on delicate scaffolds and elastomer actuators and finally 5) moderate cost and scalability to large volume manufacturing.

METHODS, ASSUMPTIONS AND PROCEDURES

Currently, the optical signature of a platform in a contested area is used to locate it. Present techniques look at the multispectral response of a system in optical bands ranging from the deep UV to the far IR. While today's systems are multispectral, in the not too distant future they will be broadband, capable of tuning over wide regions of the optical spectrum. In the next decade or so, optical radiation will also be used to destroy such platforms. Optical directed energy technology is maturing and the operational advantages (e.g. a "limitless magazine") are such that they will be deployed as soon as available. While the US leads in the development of these weapons, before very long we will be facing them as well. So in both avoiding detection and repelling an attack, the ability to use optical metamaterials where the optical signature of the platform can be engineered and optimized is a huge advantage. However, in the battlefield of the future, being static is fatal. Attacking systems will be dynamically tunable in seconds and successful defenses will require that ability as well.

Tunable optical metamaterials have been extensively developed and studied in the terahertz regime where the long wavelength (300 microns at 1 THz) allows for "atoms" that are ~50 microns and conventional MEMS devices can be used to move them. There is a large literature and a wide range of demonstrated experimental capabilities such as tunable dielectric constants, variable frequency filters and even non-reciprocal devices. However, doing the same thing in the visible and the IR has been a challenge because of the much shorter wavelength requiring "atoms" in the 100-1000 nm range.

We believed the basic structure and framework of the A2P program was ideally suited for solving this problem. The "atoms" we proposed to create would be optical metamaterials built with atomic calligraphy. This resist-free technique is scalable and allows for many (~10^6) sub-micron structures to be fabricated in parallel. In this report we show that we have succeeded in doing this. We describe the various technical elements of our approach and describe the various tunable optical metamaterials we have built.

There were three basic elements to our work plan that went forward in parallel: 1) MEMS device design, fab and characterization, 2) vacuum and macromechanical design and 3) optical characterization. We planned to have our MEMS atomic calligraphy devices built in a foundry using the MEMSCAP MUMPS process. Using a foundry let us focus on design, modeling and characterization instead of processing, lowering program costs and speeding up the time to functional devices. It also let us be able to ramp up to large volumes after we have optimized the MEMS design. Foundries are designed to provide large volumes at modest costs of optimized designs and eased the transfer of the mature technology to other vendors who may wish to use it. Foundries typically have a three month turn so in every six month period, we would get two complete iterations of our MEMS devices. An iteration consists of designing a device, submitting the design files to the foundry, having the foundry fab the device and return chips to us, we tested and characterized the device including modeling using a tool such as COMSOL, redesigned and resubmitted to the foundry. A MEMS device was usually completely functional after 1-2 iterations and optimized and mature after 2-3 iterations.

The vacuum and macromechanical design dealt with the vacuum system, source of metal atoms for writing our structures and the step and repeat mechanics. The final element of our program was the optical characterization of the “atoms”. This was done to ensure that the devices performed as desired. Our proposed work plan consisted of a 24 month base effort and an optional 18 month supplementary effort and a 12 month no cost extension. Generally, the 24 month base effort developed the technology, proved in all the required elements and confirmed the desired functionality of the “atoms”. The supplementary effort focused on increasing throughput, maximizing performance and developing lower cost platforms that leverage the basic technology but uses substrates that are more consistent with large volume, low cost production of functioning systems. The NCE extended the work to atomic scale printing using a dynamic writing method.

3. RESULTS AND DISCUSSION

3.1. High Speed Control of Electromechanical Transduction

We have demonstrated analytically and experimentally that applying well-timed drive steps at the correct amplitude with no analytical solution for the corresponding magnitude can completely eliminate the ringing of a damped (or un- damped) resonator system. The simple point mass and spring model is shown to be directly applicable to complex MEMS devices. A three-order-of-magnitude reduction in the settling time for both capacitively and magnetically actuated mirrors is demonstrated experimentally. In a thermally driven system, the periodic transient deflections can also be effectively suppressed, for which case drift behavior, resulting from long thermal relaxation times, dominates the settling time. These significant enhancements in performance are achieved without the need for self-sensing and closed-loop drive schemes. These techniques are presented as a method to tame high quality-factor devices, simplifying the control electronics. The results demonstrate that an open-loop system can perform point-to-point transitions at extremely high rates. Applications such as mechanically controlled optical switches will benefit considerably from implementing such drive modalities. Demonstrated by finite-element simulations, it is suggested that properly engineered devices can be driven by high acceleration and deceleration forces, resulting in settling times an additional order of magnitude shorter than that what has already been achieved using the double- step drive. It is believed that if such a drive modality were implemented in an actual device, its response would outperform active feedback circuits with the same maximal actuation force available. Details are provided in Ref. 1.

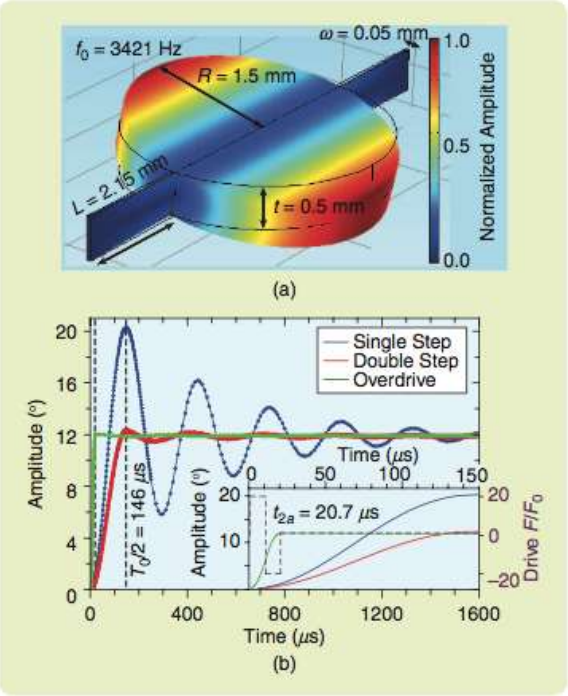


Figure 1. Simulations demonstrating the reductions in settling times we have achieved with our open loop control algorithms.

3.2. PWM as a Low Cost Method of the Analog Control of MEMS Devices

We have shown the use of PWM control signals for analog MEMS devices. We show that by applying a PWM signal to a MEMS device at frequencies well above the device resonant frequency, one can achieve precise, linear analog control of the proof mass position. Such an approach allows the system designer to replace expensive electronic components such as high precision DA’s and high voltage, linear amplifiers with a simple on-off switch. The meta trends in the electronics industry are making precise timing much cheaper as a function of time than precision analog control systems and our approach exploits these long term trends to create low cost control circuits. We also show how PWM control can linearize the positional response of devices where typically the position would depend quadratically on the applied, analog voltage. Details are provided in Ref. 2.

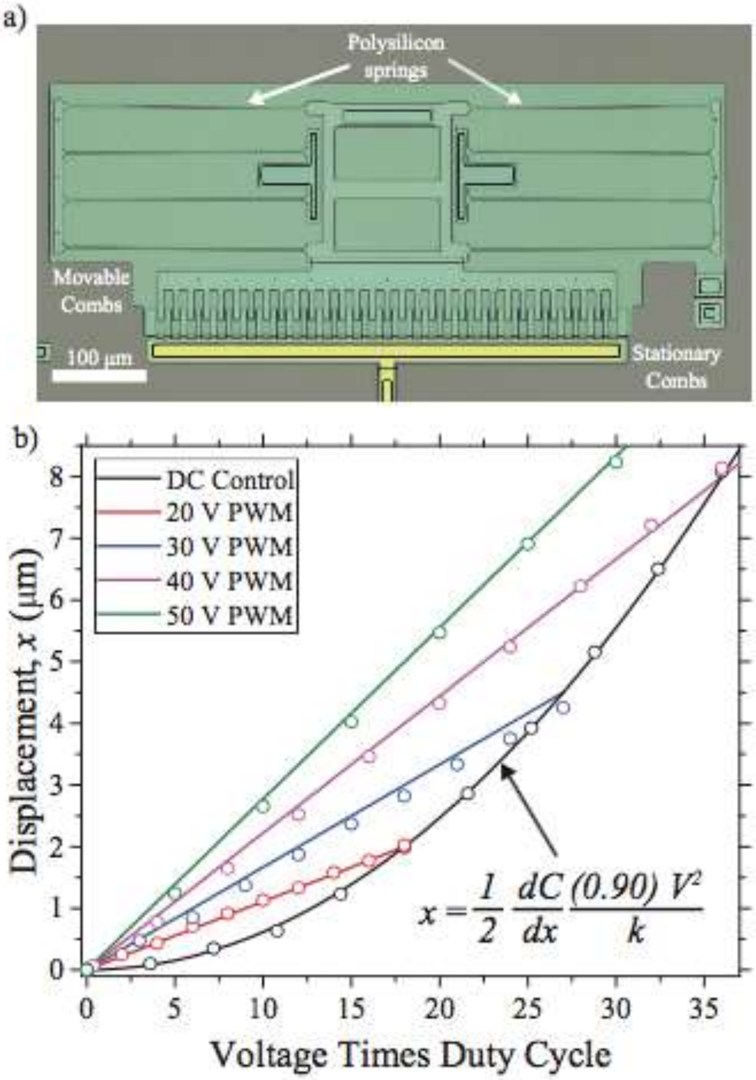
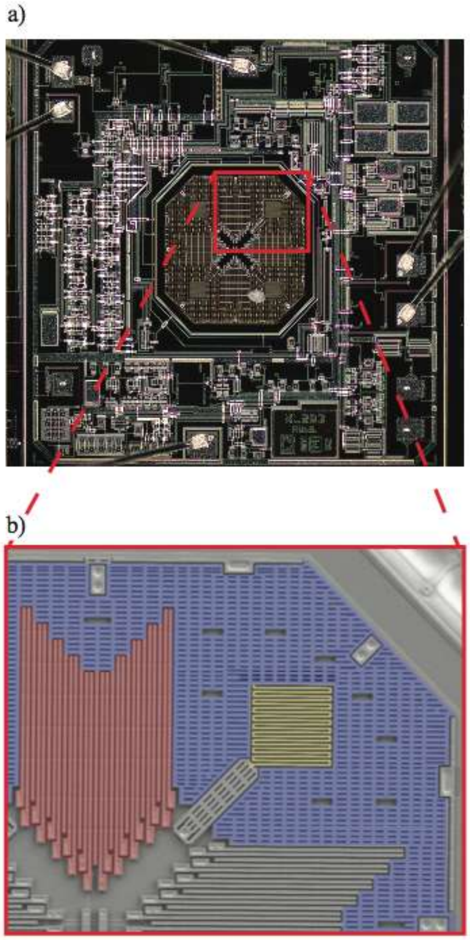


Figure 2. PWM providing analog control of a MEMS micro-motor.

3.3. Engineered PWM drives for achieving rapid step and settle times for MEMS actuation

Microelectromechanical systems (MEMS) provide engineers with a rich palette of technical solutions to a wide range of actuation and sensing challenges. MEMS devices are low cost, easily integrated with sense and drive electronics, are robust, and can be designed to respond to electrical, mechanical, or chemical stimuli. Because they are mechanical, MEMS devices suffer from being relatively slow in comparison with purely electronic devices. However, it has been shown that by using feedforward drives developed using controls theory approaches, it is possible to significantly improve the step and settle time of MEMS actuators. Our work uses this technique to demonstrate the use of pulse width modulation (PWM) to linearly drive MEMS. Furthermore, it demonstrates an overdrive method capable of improving the step and settle time of a commercial MEMS device by a factor of 1,500. The approach is general and can be used for a wide range of devices and actuation methods, such as electrostatic, electromagnetic, and thermal actuation. This provides engineers a simple method to design high *Q* MEMS devices with sub millisecond response times, opening the phase space for more micromechanical solutions. Details are provided in Ref. 3.



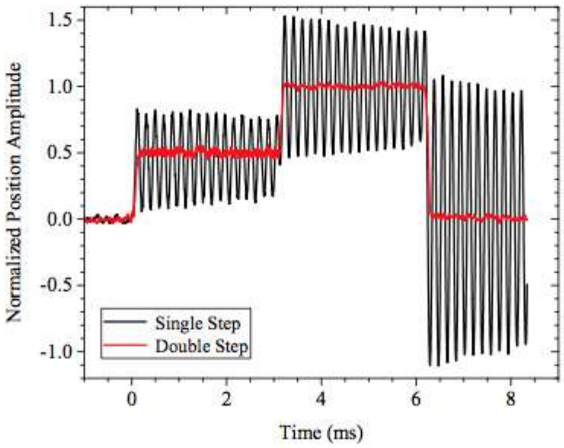


Figure 3. Shown is our MEMS system, left, and results, above in using PWM for rapidly improving the response time of MEMS devices.

3.4. Cryogenic Fab on a Chip Sticks the Landing

Using a microelectromechanical systems (MEMS)-based Fab-on-a-Chip, we quench-condense lead thin-films. Suppressing the formation of lead islands makes it possible to grow a homogeneous and continuous film as thin as 2 nm, without the use of an adhesion layer. Thermal cycling from 3 K to as low as 10 K reveals irreversible annealing of the thin-film characteristic of a metastable state. The transition to the stable state is smooth and is completed by cycling the temperature above ~42 K, where a distinctive resistance minimum is observed. This resistive minimum is accompanied by an unexpected peak in the superconducting transition temperature. After further thermal cycling, the standard metallic/superconductive behavior is established. The MEMS-based approach yields a platform for systematic studies of quench-condensed thin-film materials, making an intriguing parameter space of mesoscopic physics experimentally accessible. Details are provided in Ref. 4.

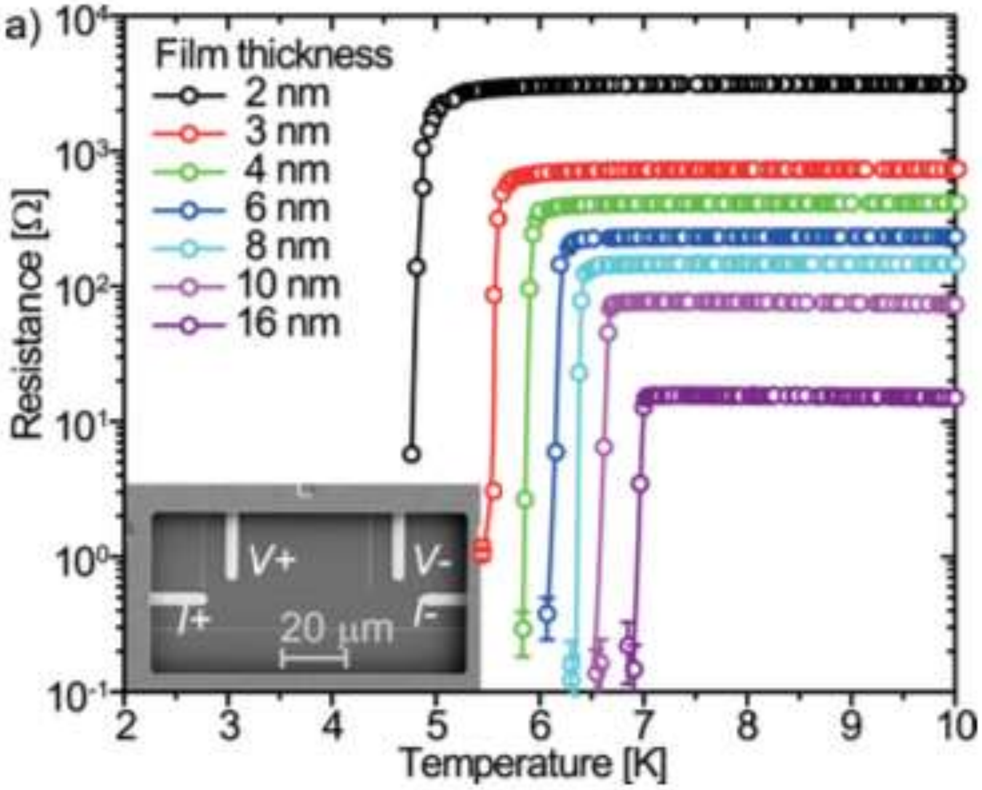


Figure 4. ***Shown are the superconducting transition results of our cryogenic Fab on a Chip.***

3.5. A Large Range of Motion 3D MEMS Scanner with Five Degrees of Freedom

In this work, we present a novel, mixed mode 3D XYZ scanner built within a single foundry process. The device has a large range of motion in X, Y and Z (14.0 µm in X,Y and 97.9 µm in Z) and can also rotate about two axes (7.4°), making it a 5 degree of freedom scanner. Vertical actuation can be accomplished with both thermal actuators, which have a larger range of motion, and capacitive actuators, which are faster, responding fully up to 3.2 kHz. Although it is useful for many applications, including scanning probe microscopy, micrometer scale optical microscopy, and manipulation of biological objects, the device was designed to be a 3D scanner for spray-painting atoms upon a surface with nanoscale precision and resolution for nanofabrication. Demonstrating the ability to combine the device with other complicated MEMS systems, it is integrated with an XY scanner designed to serve as a shutter to control the flow of atoms. The full system has 7 degrees of freedom and 12 actuation motors, and because it is built in a low cost commercial foundry with a robust, stable process, it is easy and inexpensive to fabricate multiple copies or integrate into other complicated systems, making a system of systems. Details are provided in Ref. 5.

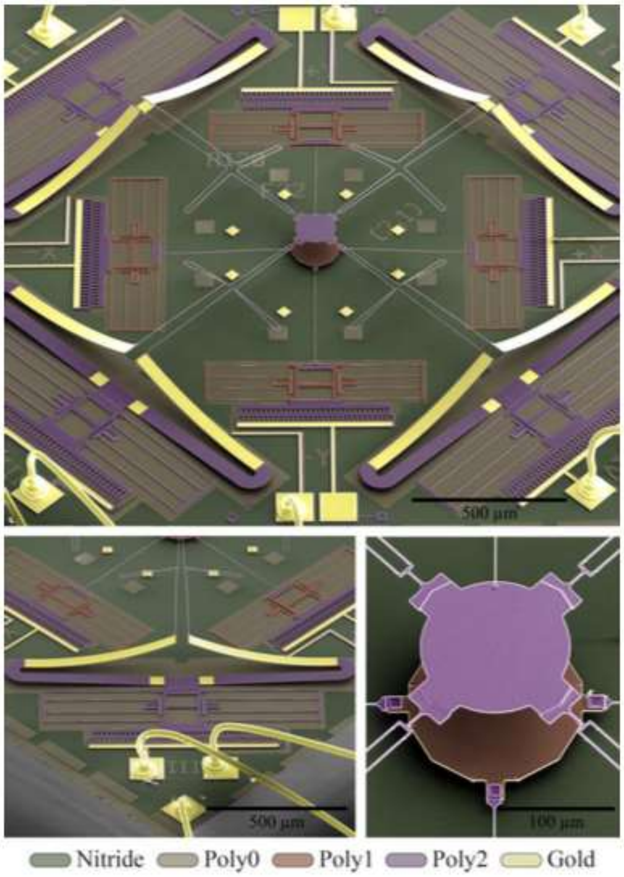


Figure 5. ***Shown is our MEMS XYZ Scanner with five degrees of freedom.***

3.6. Tunable Infrared Metasurface on a Soft Polymer Scaffold

The fabrication of metallic electromagnetic meta-atoms on a soft microstructured polymer scaffold using a MEMS-based stencil lithography technique is demonstrated. Using this technique, complex metasurfaces that are generally impossible to fabricate with traditional photolithographic techniques are created. By engineering the mechanical deformation of the polymer scaffold, the metasurface reflectivity in the mid-infrared can be tuned by the application of moderate strains. Details are provided in Ref. 6.

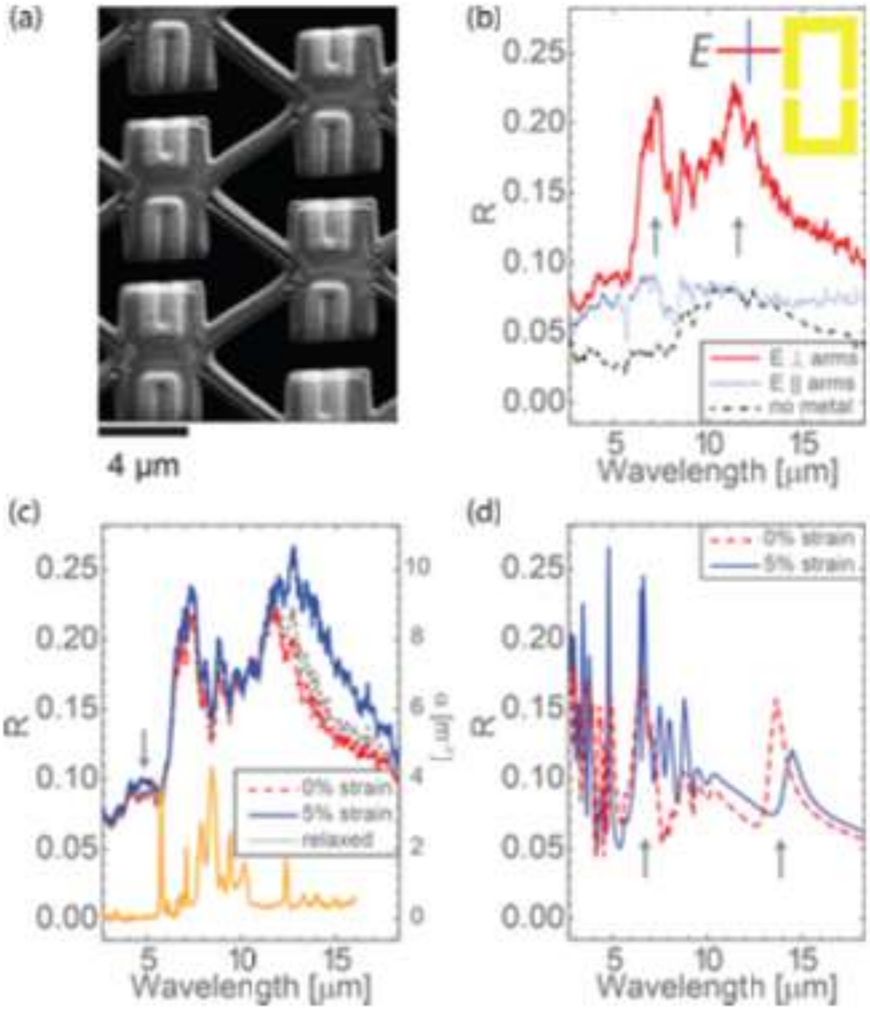


Figure 6. ***Shown is our tunable meta- device, ULHS, and its optical response.***

3.7. Dynamic Actuation of Soft 3D Micromechanical Structures using Micro-Electromechanical Systems (MEMS)

Direct laser writing (DLW) is an advanced fabrication technique that allows users to create complex 3D microstructures from polymer precursors. These microstructures can be integrated with micro-electromechanical systems (MEMS) actuators. MEMS actuators provide a convenient platform for interacting with the intricate microstructures, either to characterize their mechanical properties or cause them to deform. Structures are fabricated directly onto electrostatic comb drives and chevron thermal actuators that are produced using a commercial foundry process. By applying a voltage to the MEMS actuators, highly controlled deformation of these microstructures is observed. Mechanical behaviors of microstructures produced with different materials and fabrication conditions are compared. MEMS–DLW integration is a convenient approach to characterizing the mechanics of DLW microstructures and may well lead to a new class of dynamic 3D devices for applications ranging from tissue engineering to imaging. Details are provided in Ref. 7.

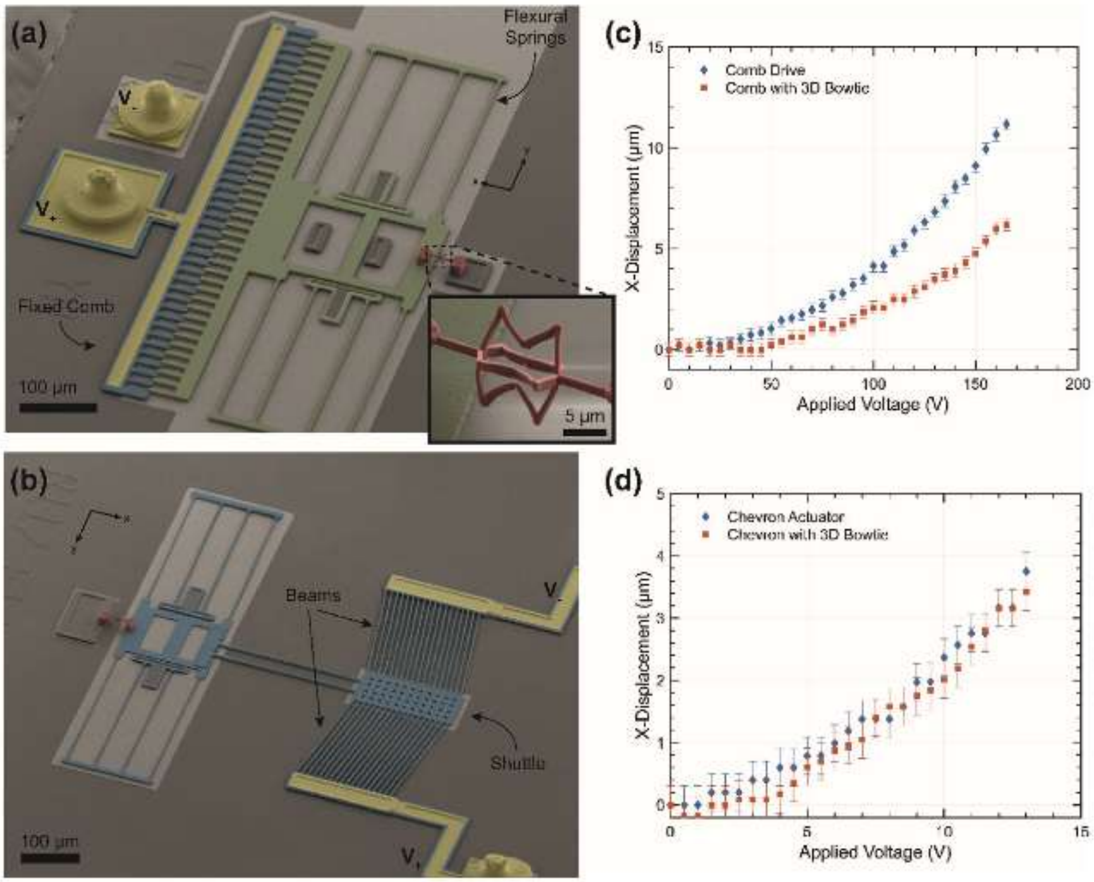


Figure 7. Shown is our polymer stretching device, left, and stretching results, right.

3.8. Fabrication of Multi-Material 3D Structures by the Integration of Direct Laser Writing and MEMS Stencil Patterning

The construction of a complex, 3D optical metamaterial challenges conventional nanofabrication techniques. These metamaterials require patterning of both a mechanical substrate and an optically-active structure with ~100nm resolution and precision. A typical optically-active device might be a split ring resonator formed from an elemental metal. The soft nature of the mechanical materials often precludes the use of resist-based techniques for patterning and FIB MOCVD approaches produce metallic structures with considerable disorder and impurities, impairing their optical response. In this paper we discuss a novel solution to this nanofabrication challenge -- the integration of direct laser lithography and MEMS stencil patterning. We demonstrate a variety of methods, including a MEMS nanofabrication workbench, that enable this integration and then show how one can produce optically active, 3D metamaterials. We present optical characterization data on one of these metamaterials to demonstrate the viability of our nanofabrication approach. Details are provided in Ref. 8.

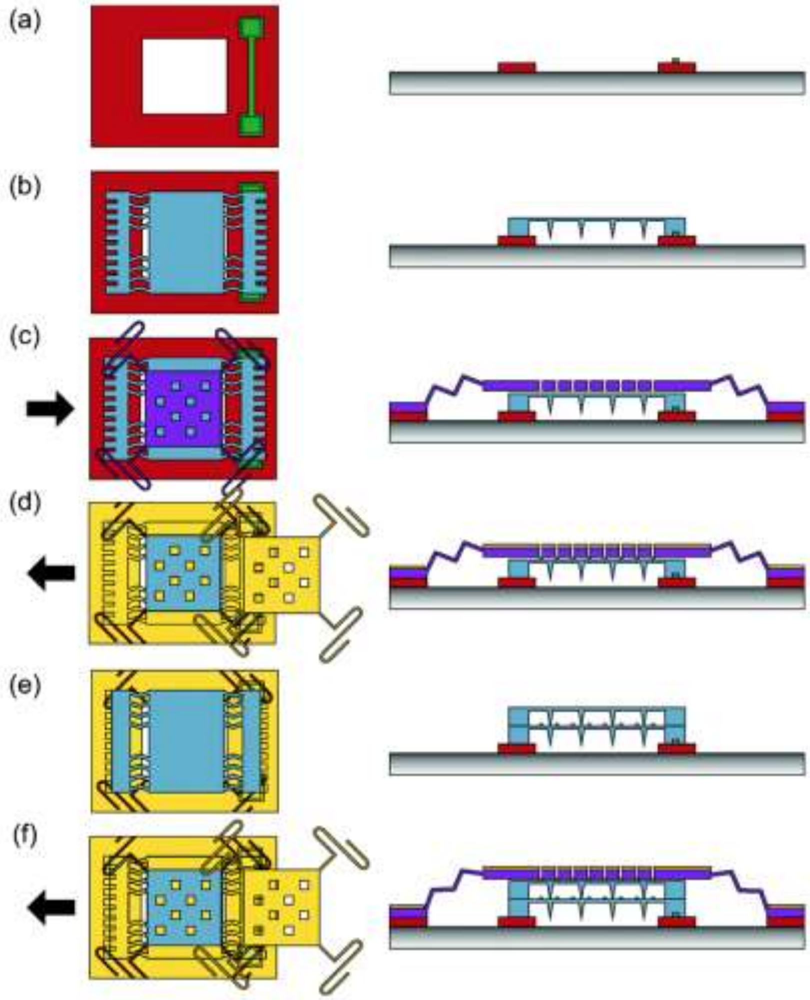


Figure 8. Shown is our fabrication approach for building 3D optical metamaterials.

3.9. Open Loop Control Theory Algorithms for High Speed 3D MEMS Optical Switches

There is a world-wide push to create the next-generation all-optical transmission and switching technologies for exascale data centers. In this work we focus on the switching fabrics. Many different types of 2D architectures are being explored including MEMS/waveguides and semiconductor optical amplifiers. However, these tend to suffer from high, path-dependent losses and crosstalk issues. The technologies with the best optical properties demonstrated to date in large fabrics (>100 ports) are 3D MEMS beam steering approaches. These have low average insertion losses and, equally important, a narrow loss distribution. However, 3D MEMS fabrics are generally dismissed from serious consideration for this application because of their slow switching speeds (~few milliseconds) and high costs ($100/port). In this paper we show how novel feedforward open loop controls can solve both problems by improving MEMS switching speeds by two orders of magnitude and costs by a factor of three. With these improvements in hand, we believe 3D MEMS fabrics can become the technology of choice for data centers. Details are provided in Ref. 9.

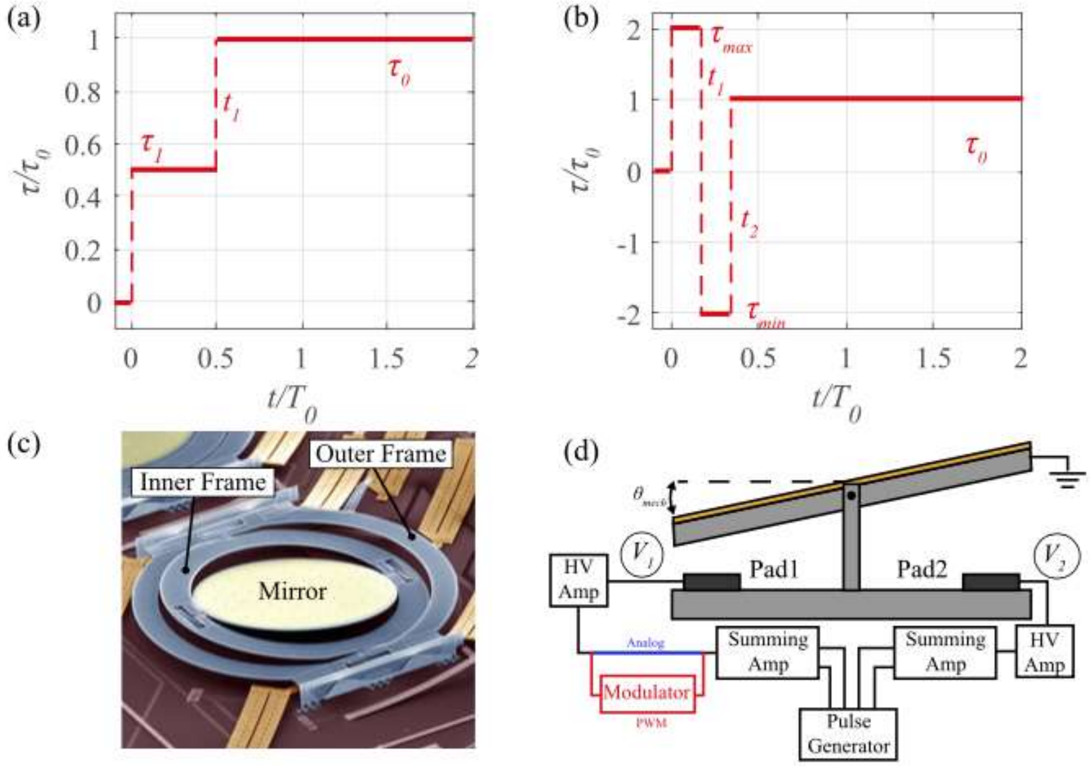


Figure 9. Shown are our optical switches, LL, experimental setup, LR and high-speed switching results, upper.

3.10. MEMS Tunable Mid-Infrared Plasmonic Spectrometer

We have developed a microelectromechanical systems (MEMS) tunable metamaterial, Fabry-Perot interferometer with a widely tunable mid-infrared response. An array of subwavelength holes in a gold firm is suspended above a gold reflector, forming an interferometer cavity whose length can be modulated over a range of 1.7 microns to 21.67 microns using MEMS electrostatic actuation. Reflectance spectra exhibit the convolution of extraordinary optical transmission through the holes and Fabry-Perot resonances with free spectral ranges from 2900 to 230.7 cm^{-1}. Measuring the free spectral range enables us to perform in situ interferometric calibration of the cavity length. We have derived a simple analytical model that describes the experimental and simulated results. This device shows promise as a surface-enhanced sensing substrate with a tunable spectral response. Details are provided in Ref. 10.

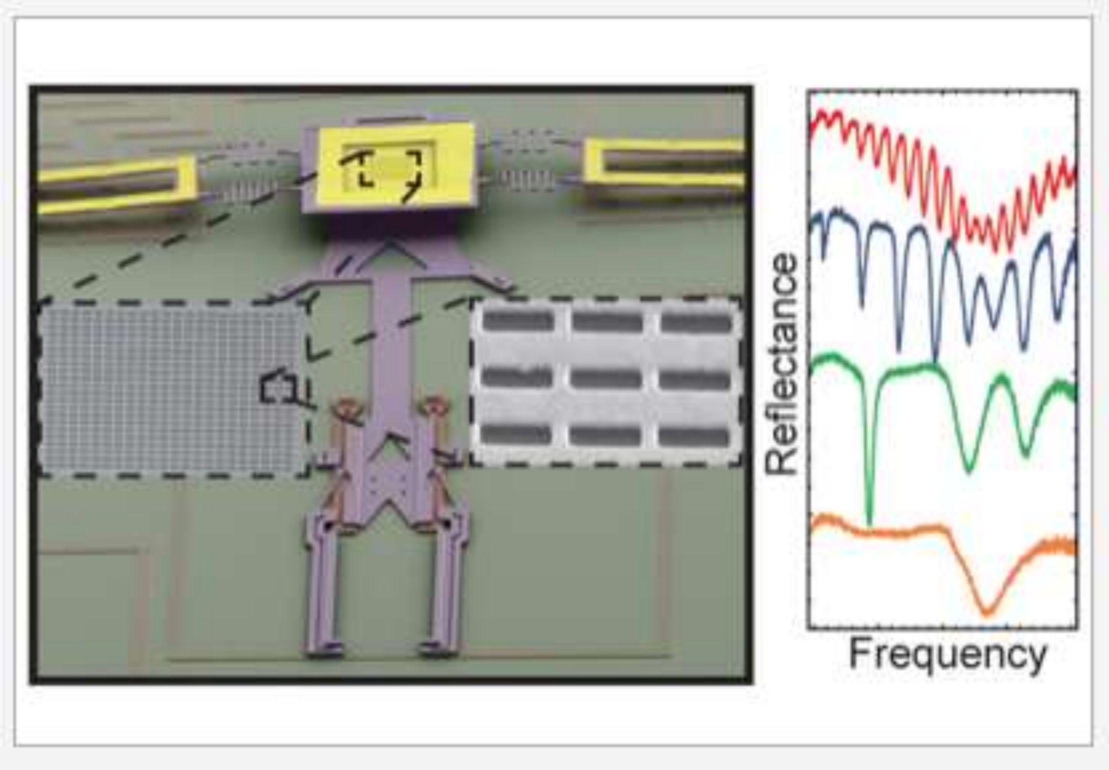


Figure 10. Shown is our tunable MEMS plasmonic spectrometer, left, and its spectral response, right.

3.11. Building a Casimir Metrology Platform with a Commercial MEMS Sensor

The Casimir Effect is a physical manifestation of quantum fluctuations of the electromagnetic vacuum. When two metal plates are placed closely together, typically much less than a micron, the long wavelength modes between them are frozen out, giving rise to a net attractive force between the plates, scaling as d^-4 (or d^-3 for a spherical-planar geometry) even when they are not electrically charged. In this paper we observe the Casimir Effect in ambient conditions using a modified capacitive MEMS accelerometer. Using a feedback assisted pick-and-place assembly process we are able to attach various micro-structures onto the post-release MEMS, converting it from an inertial force sensor to a direct force measurement platform with pN resolution. With this system we are able to directly measure the Casimir force between a silver-coated microsphere and gold-coated silicon plate. This device is a step towards leveraging the Casimir Effect for cheap, sensitive, room temperature quantum metrology. Details are provided in Ref. 11.

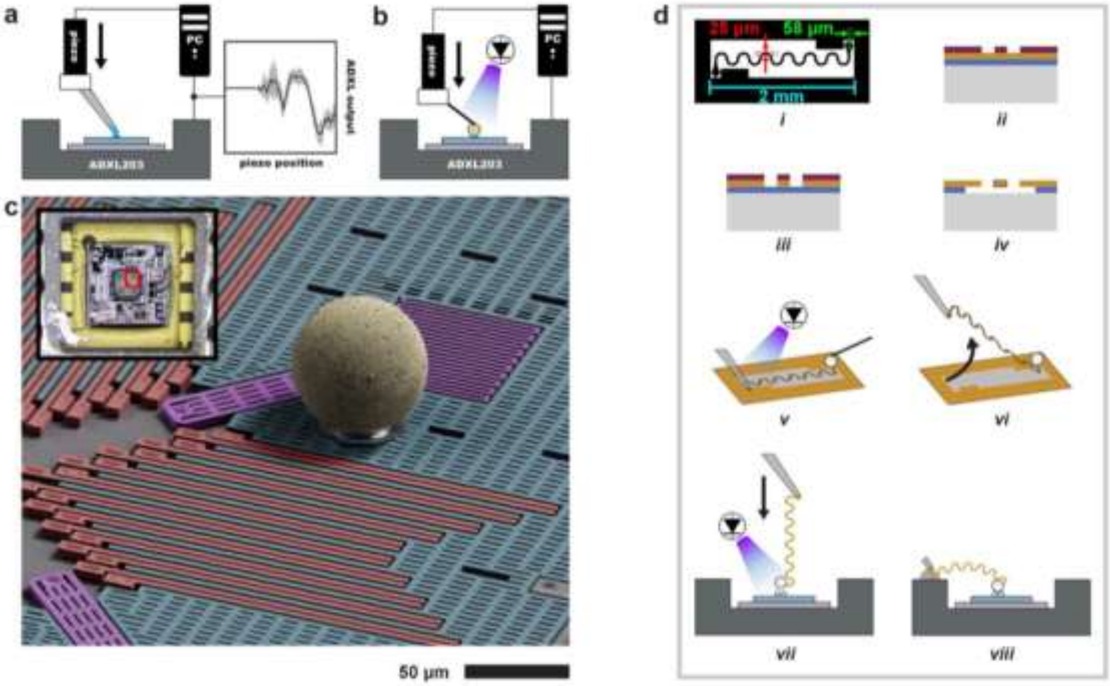


Figure 11. Shown is our Casimir metrology experiment.

3.12. Comb Drive Designs with Minimized Levitation

This work presents two capacitive comb drive designs for electrostatic actuation of MEMS with the aim to eliminate the levitation effect often observed in such systems. By placing a shield over the comb drive fingers, it is possible to balance the electric field and suppress vertical forces while maintaining the desired lateral motion. By optimizing the comb geometry, we demonstrate that our approach is able to reduce the levitation by an order of magnitude and unwanted coupling of motion from out-of-plane to in-plane by a factor of 7 compared with standard comb architectures fabricated using PolyMUMPs technology, without the need of alternating comb finger polarities or additional control electrodes. Levitation was reduced to 160 nm, for 3.6-μm lateral displacement at a driving voltage of 80 V. Details are provided in Ref. 12.

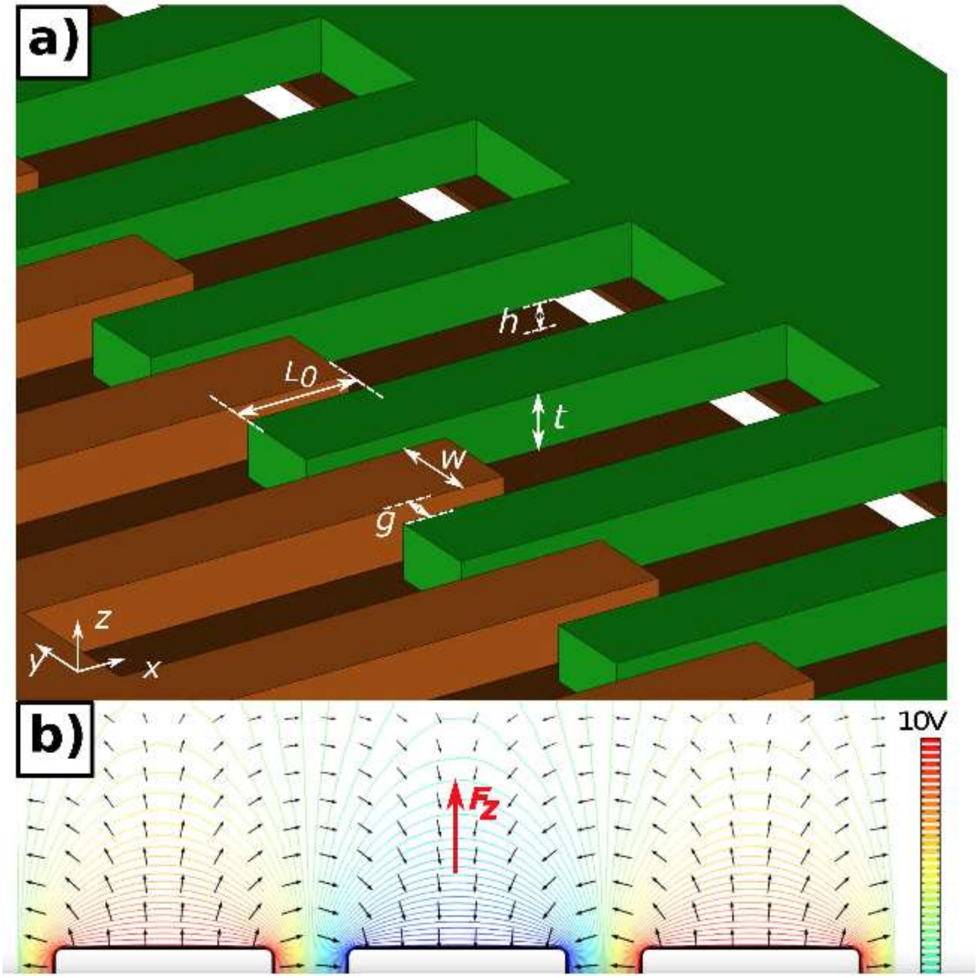


Figure 12. Shown is the combdrive levitation effect we have reduced with our approach of engineering the electric fields between the interleaved fingers.

3.13. Single Ended Capacitance Self-Sensing System for Comb Drives Driven XY Nanopositioners

Our work presents the implementation of a system to capacitively self-sense the position of a comb drive based MEMS XY nanopositioner from a single common node. The nanopositioner was fabricated using the multi-users PolyMUMPs process, on which comb capacitors fringe fields are large and out of plane forces cause considerable deflection. An extensive analysis of the comb-drive capacitance including the levitation effects and its correlation to the measurements is presented. Each axis is independently measured using frequency division multiplexing (FDM) techniques. Taking advantage of the symmetry of the nanopositioner itself, the sensitivity is doubled while eliminating the intrinsic capacitance of the device. The electrical measured noise is 2.5 aF/ Hz, for a sensing voltage $V_{sen} = 3V_{rms}$ and $f_{sen} = 150$ kHz, which is equivalent to 1.1nm/ (Hz)^.5 lateral displacement noise. This scheme can also be extended to N-degree of freedom nanopositioners. Details are provided in Ref. 13.

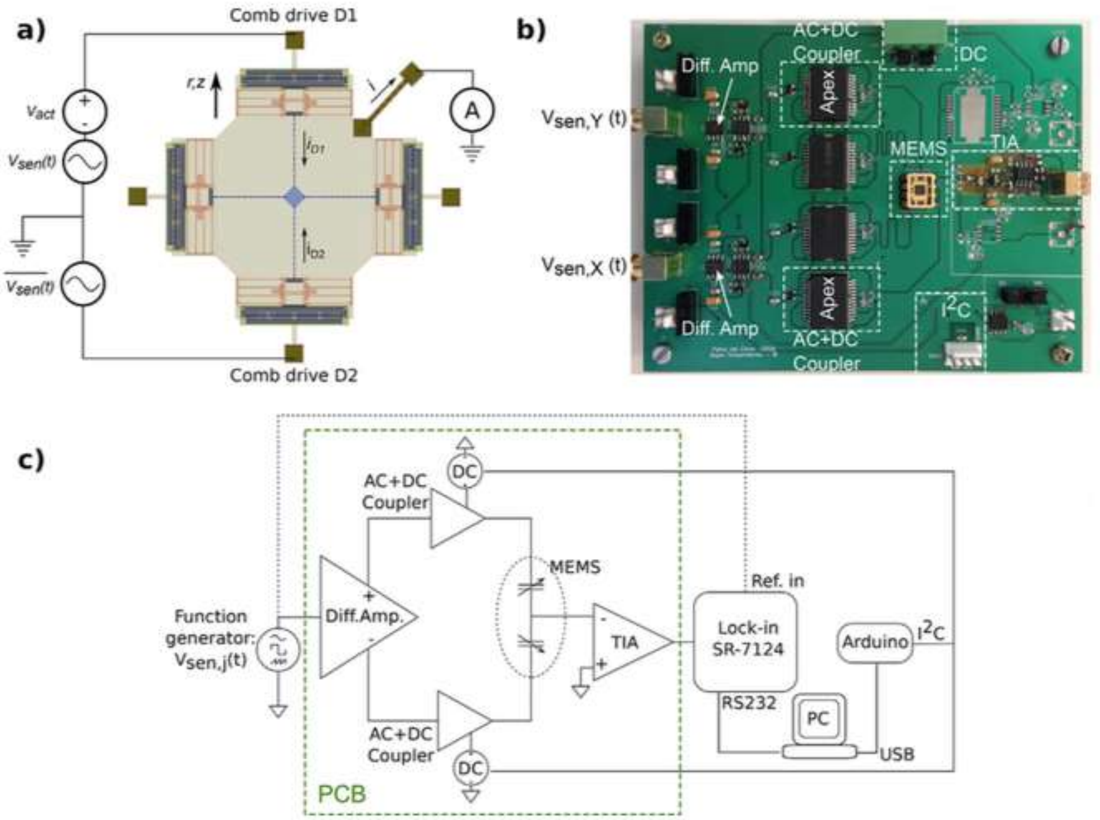


Figure 13. Shown is our metrology system for sensitively detecting the nanopositioner position.

3.14. Extreme Angle, Tip-Tilt MEMS Micromirror Enabling Full Hemispheric, Quasi-Static Optical Coverage

Beamsteering is essential for a variety of optical applications such as communication, LIDAR, and imaging. Microelectromechanical system (MEMS) mirrors are an effective method of achieving modest speeds and angular range at low cost. Typically there are a number of tradeoffs considered when designing a tip-tilt mirror, such as tilt angle and speed. For example, many mirrors are designed to scan at their resonant frequency to achieve large angles. This is effective for a scanning mode; however, this makes the device slow and ineffective as a galvo (quasi-static). We have developed a magnetic MEMS mirror with extreme quasi-static mechanical tilt angles of ±60° (±120° optical) about two rotation axes. This micromirror enables full hemispheric optical coverage without compromising speed; settling in 4.5 ms using advanced drive techniques. This mirror will enable new applications for MEMS micromirrors previously thought impossible due to their limited angular range and speed. Details are provided in Ref. 14.

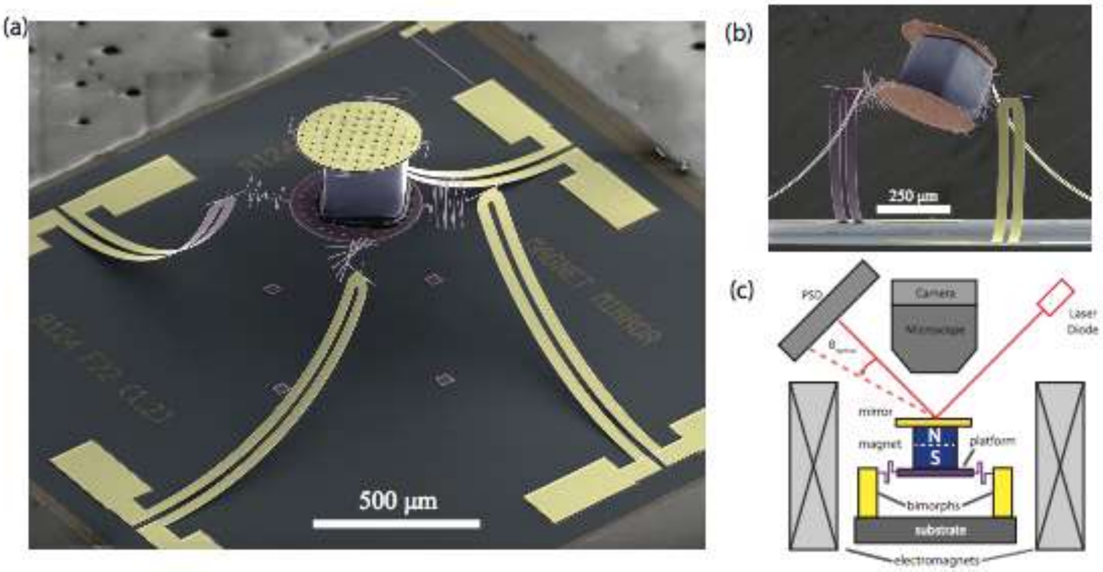


Figure 14. Shown is our full hemispheric coverage MEMS micro-mirror.

4. CONCLUSIONS

The issue of nanomanufacturing is a national challenge with nanotechnologists focusing on how to move from breathtaking scientific discoveries to commercial deployment, e.g. manufacturing these devices with nanoscale features in a practical, scalable way. The challenges in nanomanufacturing are no less daunting than those in nanotechnology research.

In this program we used our approach of atomic calligraphy to address this problem to deliver a technology of considerable interest to the DoD, tunable optical metamaterials for use in the visible and IR.

Nanomanufacturing addresses a variety of challenges quite different from the challenges related to scientific discovery. Nanoscale manufacturing typically seeks to create devices or structures that are low cost, reliable, built using scalable processes with good control over the critical dimensions with low manufacturing errors resulting in high yields. At the end of the day, the process can't cost more than the value of the device or system being built. Economic realities constrain the allowed parameter space as importantly as the laws of nature. While an AFM costing a million dollars can certainly be used to build a nanoscale transistor one atom at a time, current larger scale transistors (22nm) cost nanodollars each; this provides a serious limit on what any new, nanoscale process can cost. These are the challenges facing those working in nanomanufacturing and drove the overall goals of the A2P program.

In this work we have been able to spray paint atoms upon a wide range of surfaces including semiconductors and polymer substrates patterned using a direct laser write 3D printer (Nanoscribe). We have produced both static and dynamic optical metamaterials and written upon both 2D and 3D structures. We have developed the technical tools to write upon these structures, built them and then created tunable optical metamaterials. We have then optically characterized them, seen the desired tuning effect in their optical response and published the results.

We have also supported a robust educational program training post docs, graduate students, undergrads, high school student and high school teachers.

5. REFERENCES, PUBLICATIONS AND PRESENTATIONS

5.1. References

[1] M. Imboden, J. Chang, C. Pollock, E. Lowell, M. Akbulut, J. Morrison, T. Stark, T. G. Bifano, and D. J. Bishop, "High-speed control of electromechanical transduction," IEEE Control. Syst. Mag. **36**, 48–76 (2016).

[2] C. Pollock, L. K. Barrett, P. G. del Corro, A. Stange, T. G. Bifano, and D. J. Bishop, "PWM as a Low Cost Method for the Analog Control of MEMS Devices," J. Microelectromechanical Syst. **28**, 1–9 (2019).

[3] C. Pollock, M. Imboden, A. Stange, J. Javor, K. Mahapatra, L. Chiles, and D. J. Bishop, "Engineered PWM drives for achieving rapid step and settle times for MEMS actuation," J. Microelectromech. Syst. **27**, 513–520 (2018).

[4] M. Imboden, H. Han, T. Stark and D. J. Bishop, "Cryogenic Fab on a Chip Sticks the Landing", *ACS Nano*, vol. **11**, no. 9, pp. 8707-8716 (2017).

[5] L. Barrett, T. Stark, J. Reeves, R. Lally, A. Stange, C. Pollock, M. Imboden and D. J. Bishop,"A Large Range of Motion 3D MEMS Scanner with Five Degrees of Freedom", *Journal of Microelectromechanical Systems*, **28**, 170-179 (2019).

[6] J. Reeves, R. Jayne, T. Stark, L. Barrett, A. White, and D. J. Bishop, "Tunable Infrared Metasurface on a Soft Polymer Scaffold", *Nano Letters*, vol. 18, no. 5, pp. 2802-2806 (2018).

[7] R. Jayne, et al, "Dynamic Actuation of Soft 3D Micromechanical Structures using Micro-Electromechanical Systems (MEMS)", Advanced Materials Technologies, **3**(3), 1700293 (2018).

[8] J. Reeves, et al, "Fabrication of Multi-Material 3D Structures by the Integration of Direct Laser Writing and MEMS Stencil Patterning", Nanoscale **11**, 3261-3267 (2019).

[9] C. Pollock, et al, "Open Loop Control Theory Algorithms for High Speed 3D MEMS Optical Switches", Optics Express **28**(2), 2010-2019 (2020).

[10] T. Stark, et al, "MEMS Tunable Mid-Infrared Plasmonic Spectrometer", Nano Letters **3**(1) 14-19 (2016).

[11] A. Stange, et al "Building a Casimir Metrology Platform with a Commercial MEMS Sensor", Nature Micro and Nano **5**(14) (2019).

[12] P. del Corro, et al, "Comb Drive Designs with Minimized Levitation", JMEMS **25**(6), 1025-1032 (2016).

[13] P. Del Corro, et al, "Single Ended Capacitance Self-Sensing System for Comb Drives Driven XY Nanopositioners", Sensor and Actuators **A271**, 409-417 (2018).

[14] C. Pollock, et al, "Extreme angle, tip-tilt MEMS micromirror enabling full hemispheric, quasi-static optical coverage', Optics Express **27**(11) 15318 (2019).

5.2. Publications and Presentations

[1] M. Imboden, J. Chang, C. Pollock, E. Lowell, M. Akbulut, J. Morrison, T. Stark, T. G. Bifano, and D. J. Bishop, "High-speed control of electromechanical transduction," IEEE Control. Syst. Mag. **36**, 48–76 (2016).

[2] C. Pollock, L. K. Barrett, P. G. del Corro, A. Stange, T. G. Bifano, and D. J. Bishop, “PWM as a Low Cost Method for the Analog Control of MEMS Devices,” J. Microelectromechanical Syst. **28**, 1–9 (2019).

[3] C. Pollock, M. Imboden, A. Stange, J. Javor, K. Mahapatra, L. Chiles, and D. J. Bishop, “Engineered PWM drives for achieving rapid step and settle times for MEMS actuation,” J. Microelectromech. Syst. **27**, 513–520 (2018).

[4] M. Imboden, H. Han, T. Stark and D. J. Bishop, “Cryogenic Fab on a Chip Sticks the Landing”, *ACS Nano*, vol. **11**, no. 9, pp. 8707-8716 (2017).

[5] L. Barrett, T. Stark, J. Reeves, R. Lally, A. Stange, C. Pollock, M. Imboden and D. J. Bishop,“A Large Range of Motion 3D MEMS Scanner with Five Degrees of Freedom”, *Journal of Microelectromechanical Systems,* **28**, 170-179 (2019).

[6] J. Reeves, R. Jayne, T. Stark, L. Barrett, A. White, and D. J. Bishop, “Tunable Infrared Metasurface on a Soft Polymer Scaffold”, *Nano Letters*, vol. 18, no. 5, pp. 2802-2806 (2018).

[7] R. Jayne, et al, “Dynamic Actuation of Soft 3D Micromechanical Structures using Micro-Electromechanical Systems (MEMS)”, Advanced Materials Technologies, **3**(3), 1700293 (2018).

[8] J. Reeves, et al, “Fabrication of Multi-Material 3D Structures by the Integration of Direct Laser Writing and MEMS Stencil Patterning”, Nanoscale **11**, 3261-3267 (2019).

[9] C. Pollock, et al, “Open Loop Control Theory Algorithms for High Speed 3D MEMS Optical Switches”, Optics Express **28**(2), 2010-2019 (2020).

[10] T. Stark, et al, “MEMS Tunable Mid-Infrared Plasmonic Spectrometer”, Nano Letters **3**(1) 14-19 (2016).

[11] A. Stange, et al “Building a Casimir Metrology Platform with a Commercial MEMS Sensor”, Nature Micro and Nano **5**(14) (2019).

[12] P. del Corro, et al, “Comb Drive Designs with Minimized Levitation”, JMEMS **25**(6), 1025-1032 (2016).

[13] P. Del Corro, et al, “Single Ended Capacitance Self-Sensing System for Comb Drives Driven XY Nanopositioners”, Sensor and Actuators **A271**, 409-417 (2018).

[14] C. Pollock, et al, “Extreme angle, tip-tilt MEMS micromirror enabling full hemispheric, quasi-static optical coverage’, Optics Express **27**(11) 15318 (2019).

[15] L. Barrett, et al, “Atomic Calligraphy, a Fab on a Chip Approach to Lithography”, BAPS.2018.MAR.L15.2.

[16] A. Stange, et al, “Measuring the Casimir Force with a Commercial Accelerometer”, 2019APS..Mart70033S.

[17] T. Stark, “MEMS for Tunable Photonic Metameterial Applications”, Boston University, ProQuest Dissertations Publishing, 2017, 10622437.

[18] C. Pollock, “MEMS Mirrors and Controls for Indoor Wireless Communication”, Boston University, ProQuest Dissertations Publishing, 2019, 22616322.

Four more publications are in preparation. One will be the published thesis of Lawrence Barrett, a second will be on a new type of atomic source we have built, the third will be a large summary article on atomic calligraphy and the fourth on a novel open loop control algorithm for sensors.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AFRL	Air Force Research Laboratory
DARPA	Defense Advanced Research Projects Agency
DLW	Direct Laser Writing
FDM	Frequency Division Multiplexing
IR	Infrared
MEMS	Microelectromechanical systems
PWM	Pulse Width Modulation
RXAN	Nanoelectronic Materials Branch, Functional Materials Division, Materials and Manufacturing Directorate of AFRL
WPAFB	Wright Patterson Air Force Base