

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 30-05-2021		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 20-Apr-2016 - 19-Oct-2020	
4. TITLE AND SUBTITLE Final Report: 4.2 Optoelectronics: Optoelectronic Technology for Nanosecond WDM-based Chip-scale Optical Networking			5a. CONTRACT NUMBER W911NF-16-1-0245		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611102		
6. AUTHORS			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of California - San Diego Office of Contract & Grant Adm 9500 Gilman drive, MC 0934 La Jolla, CA 92093 -0934			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 69182-EL.16		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Yeshaiahu Fainman
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 858-534-8909

RPPR Final Report

as of 02-Jun-2021

Agency Code: 21XD

Proposal Number: 69182EL

Agreement Number: W911NF-16-1-0245

INVESTIGATOR(S):

Name: Yeshaiahu Fainman
Email: fainman@ece.ucsd.edu
Phone Number: 8585348909
Principal: Y

Organization: **University of California - San Diego**

Address: Office of Contract & Grant Adm, La Jolla, CA 920930934

Country: USA

DUNS Number: 804355790

EIN: 956006144

Report Date: 19-Jan-2021

Date Received: 30-May-2021

Final Report for Period Beginning 20-Apr-2016 and Ending 19-Oct-2020

Title: 4.2 Optoelectronics: Optoelectronic Technology for Nanosecond WDM-based Chip-scale Optical Networking

Begin Performance Period: 20-Apr-2016

End Performance Period: 19-Oct-2020

Report Term: 0-Other

Submitted By: Yeshaiahu Fainman

Email: fainman@ece.ucsd.edu

Phone: (858) 534-8909

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

STEM Degrees:

STEM Participants:

Major Goals: The goal of this proposal is to focus on fundamental research to develop novel optical technologies for WDM-based optical circuit switching (OCS) networks by exploiting spectral degrees of freedom enabled by fast tunable arrays of lasers and High-Speed Adaptive Receivers (HSAR). The specific objectives include: (i) design, fabrication and testing of fast tunable and intensity modulated laser sources and their arrays; (ii) design, fabrication and testing of fast tunable HSARs and their arrays; (iii) development of a novel characterization tool to measure the developed tunable lasers and HSAR operating in pulsed regime (i.e., data modulated regime) by exploiting the second-order intensity correlation technique; and (iv) design, manufacturing (via tape out foundries) and testing of the scaled-down system.

Accomplishments: In the first year, we conducted investigation of the fundamental physics and practical technological applications of metal-clad nanolasers. We summarize our effort in measuring and understanding a nonlinear dynamical phenomenon and its implications in a high- β metallo-dielectric nanolaser (see attached). We also applied the same characterization technique to near-unity- β nanolasers to determine the location of the threshold (see attached). To advance the electrically pumped metal-clad nanolaser, we investigated a new carrier injection method by adding a heavily doped tunnel junction to reduce the lasing threshold and therefore, Joule heating (see attached). We believe this novel design will lead to room temperature lasing and to a more robust device compared to our previous design. In order to investigate the tunability in metallo-dielectric nanolasers, we performed numerical simulations to confirm the significant modulation possible in such devices prior to beginning the processes of fabrication and testing (see attached).

During this second year, we studied material systems suitable for switching and modulation applications in HSAR. First, we summarize our efforts in furthering our understanding of the dynamics of a single metallo-dielectric nanolaser (see attached). We then detail our investigations into transitioning from one nanolaser to a dual nanolaser system and the coupling that is observed between the resonators (see attached). Studying such a coupled system is a necessary step towards designing and implementing larger arrays of subwavelength sources. We then discuss our results in observing second-order nonlinearities in two different material systems and how this response can be tuned. We first summarize our use of a metal-semiconductor-metal device consisting of an a-Si layer sandwiched between two metal electrodes that exhibits a high, tunable effective second-order nonlinear coefficient (see attached). Then, another material – silicon-rich nitride – is shown to exhibit a significant nonlinear response which can be tuned by both the content of silicon in the films as well as by an external field applied across the films (see attached). Additionally, this material is shown to be highly dispersive to the pump wavelength used, which can serve as another way to control the response of the material.

RPPR Final Report as of 02-Jun-2021

In the third year of this project, we continued our investigation into the fundamental physics of metal-clad nanolasers as well as second-order nonlinearities for HSAR applications. First, we summarize our efforts in furthering our understanding of the intensity noise properties of a single metallo-dielectric nanolaser (see attached). We also investigate the linewidth broadening due to fundamental thermal fluctuations (see attached). We then discuss our development of a low-resistance nanolaser based on a tunnel junction (see attached). This progress paves the way toward the development of low threshold nanolasers.

During the fourth year, we completed our investigation of the tuning and modulation properties of metal-clad nanolasers. We also demonstrated electro-optic switching in a novel CMOS compatible nonlinear material platform. First, we summarize our work in experimental demonstration of the wavelength tuning and intensity modulation properties of a single metallo-dielectric nanolaser (see attached). We then present our progress in realizing electro-optic switching in Silicon-Rich Nitride (SRN) waveguides by exploiting the third order nonlinear susceptibility, $\chi^{(3)}$ (see attached). The extracted $\chi^{(3)}$ from our fabricated SRN film exceeds the highest index in literature that uses the same material platform. Our SRN waveguides also allows switching for both TE and TM electric fields for the same vertical field. Our work proves that SRN is a very promising material platform for a variety of on-chip applications.

In the final year, we conducted a study about laterally coupled devices and present our recent progress in understanding the impact of the spontaneous emission factor β on the dynamics and stabilities of coupled nanolasers. (see attached). We show that high- β enhances the stability of laterally coupled lasers, which states the importance of nanolasers with intrinsic large β to be implemented in phase-locked laser arrays for high power and steerable beam generation.

Training Opportunities: The graduate and undergraduate students involved in this project obtain comprehensive research training in basic research, nanofabrication, characterization as well as testing system engineering. Their training includes developing rigorous electromagnetic, electronic and thermal modeling tools to design and analyze nanoscale semiconductor-metal-dielectric nanolasers and nonlinear optical composite metamaterials that possess enhanced nonlinear optical susceptibility for ultrafast switching. They also are trained in establishing the advanced tools and techniques required to fabricate these nanophotonic materials and devices, and use advanced characterization techniques such as measurements of electro-optic effect and nonlinear wave mixers. We recently constructed an apparatus for measurement of g_2 as well as second order susceptibility in constructed metamaterials both in free space and guided wave geometries in a wide spectral range from visible to near infrared optical frequencies range. Our previous and current grant have contributed to the education and development of human resources in science and engineering at the postdoctoral, graduate, and undergraduate levels. We modified our undergraduate Photonics Instructional Laboratory by extending the experiment on computer holography, nonlinear optics and using soft lithography for rapid prototyping. The members of our group hold weekly technical meetings facilitating work in a team environment. Group members also hold weekly seminars where they make presentations on the progress of their work, new results in their research field, and other relevant science and technology topics. We also recruit undergraduate students to work in the lab through the NSF REU program. Their education will be enhanced by working alongside faculty, graduate students, and researchers in projects carried out by the faculty involved in this proposal as discussed above. To support K-12 education, we have continued developing modules for the California State Summer School for Mathematics and Science (COSMOS) program which brings high school students to the UCSD campus each summer. We will also further advance innovative education and outreach projects with the Preuss School and Sweetwater Union High School District, designed for students coming from disadvantaged households in grades 6-12 grades.

An RET (Research Experiences for Teachers) program of NSF has recently been established at the ECE department in conjunction with the NSF's CIAN ERC. This program provides a unique opportunity for middle and high school teachers of science and mathematics to participate in frontline academic research. We equip them with knowledge of cutting-edge modern science and technology and with resources to build lectures/experiments that excite and revitalize their students. Working collaboratively with schoolteachers, we look for ways to attract more high school graduates into the fields of engineering and science. The RET program has been highly successful in introducing new experiences and knowledge into the classroom learning process. Our goal is to continue and expand the program in the future. We will continue our relationship that has been established with the Preuss Middle/High- School. Meanwhile, we seek opportunities to build long term collaboration with several other high schools, such as HTH, Sweetwater HS, Lincoln HS. Our goal is to reach out for more underrepresented students and expand our impact to a diverse population.

RPPR Final Report as of 02-Jun-2021

Results Dissemination: During the reporting period our group contributed to over 35 manuscripts in refereed journals, a book ("Semiconductor Nanolasers," University Printing House, Cambridge, UK, Cambridge University Press, pp. 1-324, 2017) and over 45 conference presentations. Further examples of data dissemination can be found at <https://www.unogroup-ucsd.com/>. For this project we are using our past mechanisms for data dissemination.

Honors and Awards: Joseph Fraunhofer Award/Robert M. Burley Prize, OSA, recognized for pioneering, seminal and wide ranging contributions to nanoscale engineering of linear and nonlinear optical materials and components (2017)

Protocol Activity Status:

Technology Transfer: 1. Technical interaction with Dr. J. Ptasinski and Dr. A. Smolyaninov at SPAWAR on Si Photonics.
2. Participation in MOAB DARPA program on CMOS compatible beam forming and in NLM DARPA program on metamaterials with gain.

PARTICIPANTS:

Participant Type: PD/PI

Participant: Yeshaiahu Fainman

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Staff Scientist (doctoral level)

Participant: Abdelkrim El Amili

Person Months Worked: 6.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Athena Pan

Person Months Worked: 6.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Suruj Deka

Person Months Worked: 6.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Chenghi Fang

Person Months Worked: 6.00

Project Contribution:

National Academy Member: N

Funding Support:

RPPR Final Report
as of 02-Jun-2021

Participant Type: Graduate Student (research assistant)

Participant: Sizhu Jiang

Person Months Worked: 3.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Felipe Vallini

Person Months Worked: 3.00

Funding Support:

Project Contribution:

National Academy Member: N

ARTICLES:

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Optics Express

Publication Identifier Type: DOI

Publication Identifier: 10.1364/OE.24.016923

Volume: 24

Issue: 15

First Page #: 16923

Date Submitted: 7/30/16 12:00AM

Date Published: 7/1/16 7:00AM

Publication Location:

Article Title: Observation of second-harmonic generation in silicon nitride waveguides through bulk nonlinearities

Authors: Matthew W. Puckett, Rajat Sharma, Hung-Hsi Lin, Mu-han Yang, Felipe Vallini, Yeshaiah Fainman

Keywords: Nonlinear optics, materials; Harmonic generation and mixing; Integrated optics devices

Abstract: We present experimental results on the observation of a bulk second-order nonlinear susceptibility, derived from both free-space and integrated measurements, in silicon nitride. Phase-matching is achieved through dispersion engineering of the waveguide cross-section, independently revealing multiple components of the nonlinear susceptibility, namely $\chi^{(2)}_{yyy} = 0.14 \pm 0.08$ pm/V and $\chi^{(2)}_{xxy} = 0.30 \pm 0.18$ pm/V. Additionally, we show how the second-harmonic signal may be tuned through the application of bias voltages across silicon nitride. The material properties measured here are anticipated to allow for the realization of new nanophotonic devices in CMOS-compatible silicon nitride waveguides, adding to their viability for telecommunication, data communication, and optical signal processing applications.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

RPPR Final Report as of 02-Jun-2021

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

Journal: Optics Letters

Publication Identifier Type: DOI

Publication Identifier: 10.1364/OL.41.004445

Volume: 41

Issue: 19

First Page #: 4445

Date Submitted: 10/5/17 12:00AM

Date Published: 9/2/16 4:00AM

Publication Location:

Article Title: Plasmonic enhanced two-photon absorption in silicon photodetectors for optical correlators in the near-infrared

Authors: Alexei Smolyaninov, Mu-Han Yang, Lin Pang, Yeshaiah Fainman

Keywords: Plasmonics; Multiphoton processes; Correlators; Ultrafast technology; Photodetectors.

Abstract: A high-density array of plasmonic coaxial nanoantennas is used to enhance the two-photon absorption (TPA) process in a conventional silicon photodetector from a mode-locked 76 MHz Ti:sapphire laser over a spectral range from 1340 to 1550 nm. This enhanced TPA was used to generate an interferometric autocorrelation trace of a 150 fs laser pulse. Unlike second-harmonic generation, this technique does not require phase matching or a bulky crystal and can be used on a low-cost integrated silicon platform over a wide range of near-IR wavelengths compatible with modern commercial tunable femtosecond sources.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

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

Journal: IEEE Journal of Selected Topics in Quantum Electronics

Publication Identifier Type: DOI

Publication Identifier: 10.1109/JSTQE.2017.2679134

Volume: 23

Issue: 6

First Page #: 1

Date Submitted: 10/5/17 12:00AM

Date Published: 11/1/17 7:00AM

Publication Location:

Article Title: Low Resistance Tunnel Junctions for Efficient Electrically Pumped Nanolasers

Authors: Cheng-Yi Fang, Felipe Vallini, Abdelkrim El Amili, Joseph S. T. Smalley, Yeshaiah Fainman

Keywords: Nanotechnology, semiconductor lasers, semiconductor device modeling, tunnel diodes, laser thermal factors

Abstract: Extremely compact nanoscale devices such as electrically pumped nanolasers are difficult to operate at room temperature due to the high electrical resistance inherent to small cavities. As a consequence, large voltages are necessary to reach the lasing threshold, which generates heat and reduces device efficiency. The poor heat sinking of small devices makes matters worse, dramatically reducing the laser efficiency. Instead of looking for solutions to dissipate heat from small structures more efficiently, designing nanolasers to produce less heat in the first place is an important goal. Here we propose and theoretically analyze the effect of adding an InGaAsP tunnel junction for efficient carrier injection in metallo-dielectric nanolasers. With our theoretical model we show that the device resistance is reduced by a factor of ~ 6.5 . The applied voltage at the room temperature lasing threshold is reduced from 3.05 to 1.35 V, a reduction of 69% in heat generation.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

RPPR Final Report as of 02-Jun-2021

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Applied Physics Letters

Publication Identifier Type: DOI

Publication Identifier: 10.1063/1.4978640

Volume: 110 Issue: 11

First Page #: 113103

Date Submitted: 10/5/17 12:00AM

Date Published: 3/1/17 8:00AM

Publication Location:

Article Title: Synthesis of second-order nonlinearities in dielectric-semiconductor-dielectric metamaterials

Authors: Hung-Hsi Lin, Mu-Han Yang, Rajat Sharma, Matthew W. Puckett, Sergio Montoya, Christian D. Wurm, F

Keywords: Nonlinear Optics, Integrated Optics, Si Photonics

Abstract: We demonstrate a large effective second-order nonlinear optical susceptibility in electronic optical metamaterials based on sputtered dielectric-semiconductor-dielectric multilayers of silicon dioxide/ amorphous silicon (a-Si)/aluminum oxide. The interfacial fixed charges (Q_f) with opposite signs on either side of dielectric-semiconductor interfaces result in a non-zero built-in electric field within the a-Si layer, which couples to the large third-order nonlinear susceptibility tensor of a-Si and induces an effective second-order nonlinear susceptibility tensor determined experimentally to be 2 pm/V for the as-fabricated metamaterials and increases to 8.5 pm/V after the post-thermal annealing process. The constituents and fabrication methods make these metamaterials CMOS compatible, enabling efficient nonlinear devices for chip-scale silicon photonic integrated circuits.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Optics Letters

Publication Identifier Type: DOI

Publication Identifier: 10.1364/OL.41.005576

Volume: 41 Issue: 23

First Page #: 5576

Date Submitted: 10/5/17 12:00AM

Date Published: 11/1/16 2:00PM

Publication Location:

Article Title: Magnetically controllable silicon microring with ferrofluid cladding

Authors: A. El Amili, M. C. M. M. Souza, F. Vallini, N. C. Frateschi, Y. Fainman

Keywords: Integrated optics; Integrated optics devices; Magneto-optic systems; Resonators;

Abstract: We experimentally investigate the application of magnetic fluids (MFs) on integrated silicon photonics. Using a ferrofluid-clad silicon microring resonator, we demonstrate active control of resonances by applying an external magnetic field. Relatively high loaded quality factors on the order of 6000 are achieved, despite the optical losses introduced by the magnetic nanoparticles. We demonstrate resonance shifts of 185 pm in response to a 110 Oe strong magnetic field, corresponding to an overall refractive index change of 3.2×10^{-3} for the cladding MF. The combination of MFs and integrated photonics could potentially lead to the development of magnetically controllable optical devices and ultra-compact cost-effective magnetic field sensors.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

RPPR Final Report as of 02-Jun-2021

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

Journal: Optica

Publication Identifier Type: DOI

Publication Identifier: 10.1364/OPTICA.3.001260

Volume: 3 Issue: 11

First Page #: 1260

Date Submitted: 10/5/17 12:00AM

Date Published: 10/1/16 7:00AM

Publication Location:

Article Title: Dynamic hysteresis in a coherent high- β nanolaser

Authors: Si Hui Pan, Qing Gu, Abdelkrim El Amili, Felipe Vallini, Yeshaiahu Fainman

Keywords: Nanophotonics and photonic crystals; Bistability; Photon statistics; Coherence; Semiconductor lasers; Integrated optics devices

Abstract: The quest for an integrated light source that promises high energy efficiency and a fast modulation for high-performance photonic circuits has led to the development of room-temperature telecom-wavelength nanoscale lasers with a high spontaneous emission factor β . The coherence characterization of this type of laser using the conventional measurement of output light intensity versus input pump intensity is inherently difficult due to the diminishing kink in the measurement curve. We demonstrate that the transition from incoherent to coherent emission of a high- β pulse-pump metallo-dielectric nanolaser can be determined by examining the width of a second-order intensity correlation peak that shrinks below and broadens above the threshold. Our photon fluctuation study, the first ever reported for this type of nanolaser, confirms the validity of this measurement technique. Additionally, we show that the width variation above the threshold results from the delayed threshold phenomenon.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

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

Journal: Progress in Quantum Electronics

Publication Identifier Type: DOI

Publication Identifier: 10.1016/j.pquantelec.2018.05.001

Volume: 59 Issue:

First Page #: 1

Date Submitted: 10/8/18 12:00AM

Date Published: 5/1/18 7:00AM

Publication Location:

Article Title: Nanolasers: Second-order intensity correlation, direct modulation and electromagnetic isolation in array architectures

Authors: Si Hui Pan, Suruj S. Deka, Abdelkrim El Amili, Qing Gu, Yeshaiahu Fainman

Keywords: Semiconductor lasers; Nanolasers; Laser Dynamics

Abstract: Ideal integrated light emitters for optical interconnects should be compact in size, high in modulation bandwidth, efficient in energy consumption and tunable in frequency. Nanolasers are excellent candidates for such an application. In this article, we review and offer further in-depth analyses in three key aspects of recent nanolaser research, including second order intensity correlation, $g_2(\tau)$, characterizations, direct modulation and electromagnetic isolation in a dual nanolaser system. For coherence characterization, we review a technique exploiting not only the photon bunching peak, but also the $g_2(\tau)$ pulse width to determine the spontaneous emission (SE), amplified SE and lasing regimes of a nanolaser with a high SE factor, β . We show that this technique is applicable for lasers with β s ranging from 10^{-5} to unity. Additionally, we demonstrate the first direct current modulation of an electrically pumped metallo-dielectric nanolaser (MDNL) at 30 MHz. Considering the viability of

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

RPPR Final Report as of 02-Jun-2021

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevLett.120.243904
Volume: 120 **Issue:** 24 **First Page #:**
Date Submitted: 10/8/18 12:00AM **Date Published:** 6/1/18 7:00AM
Publication Location:

Article Title: Nonlocal and Nonlinear Surface Plasmon Polaritons and Optical Spatial Solitons Induced by the Thermocapillary Effect

Authors: Shimon Rubin, Yeshaiahu Fainman

Keywords: Optical solitons; nonlinear optics;

Abstract: We study the propagation of surface plasmon polaritons (SPPs) on a metal surface which hosts a thin film of a liquid dielectric. The Ohmic losses that are inherently present due to the coupling of SPPs to conductors' electron plasma, induce temperature gradients and fluid deformation driven by the thermocapillary effect, which lead to a nonlinear and nonlocal change of the effective dielectric constant. The latter extends beyond the regions of highest optical intensity and constitutes a novel thermally selfinduced mechanism that affects the propagation of the SPPs. We derive the nonlinear and nonlocal Schrödinger equation that describes propagation of low intensity SPP beams, and show analytically and numerically that it supports a novel optical spatial soliton excitation.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Scientific Reports
Publication Identifier Type: DOI **Publication Identifier:** 10.1038/s41598-017-10304-2
Volume: 7 **Issue:** 1 **First Page #:**
Date Submitted: 10/8/18 12:00AM **Date Published:** 8/1/17 7:00AM
Publication Location:

Article Title: Electronic Metamaterials with Tunable Second-order Optical Nonlinearities

Authors: Hung-Hsi Lin, Felipe Vallini, Mu-Han Yang, Rajat Sharma, Matthew W. Puckett, Sergio Montoya, Christi

Keywords: Nonlinear optics; Electro-optic modulator

Abstract: The ability to engineer metamaterials with tunable nonlinear optical properties is crucial for nonlinear optics. Traditionally, metals have been employed to enhance nonlinear optical interactions through field localization. Here, inspired by the electronic properties of materials, we introduce and demonstrate experimentally an asymmetric metal-semiconductor-metal (MSM) metamaterial that exhibits a large and electronically tunable effective second-order optical susceptibility ($\chi^{(2)}$). The induced $\chi^{(2)}$ originates from the interaction between the third-order optical susceptibility of the semiconductor ($\chi^{(3)}$) with the engineered internal electric field resulting from the two metals possessing dissimilar work function at its interfaces. We demonstrate a five times larger second-harmonic intensity from the MSM metamaterial, compared to contributions from its constituents with electrically tunable nonlinear coefficient ranging from 2.8 to 15.6 pm/V.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: Y

RPPR Final Report as of 02-Jun-2021

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Science

Publication Identifier Type: DOI

Publication Identifier: 10.1126/science.aao4551

Volume: 358

Issue: 6363

First Page #: 636

Date Submitted: 10/8/18 12:00AM

Date Published: 11/1/17 7:00AM

Publication Location:

Article Title: Nonreciprocal lasing in topological cavities of arbitrary geometries

Authors: Babak Bahari, Abdoulaye Ndao, Felipe Vallini, Abdelkrim El Amili, Yeshaiah Fainman, Boubacar Kanté

Keywords: Nanolasers; semiconductor lasers

Abstract: Resonant cavities are essential building blocks governing many wave-based phenomena, but their geometry and reciprocity fundamentally limit the integration of optical devices. We report, at telecommunication wavelengths, geometry-independent and integrated nonreciprocal topological cavities that couple stimulated emission from one-way photonic edge states to a selected waveguide output with an isolation ratio in excess of 10 decibels. Nonreciprocity originates from unidirectional edge states at the boundary between photonic structures with distinct topological invariants. Our experimental demonstration of lasing from topological cavities provides the opportunity to develop complex topological circuitry of arbitrary geometries for the integrated and robust generation and transport of photons in classical and quantum regimes.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Nature Photonics

Publication Identifier Type: DOI

Publication Identifier: 10.1038/s41566-019-0360-3

Volume: 13

Issue: 6

First Page #: 431

Date Submitted: 7/29/19 12:00AM

Date Published: 2/2/19 8:00AM

Publication Location:

Article Title: Programmable plasmonic phase modulation of free-space wavefronts at gigahertz rates

Authors: Alexei Smolyaninov, Abdelkrim El Amili, Felipe Vallini, Steve Pappert, Yeshaiah Fainman

Keywords: spatial light modulator

Abstract: Space-variant control of optical wavefronts is important for many applications in photonics, such as the generation of structured light beams, and is achieved with spatial light modulators. Commercial devices, at present, are based on liquid-crystal and digital micromirror technologies and are typically limited to kilohertz switching speeds. To realize significantly higher operating speeds, new technologies and approaches are necessary. Here we demonstrate two-dimensional control of free-space optical fields at a wavelength of 1,550 nm at a 1 GHz modulation speed using a programmable plasmonic phase modulator based on near-field interactions between surface plasmons and materials with an electrooptic response. High $\epsilon(2)$ and $\epsilon(3)$ dielectric thin films of either aluminium nitride or silicon-rich silicon nitride are used as an active modulation layer in a surface plasmon resonance configuration to realize programmable space-variant control of optical wavefronts in an array at high speed.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

RPPR Final Report as of 02-Jun-2021

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

Journal: Communications Physics

Publication Identifier Type: DOI

Publication Identifier: 10.1038/s42005-018-0036-1

Volume: 1

Issue: 1

First Page #:

Date Submitted: 7/29/19 12:00AM

Date Published: 7/1/18 9:00PM

Publication Location:

Article Title: Channel dispersed Fourier transform spectrometer

Authors: Brandon Hong, Faraz Monifi, Yeshaiahu Fainman

Keywords: Spectroscopy

Abstract: The high signal throughput of Fourier transform spectroscopy has proved a boon to overcoming the difficulties of otherwise overwhelming detector noise in chemical infrared spectroscopy and near-infrared Raman spectroscopy, and is desirable for in situ measurement. Here we introduce a stationary channel dispersed Fourier transform (CDFT) spectrometer that efficiently utilizes two-dimensional imagers to obtain high-resolution input spectra in low-pixel-density imagers. By angularly dispersing a vertical one-dimensional interference pattern along a horizontal axis, an array of bandlimited interferogram channels is measured with reduced sampling constraints in each channel. CDFT spectrometers can use existing imagers to measure spectra with 0.0025 cm^{-1} resolution over an 800 cm^{-1} bandwidth. Moreover, this approach reduces the quantization noise present in low dynamic range imagers significantly.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

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

Journal: Optics Express

Publication Identifier Type: DOI

Publication Identifier: 10.1364/OE.27.008186

Volume: 27

Issue: 6

First Page #: 8186

Date Submitted: 7/29/19 12:00AM

Date Published: 3/1/19 8:00AM

Publication Location: United States

Article Title: Intensity noise and bandwidth analysis of nanolasers via optical injection

Authors: Zijun Chen, Suruj S. Deka, Si Hui Pan, Sizhu Jiang, Cheng-Yi Fang, Yeshaiahu Fainman, Abdelkrim El

Keywords: lasers

Abstract: A measurement method that can be used to extract the relative intensity noise of a nanolaser is introduced and analyzed. The method is based on optical injection of emission from a nanolaser serving as a master oscillator, transferring its intensity fluctuations to a low-noise semiconductor laser serving as a slave oscillator. Using the stochastic rate equation formalism, we demonstrate that the total relative intensity noise of the system is a weighted superposition of the relative intensity noise of individual lasers. We further discuss the analytical relations that can be used to extract the relative intensity noise spectrum of a nanolaser. Finally, we use mutual correlation as a mathematical tool to quantify the degree of resemblance between the injected and extracted intensity fluctuations, theoretically confirming that the spectra are at least 97% correlated within the 3-dB bandwidth when an injection strength is chosen properly.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

RPPR Final Report as of 02-Jun-2021

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: APL Photonics

Publication Identifier Type: DOI

Publication Identifier: 10.1063/1.5053704

Volume: 4

Issue: 3

First Page #: 036101

Date Submitted: 7/29/19 12:00AM

Date Published: 3/1/19 8:00AM

Publication Location: United States

Article Title: On the observation of dispersion in tunable second-order nonlinearities of silicon-rich nitride thin films

Authors: Hung-Hsi Lin, Rajat Sharma, Alex Friedman, Benjamin M. Cromeey, Felipe Vallini, Matthew W. Puckett, I

Keywords: nonlinear optics

Abstract: We present experimental results on second-harmonic generation in non-stoichiometric, silicon-rich nitride films. The asdeposited film presents a second-order nonlinear coefficient, or $X(2)$, as high as 8 pm/V. This value can be widely tuned using the electric field induced second harmonic effect, and a maximum value of 22.7 pm/V was achieved with this technique. We further illustrate that the second-order nonlinear coefficient exhibited by these films can be highly dispersive in nature and require further study and analysis to evaluate their viability for in-waveguide applications at telecommunication wavelengths.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

BOOKS:

Publication Type: Book

Peer Reviewed: N

Publication Status: 1-Published

Publication Identifier Type: ISBN

Publication Identifier: 978-1107110489

Book Edition:

Volume:

Publication Year: 2017

Date Received: 05-Oct-2017

Publication Location: Cambridge, UK

Publisher: Cambridge University Press

Book Title: Semiconductor Nanolasers

Authors: Qing Gu, Yeshaiah Fainman

Editor:

Acknowledged Federal Support: Y

Partners

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

Signature: Y. Fainman

Signature Date: 5/30/21 3:34PM

Final ARO report: Optoelectronic Technology for Nanosecond WDM-based Chip-scale Optical Networking, Y. Fainman – PI, UCSD

In this final report, we start by summarizing our achievements in the four years of this project, the details of each project of which can be found in appendices A1-C3. We then discuss the progress made in the final year of the project which includes analyzing the effects of high- β on the phase-locking stability between two laterally coupled lasers.

Year 1: 2016-17

In the first year, we conducted investigation of the fundamental physics and practical technological applications of metal-clad nanolasers. We summarize our effort in measuring and understanding a nonlinear dynamical phenomenon and its implications in a high- β metallo-dielectric nanolaser (see appendix A1). We also applied the same characterization technique to near-unity- β nanolasers to determine the location of the threshold (appendix A2). To advance the electrically pumped metal-clad nanolaser, we investigated a new carrier injection method by adding a heavily doped tunnel junction to reduce the lasing threshold and therefore, Joule heating (appendix A3). We believe this novel design will lead to room temperature lasing and to a more robust device compared to our previous design. In order to investigate the tunability in metallo-dielectric nanolasers, we performed numerical simulations to confirm the significant modulation possible in such devices prior to beginning the processes of fabrication and testing (appendix A4).

Year 2: 2017-18

During this second year, we studied material systems suitable for switching and modulation applications in HSAR. First, we summarize our efforts in furthering our understanding of the dynamics of a single metallo-dielectric nanolaser (appendix B1). We then detail our investigations into transitioning from one nanolaser to a dual nanolaser system and the coupling that is observed between the resonators. (appendix B2). Studying such a coupled system is a necessary step towards designing and implementing larger arrays of subwavelength sources. We then discuss our results in observing second-order nonlinearities in two different material systems and how this response can be tuned. We first summarize our use of a metal-semiconductor-metal device consisting of an a-Si layer sandwiched between two metal electrodes that exhibits a high, tunable effective second-order nonlinear coefficient (appendix B3.1). Then, another material – silicon-rich nitride – is shown to exhibit a significant nonlinear response which can be tuned by both the content of silicon in the films as well as by an external field applied across the films (appendix B3.2). Additionally, this material is shown to be highly dispersive to the pump wavelength used, which can serve as another way to control the response of the material.

Year 3: 2018-19

In the third year of this project, we continued our investigation into the fundamental physics of metal-clad nanolasers as well as second-order nonlinearities for HSAR applications. First, we summarize our efforts in furthering our understanding of the intensity noise properties of a single metallo-dielectric nanolaser (appendix C1). We also investigate the linewidth broadening due to

fundamental thermal fluctuations (appendix C2). We then discuss our development of a low-resistance nanolaser based on a tunnel junction (appendix C3). This progress paves the way toward the development of low threshold nanolasers.

Year 4: 2019-20

During the fourth year, we completed our investigation of the tuning and modulation properties of metal-clad nanolasers. We also demonstrated electro-optic switching in a novel CMOS compatible nonlinear material platform. First, we summarize our work in experimental demonstration of the wavelength tuning and intensity modulation properties of a single metallo-dielectric nanolaser (appendix D1). We then present our progress in realizing electro-optic switching in Silicon-Rich Nitride (SRN) waveguides by exploiting the third order nonlinear susceptibility, $\chi^{(3)}$ (appendix D2). The extracted $\chi^{(3)}$ from our fabricated SRN film exceeds the highest index in literature that uses the same material platform. Our SRN waveguides also allows switching for both TE and TM electric fields for the same vertical field. Our work proves that SRN is a very promising material platform for a variety of on-chip applications.

Year 5: 2020-21

In the final year, we conducted a study about laterally coupled devices and present our recent progress in understanding the impact of the spontaneous emission factor β on the dynamics and stabilities of coupled nanolasers. (see Sect. 1 below). We show that high- β enhances the stability of laterally coupled lasers, which states the importance of nanolasers with intrinsic large β to be implemented in phase-locked laser arrays for high power and steerable beam generation.

1. Effects of High- β on Phase-locking Stability in Coupled Nanolasers

Understanding the phase-locking stability and the nonlinear dynamics of coupled nanolasers becomes the natural step after individual devices are vastly investigated in both theories and experiments. Phase-locked laser arrays are of great interest for their potential in generating high power optical beam as well as steerable coherent optical beams. Theoretical analysis of such laterally coupled lasers reported in the literature thus far have overlooked the effects of the spontaneous emission factor β . With the development of micro- and nanolasers with intrinsic high- β factors over the past two decades, however, the impact of this parameter must be considered. In this work, we present the theoretical effects of varying β on the stability of phase-locking, with varying pump rates and frequency detuning considered. The stable and unstable regimes of the coupled lasers are identified through a bifurcation analysis.

The coupled rate equations, with β included, that govern the temporal dynamics two laterally coupled laser cavities considered here are given by:

$$\frac{d|E_{1,2}|}{d\tau} = \frac{1}{2} \left(\Gamma G(N_{1,2}) - \frac{1}{\tau_p} \right) |E_{1,2}| + \frac{\Gamma F_p \beta N_{1,2}}{2\tau_{rad} |E_{1,2}|^2} |E_{1,2}| \mp \kappa \cos(\Delta\Phi) |E_{2,1}| + \gamma \sin(\Delta\Phi) |E_{2,1}| \quad (1a)$$

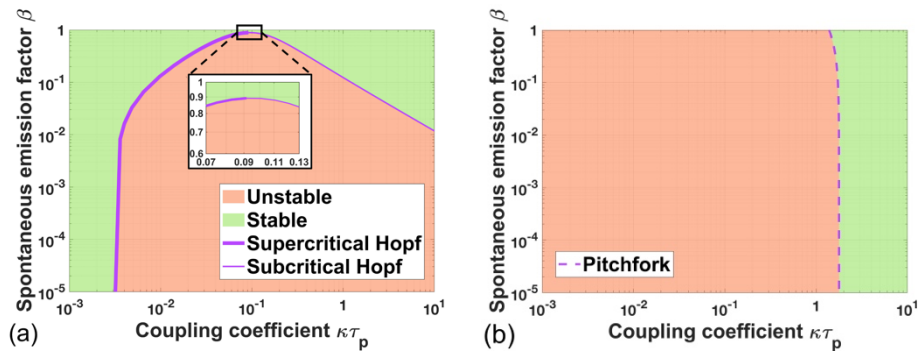
$$\frac{dN_{1,2}}{d\tau} = P_{1,2} - \frac{N_{1,2}}{\tau_{nr}} - \frac{(F_p \beta + 1 - \beta) N_{1,2}}{\tau_{rad}} - G(N_{1,2}) |E_{1,2}|^2 \quad (1b)$$

$$\frac{d\Delta\Phi}{d\tau} = \frac{\alpha}{2}\Gamma(G(N_2) - G(N_1)) + \Delta w + \kappa\left(\frac{|E_1|}{|E_2|} - \frac{|E_2|}{|E_1|}\right)\cos(\Delta\Phi) - \gamma\left(\frac{|E_1|}{|E_2|} + \frac{|E_2|}{|E_1|}\right)\sin(\Delta\Phi) \quad (1c)$$

where $|E_{1,2}|$ are the amplitudes of the electric fields in cavities 1 and 2, $|E_{1,2}|^2$ are the photon densities, $N_{1,2}$ are the carrier densities, $\Delta\Phi = \Phi_2 - \Phi_1$ is the phase difference between the two cavities, $\Delta w = w_2 - w_1$ is the frequency detuning between the cavities, α is the linewidth enhancement (Henry) factor, τ_p is the photon lifetime, τ_{rad} and τ_{nr} are the radiative and nonradiative lifetimes of the carriers, respectively, Γ is the confinement factor, F_p is the Purcell factor, $P_{1,2}$ are the pump rate, and $G(N_{1,2})$ are the carrier density-dependent gain functions. The coupling between two lasers are phenomenologically considered by introducing a complex coupling coefficient $i\kappa + \gamma$. κ denotes the dispersive coupling that quantifies the frequency difference between two supermodes, and γ denotes the dissipative coupling that quantifies the loss difference between the two supermodes.

1.1 Effects of β on the stability conditions

The simplest representation of the model assumes zero frequency detuning $\Delta w = 0$, a constant pump rate $P_1 = P_2$, and a purely imaginary coupling coefficient, i.e. $\gamma = 0$. Fig. 1(a) and (b) illustrate the stability maps for in-phase and out-of-phase solutions, respectively, as a function of κ and β ; the variable P_{th} denotes the pump power at lasing threshold for a single device. It can be observed in both figures that the stable phase-locking region grows as β is increased from 10^{-5} to 1. Specifically, for the in-phase solutions shown in Fig. 1(a), it can be observed that increasing β leads to a narrowing of the unstable region as the boundaries of the two Hopf bifurcations move towards each other. In fact, when $\beta = 0.89$, the two bifurcation branches become connected at $\kappa\tau_p \approx 0.09$ as shown in the inset of Fig. 1(a). For values of β beyond this point of confluence (i.e. $\beta > 0.89$), the steady-state solutions of the rate equations yield in-phase, stable solutions irrespective of the coupling strength. This result holds major significance as it suggests that nanolasers with β approaching 1 are ideal candidates to be used in phase-locking arrays to generate higher power. For example, $\beta = 0.25$ has been demonstrated in our previous work in metallo-dielectric nanolasers [1] as well as $\beta = 1$ in coaxial nanolasers [2].



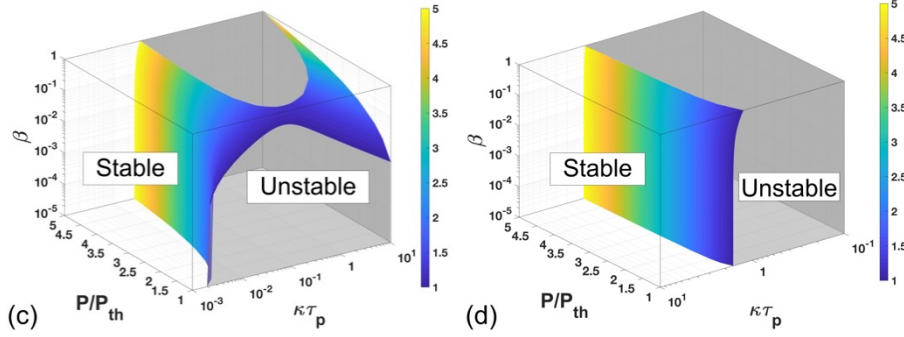


Fig. 1: 2-parameter bifurcation diagrams of the (a) in-phase solution and (b) out-of-phase solution in $(\kappa\tau_p, \beta)$ plane with $P_1 = P_2 = 1.2P_{th}$. Stable locking region is in green, unstable region is in orange. Purple lines are the supercritical (thick) and subcritical (thin) Hopf bifurcation boundary. Dashed line is the pitchfork bifurcation. (c) 3-dimensional stability plot in the $(\kappa\tau_p, P/P_{th}, \beta)$ plane for in-phase solutions. The 3-D surface is the Hopf bifurcation stability boundary. The color denotes various pump rate as shown in the colorbar. Stable phase locking region is in white, and the unstable region is in grey. (d) 3-D stability plot in the $(\kappa\tau_p, P/P_{th}, \beta)$ plane for out-of-phase solutions using same color convention as in (c).

1.2 Effects of pumping rate

In order to gauge whether increasing β leads to a similar expansion in the stability regions when the pump rate is varied, 3-dimensional (3-d) stability plots for the in-phase and out-o-phase solutions are created as shown in Fig. 1(c) and (d), respectively. Despite the complex shape of the surface in Fig. 1(c), which is the Hopf bifurcation stability boundary, higher β values always contribute towards increased in-phase locking for arbitrary pumping rate $P/P_{th} \in [1, 5]$. A varying pump rate has negligible effect on the stability of out-of-phase solutions, as seen in Fig. 1(d).

1.3 Effects of frequency detuning

In practice, slight dissimilarities in the dimensions of the resonators can easily result due to fabrication imperfections, which consequentially yield disparate resonance frequencies. Therefore, it is imperative to investigate whether the advantageous characteristics of high- β with regards to stability hold true even when the frequencies of the two lasers are detuned relative to each other. We focus our analysis on the in-phase solution as it is more interesting for most applications. The stability plot in 3-d parameter space $(\kappa\tau_p, \Delta\omega\tau_p, \beta)$ are derived from the bifurcation analysis and are further divided into $\kappa\tau_p \in [10^{-3}, 0.1]$ in Fig. 2(a) and $\kappa\tau_p \in [0.1, 200]$ in Fig. 2(b) for better visualization. Detuning of the frequencies give rise to two symmetric saddle-node (SN) bifurcation boundaries, that enclose the in-phase stable locking region together with the Hopf bifurcation boundary when $\kappa\tau_p < 0.1$. It can be observed that, as β increases, although the SN boundaries remain largely unperturbed, the supercritical Hopf branch relocates to higher $\kappa\tau_p$ values. This, in return, expands the stable locking region for weak coupling ($\kappa\tau_p < 0.1$). For strong coupling regime in Fig. 2(b), where $\kappa\tau_p > 0.1$, the second stable phase locking region is solely determined by another Hopf boundary, which shifts towards smaller $\kappa\tau_p$ for higher β , thereby increasing the area of stable phase locking. The results here indicate that increasing β expands the stability regions in both weak and strong coupling cases, despite the lasers demonstrating dissimilar frequencies. Such effect becomes even more significant for β exceeding 0.1. Therefore,

nanolasers with intrinsic high β values have great potential to be implemented in laser arrays, where shifted frequencies between adjacent elements are required to build ultra-high-resolution lidar systems for distance-angle beam steering tasks [3].

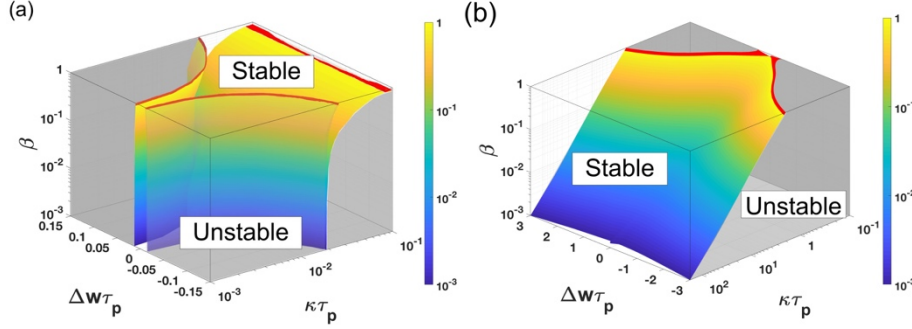


Fig. 2: (a) 3-dimensional stability plot in the $(\kappa\tau_p, \Delta w\tau_p, \beta)$ plane for in-phase solutions with $\kappa\tau_p \in [10^{-3}, 10^{-1}]$. The 3-D surfaces are the stability boundaries for Hopf and SN bifurcations. The colors denote varying β as shown in the colorbar. The red region denotes $\beta \geq 0.89$. Stable phase locking region is shown in white, and the unstable region is colored in grey. (b) 3-D stability plot in the $(\kappa\tau_p, \Delta w\tau_p, \beta)$ plane for in-phase solutions with $\kappa\tau_p \in [10^{-1}, 200]$ using the identical color convention as in (b).

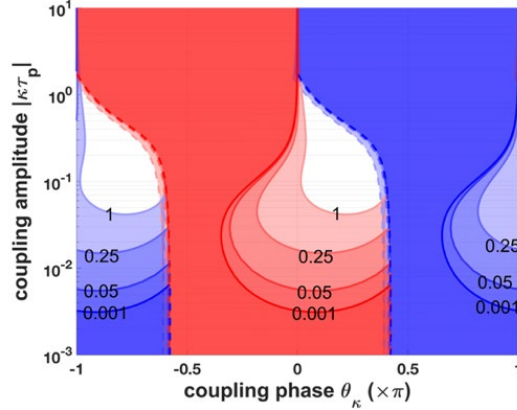


Fig. 3: 2-parameter bifurcation diagrams of in-phase and out-of-phase solutions in the $(|\kappa\tau_p|, \theta_\kappa)$ plane with $\beta = 10^{-3}, 0.05, 0.25$ and 1 . The stable in-phase locking region is shown in red; the stable out-of-phase locking region is colored in blue and the unstable region is shown in white. The solid lines denote Hopf bifurcations, while the dashed lines denote Pitchfork bifurcations.

To further extend our theoretical model to cover various coupling platforms, it is necessary to consider the dissipative coupling coefficient γ due to the loss difference between the supermodes arising from the coupling. To simplify the ensuring bifurcation analysis, instead of simply using κ and γ , the coupling amplitude and phase are used by setting $i|\kappa|e^{j\theta_\kappa} = i\kappa + \gamma$, where $\theta_\kappa \in [-\pi, \pi]$. Frequency detuning between coupled lasers is neglected for simplicity. Fig. 3 presents the stability plots for $\beta = 10^{-3}, 0.05, 0.25$ and 1 while considering complex coupling coefficient. It can be observed that the stability regions of in-phase (red) and out-of-phase (blue) with the same β values are identical in shape albeit shifted with respect to each other by π radians. The more significant finding from the figure is that as β increases, both the in-phase and out-of-phase solutions expand in size for the complex coupling coefficient model considered here.

In summary, with regards to stable phase-locking, increasing β unequivocally leads to an expansion in the stability regions despite considering varying pump rates, detuned resonance

frequencies and both purely imaginary and complex coupling coefficients. The robustness of the desirable effects of high- β on stability truly emphasize the tantalizing potential that nanolasers, that harness this advantage, demonstrate in being used for developing next generation high-power laser arrays and optical phased arrays. The manuscript that summarizes this presented work has been submitted for publication [4]. As a continuation of this theoretical work, we are working on the design, fabrication, and demonstration of two coupled nanolasers locking in-phase.

Appendix A1. Nonlinear dynamical phenomenon in a high- β metal-clad nanolaser

Metal-clad nanolasers with high spontaneous emission factors (β) represent a class of ultra-compact light emitters with applications in fiber-optic communications, hybrid and all optical computing, imaging and sensing. In-depth studies on the dynamical properties of these emitters are necessary before practical applications can be realized. This year we successfully observed the delay threshold phenomenon induced dynamical hysteresis (DH) [1] with a metallo-dielectric nanolaser designed and fabricated in our laboratory. This observation was enabled by measuring the second order intensity correlation function, $g^2(\tau)$, with a Hanbury Brown-Twiss interferometer setup constructed during the first two years of this program.

We utilized a coupled rate-equation model to predict the measured $g^2(\tau)$ of our nanolaser under nanosecond pulse pumping by first simulating the output photon pulse of the nanolaser. Fig. 4 shows the theoretically predicted $g^2(\tau)$ of our nanolaser below (Fig. 4f, g), at around (Fig. 4h) and far above threshold (Fig. 4i, j). As shown, the nanolaser $g^2(\tau)$ narrows at pump intensity far below threshold, reaches a minimum in width at around threshold and broadens above threshold. This evolutionary trend is better represented in Fig. 5, when the full width at half maximum (FWHM) of the simulated $g^2(\tau)$ pulse is plotted as a function of pump intensity. Since the intensity correlation function is equivalent to the autocorrelation of the simulated output photon pulse of the nanolaser, we generated the transient temporal behavior of the nanolaser output (Fig. 4a-e) to better understand the dependency of the $g^2(\tau)$ FWHM on the pump intensity. Our simulation reveals that at low pump power, the emitted photon pulse width depends primarily on the pump pulse width, the photon lifetime (τ_p) and the radiative recombination lifetime (τ_{rc}). As the pump intensity increases, stimulated emission grows in proportion. Thus, τ_{rc} decreases, which leads to a shorter output pulse and therefore, the below-threshold narrowing effect. Once the peak pump intensity becomes greater than the threshold pump intensity, a nonlinear effect called delayed threshold phenomenon (DTP) appears [5], which truncates part of the output photon pulse (Fig. 4c, d, e). Such truncation accounts for the additional pulse shortening effect around threshold. However, as the peak pump intensity further increases, the pump pulse crosses threshold at an earlier time, truncating less of the output photon pulse (Fig. 4d, e). Therefore, pulse broadening effect is observed above threshold.

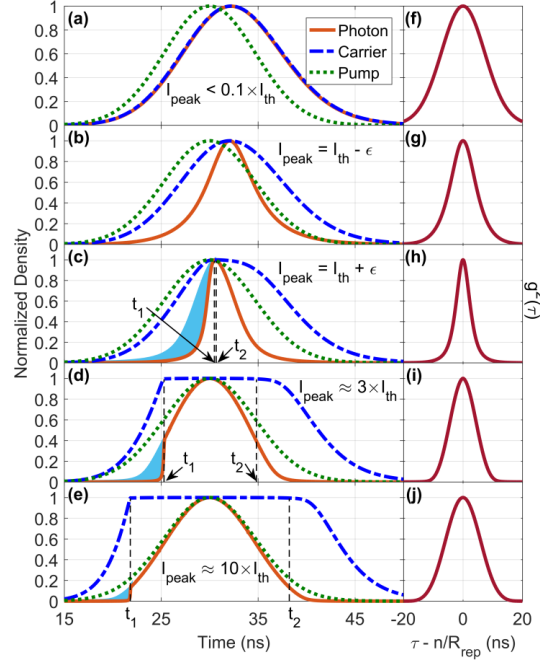


Fig. 4. (a) – (e), Normalized output photon, carrier and pump (injection) photon densities as functions of time at peak pump intensities, I_{peak} , far below threshold (a), slightly below threshold (b), slightly above threshold (c) and far above threshold [(d), (e)]. Black dashed lines and labels t_1 and t_2 in (c), (d) and (e) indicate when the pump pulse crosses I_{th} . The output photon pulse follows the shape of the pump pulse in the SE regime (a), but narrows as the pump intensity increases (b). In the far below threshold regime, the narrowing rate is predominantly influenced by the SE lifetime. Above threshold [(c), (d), (e)], DTP induced DH is observed, truncating part of the photon pulse (see blue shaded regions), which leads to an asymmetrical pulse shape. As the pump intensity increases above threshold, the pump pulse crosses threshold at a smaller t_1 and the DH effect trims away less of the output (i.e. blue shaded regions reduce in area), leading to pulse broadening. (f) – (j), The normalized autocorrelations, $g^2(\tau)$, of the photon pulses shown in (a) – (e). The cross correlations of neighboring photon pulses are identical to the autocorrelations, but are located at $\tau_n = n/R_{rep}$. By definition, $g^2(\tau)$ pulses are symmetrical, but their FWHM is proportional to those of the output photon pulses and therefore, retain the width information of the output photon pulse. The FWHM of the pulses shown are (f) 17.32, (g) 9.86, (h) 5.38, (i) 9.94, (j) 13.38 [ns].

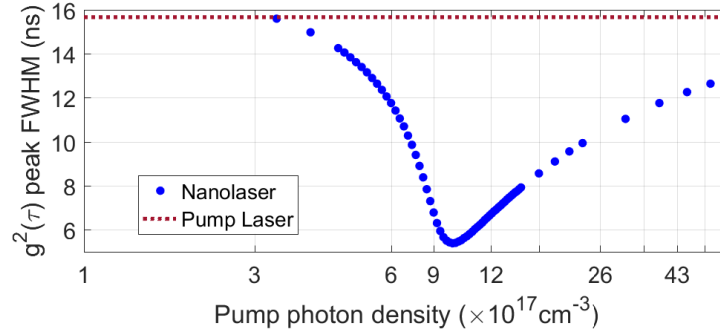


Fig. 5. Simulated $g^2(\tau)$ FWHM as a function of pump intensity, reproducing the narrowing and broadening behaviors observed experimentally.

Following our theoretical prediction, we conducted the $g^2(\tau)$ experiment under nanosecond pulse pumping and plotted the experimental $g^2(\tau)$ FWHM as a function of pump intensity in Fig. 6. Comparison between Fig. 5 and 6 shows good agreement between our theoretical and experimental results. Intuitively, DTP arises because lasing cannot happen instantaneously. Therefore, when the pump intensity is swept from below to above threshold, the nanolaser remains in its nonlasing state

for some time until enough stimulated photons are generated to statistically dominate the emission. When this happens, the device transitions to its lasing state rapidly, resulting in an output intensity jump observed in Fig. 4c-e. Such an intensity jump does not happen when the pump intensity is swept from above to below threshold since the process of photon decay inside the cavity can happen continuously. Therefore, if we plot the nanolaser output photon density as a function of pump intensity, we find a hysteresis loop shown in Fig. 7, which is referred to as dynamical hysteresis (DH) in the literature. Both DTP and DH has been observed with macroscopic lasers [5]. Observations of these dynamical phenomena in our nano-device independently confirms its lasing characteristics. We believe such dynamical effects can be exploited to identify the threshold of near-unity- β nanolasers when the conventional L-L curve fails to be accurate.

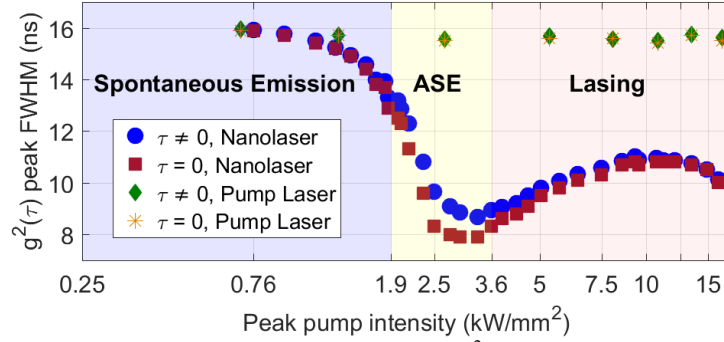


Fig. 6. Experimental FWHM of the nanolaser and pump laser $g^2(\tau)$ pulses as functions of the pump intensity. FWHM narrows below threshold due to increasing radiative recombination rate as stimulated emission increases in fraction. Above threshold, DTP or DH leads to broadening of the FWHM until self-heating dominates beyond 12.5 kW/mm² of pump intensity, at which point width narrowing is again observed.

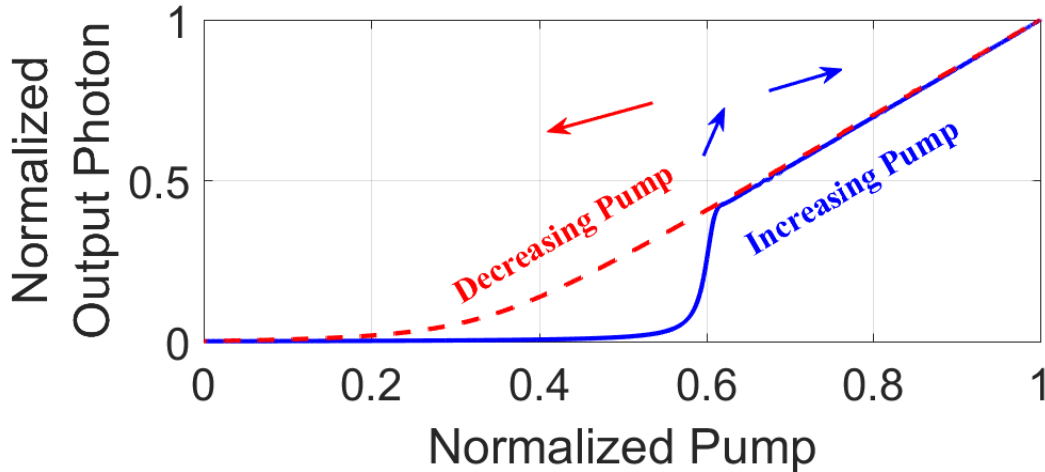


Fig. 7. Output photon density as a function of pump carrier density, showing a DH loop.

Appendix A2. Coherence characterization of near-unity- β coaxial nanolasers

By designing a laser cavity to eliminate all but one cavity mode, it is possible to theoretically achieve a β of unity. Such a unity- β nanolaser would have an extremely low threshold as nearly all the spontaneous emission would be directed into the lasing mode. However, by solving the laser rate equations at steady state, the normal kink in the L-L curve vanishes as β approaches the limit of one, seen in Fig. 8. As a result, the conventional kink cannot be used as the distinguishing feature to establish lasing in the device. In this scenario, the $g^2(\tau)$ measurements described earlier can shed light on the coherence of the emission.

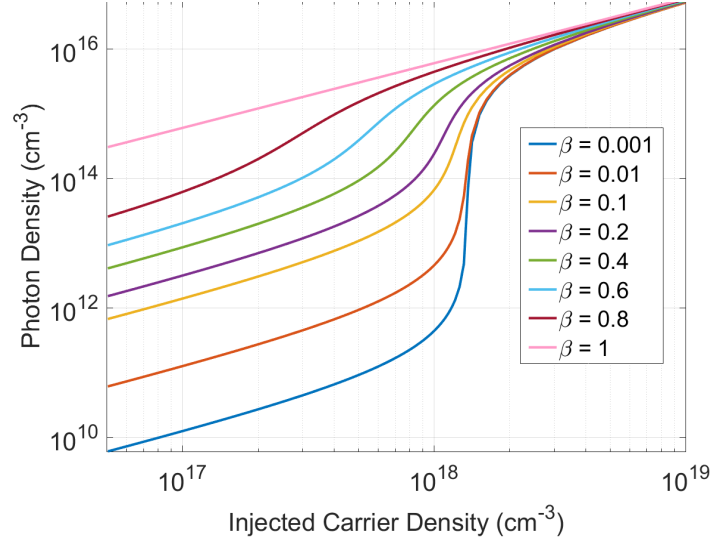


Fig. 8. L-L curve for varying β values. As β approaches its maximum value of one, no discernible kink is observed. In collaboration with a group from CREOL in University of Central Florida, we recently applied our $g^2(\tau)$ characterization technique on some coaxial nanolasers, the results of which are depicted in Fig. 9. The L-L curve measurement for this device (Fig. 9a) yielded a linear relationship between output and input power due to the absence of any kink. However, $g^2(\tau = 0)$ approaches unity above threshold (Fig. 9b) as is expected for a coherent source. Additionally, the observation of dynamical hysteresis i.e. the $g^2(\tau)$ FWHM shrinking below threshold, reaching a minimum near the threshold and broadening above threshold (Fig. 9c) served as an independent confirmation of lasing. These preliminary results not only demonstrate that unity- β lasing can be achieved but also that the former does not imply the lack of a threshold. We hope to further consolidate this data by comparing the $g^2(\tau)$ results for a non-unity- β device and comparing the difference in threshold which should be much lower for a unity- β nanolaser.

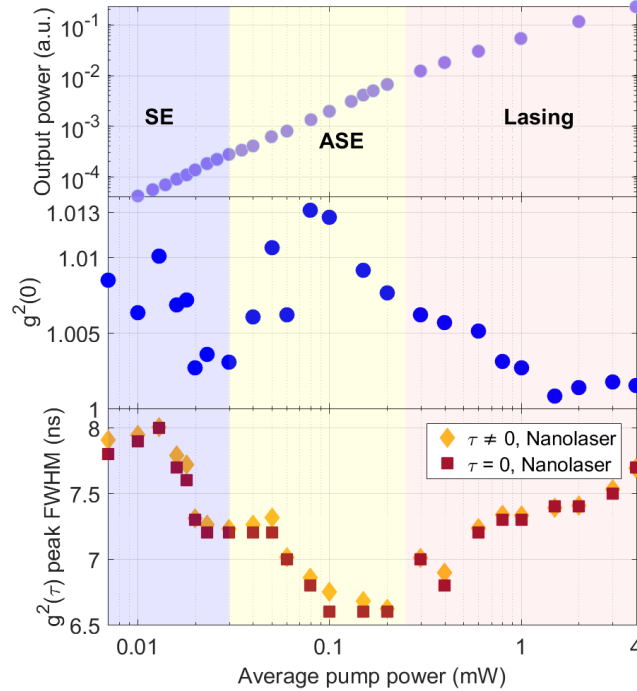


Fig. 9. (a) L-L curve for a unity- β device does not exhibit any observable kink. (b) $g^2(\tau = 0)$ approaches unity above threshold but fluctuates significantly below threshold due to lower SNR. (c) $g^2(\tau)$ FWHM demonstrates dynamical hysteresis phenomena that serves as an independent confirmation of coherence

Appendix A3. InGaAsP tunnel junction assisted electrically-pumped metal-clad semiconductor nanolasers

The co-optimization of multiple design aspects becomes necessary to further advance the field of electrically-pumped nanolasers. In previous works, we have focused on pure electromagnetic designs, material choices and thermal management. Due to their extremely small radii, Joule heating in an electrically pumped nanolaser can contribute significantly to self-heating and ultimately limit the nanolaser's performance, particularly for lasers with high threshold currents. Here we have studied and theoretically analyzed the effect of adding an InGaAsP tunnel junction for efficient carrier injection [6]. By doing so, the device resistance can be reduced and thermal management can be further improved, which is necessary to realize stable room temperature nanolasers.

The schematic of the electrically pumped nanolaser under consideration is shown in Fig. 10(a). The tunnel junction consists of a heavily doped InGaAsP PN junction. The doping concentration for both p- and n-type layers are $5 \times 10^{19} \text{ cm}^{-3}$. By incorporating the tunnel junction, we can replace the poorly conductive p-InGaAsP and p-InP ($5 \times 10^{18} \text{ cm}^{-3}$) layers by n-InGaAsP and n-InP ($5 \times 10^{18} \text{ cm}^{-3}$) layers respectively.

To calculate the quality factor and the confinement factor of the laser cavities, we used the finite element method (FEM) software (COMSOL) for 3D modeling. Fig. 10(b) shows the electric field of the desired lasing mode. The Q-factor, resonant wavelength (λ), confinement factor (Γ) and threshold gain (g_{th}) are also presented. Because of the free carrier absorption in the heavily doped tunnel junction, the overall optical losses in the cavity become more important than a cavity without a tunnel junction. Therefore, we have optimized the position of the tunnel junction with respect to the active region to mitigate the reduction of Q and thus the threshold gain. We then place the tunnel junction 750nm below the gain region to minimize the mode overlap with the tunnel junction and obtain the threshold gain of 339.6 cm^{-1} with the tunnel junction compared to 363.8 cm^{-1} without it.

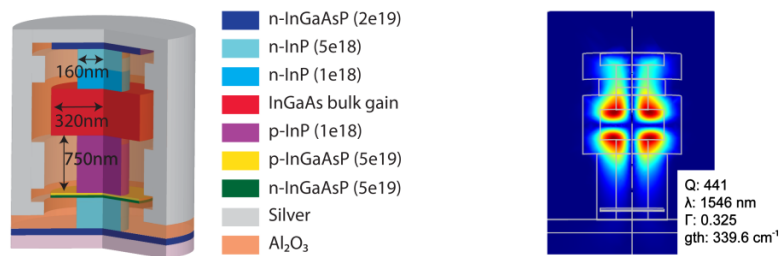


Fig. 10. (a) Schematic of the nanolaser with a tunnel junction. The radius of the gain medium is 320nm and the InP undercut is 160nm. The distance between the gain media and the tunnel junction is 750nm. (b) Electric field of the lowest threshold mode, TE_{012} .

To further advance our analysis, we have solved the laser rate equations to obtain the threshold carrier density shown in Fig. 11(a). Laser parameters are extracted from the simulations in Fig. 11(b). We have also used the commercial software SILVACO's ATLAS to simulate the current injection through the heterojunction. Fig. 11(b) shows the simulated I-V curves demonstrating that the nanolaser with the tunnel junction has a better electrical efficiency compared to the nanolaser

without the tunnel junction. This occurs due to low hole mobility, which impairs the current injection in the device without the tunnel junction.

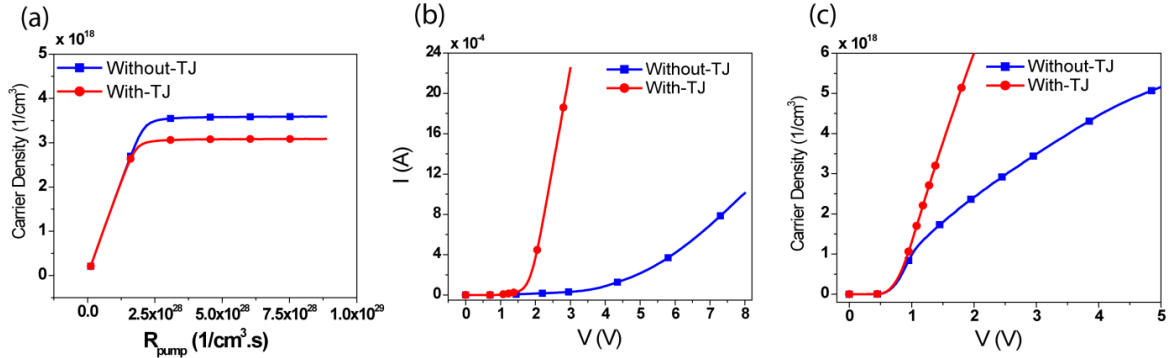


Fig. 11. (a) Carrier density as a function of the injection pumping rate. (b) I-V curve and (c) carrier density in the gain media with respect to applied voltages.

By inserting tunnel junctions, the high resistance coming from p-type layers can be minimized; the device resistance can be reduced by a factor of 6.5. In Fig. 11(c), for nanolaser without tunnel junctions, the threshold voltage is 3.05V, which reduces to just 1.35V when a tunnel junction is introduced into the design.

We have also analyzed the tunnel junction doping concentration influence on the threshold voltage and Joule heating. We considered only the optimized device shown in Fig. 10(a), but with tunnel junction doping concentrations of $5 \times 10^{18} \text{ cm}^{-3}$, $1 \times 10^{19} \text{ cm}^{-3}$ and $2 \times 10^{19} \text{ cm}^{-3}$. Since the tunnel junction is 725nm below the gain region, the mode overlap with the tunnel junction was neglected. Therefore, we assume Q , Γ and g_{th} do not change with the doping concentration of the tunnel junction in this case. The calculated threshold voltages are then 2.4V, 1.75V and 1.5V, reducing the Joule heating by 44%, 60% and 62% respectively. These results show tunnel junctions are reliable even for lower doping concentrations.

We have now fabricated and measured our first batch of devices which show emission and a narrow peak at 77k.

Fig. 12 (a)-(d) show our fabrication results. We first used reactive ion etching (RIE) to form cylindrical pillar structures (Fig. 12a). Next, we selectively wet etch the InP layers, without affecting the InGaAs gain layer, InGaAsP contact layer and tunnel junction, to create InP pedestals (Fig. 12b). We then deposited Al_2O_3 layer by using ALD (Atomic Layer Deposition) (Fig. 12c). To access the n- InGaAsP contact layer for n-type metal electrode, the Al_2O_3 region on top of the pillar structure is removed through photoresist planarization and etching of Al_2O_3 . The metal contact is then deposited through e-beam evaporation (Fig. 12d). Cavity metal (Ag) is then formed through sputtering (not shown here).

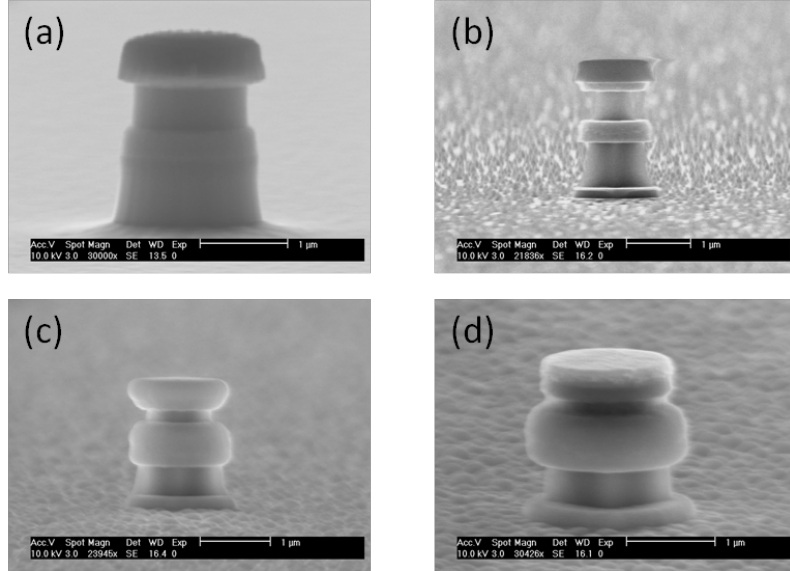


Fig. 12. (a)-(d) SEM images of nanolasers (a) after RIE (b) after wet etching (c) after Al_2O_3 deposition (d) after metal contact formation.

We characterize the device at an ambient temperature of 77K. The nanolaser is forward biased by a DC voltage source, and CW emission through the substrate is collected through a 20x objective lens. Fig. 13 shows the measured emission spectra. The lasing peak was observed at 1.49 μm as the injection current was increased. At 95 μA , a clear spectral narrowing of the peak linewidth indicated a possible lasing mode.

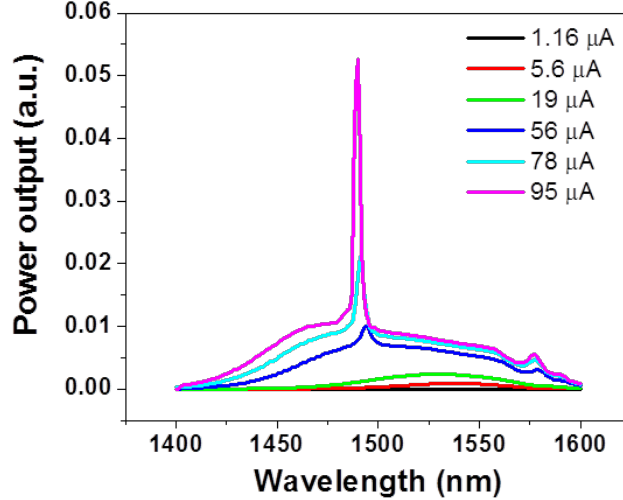


Fig. 13. Measured spectral evolution with increasing injection current at 77K.

We are currently working on optimizing the metal contact on the n-InGaAsP layer. With better metal contacts, the device resistance could be further reduced and self-heating in the device could be alleviated which may consequently allow for room-temperature lasing.

Appendix A4. Optically pumped tunable metallo-dielectric nanolasers based on quantum confinement stark effect

Self-modulated semiconductor nanolasers would forgo the need for external mechanisms to tune the lasing wavelength and/or intensity. One way to create such a tunable source is to exploit the Quantum Confinement Stark Effect (QCSE) where an external electric field induces changes in the emission properties of a quantum well structure. In the initial phase of this project, we performed some numerical simulations to predict the range of tunability theoretically achievable with the proposed design. We are currently optimizing the final steps of the fabrication process after which we can proceed with the testing and characterization phase.

In QCSE, when an external electric field is applied parallel to the growth direction of a multiple quantum well (MQW) gain medium, two phenomena are observed: 1) the external field pushes electron and hole wavefunctions in opposite directions; and 2) the bound states for both carriers are also shifted. The result is that the wavefunction overlap of the carriers and the transition energy both decrease, leading to a consequent decrease in the output light intensity and an increase in the emission wavelength respectively. To quantify this change, we used SILVACO to design a device that incorporates additional layers of dielectric and ITO, the latter of which acts as a transparent electrode as shown in Fig. 14. Figure 15 illustrates the results of applying a DC electric field to this device structure. To predict the modulation possible in emitted light intensity, the modal gain of the MQW structure was calculated and it was found that the parameter changed by about 12.7 % per V of external field applied. Similarly, the peak gain wavelength was found to vary by 2.69 nm per V.

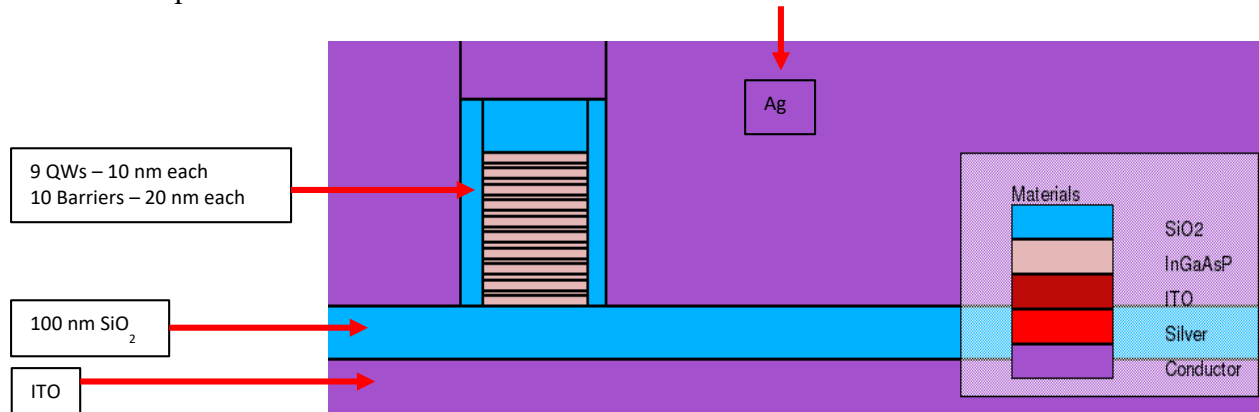


Fig. 14. The simulated device schematic with MQWs of InGaAsP cladded with a dielectric shield of SiO₂. The ITO on the bottom and the Ag serve as the two electrodes where the external field is applied.

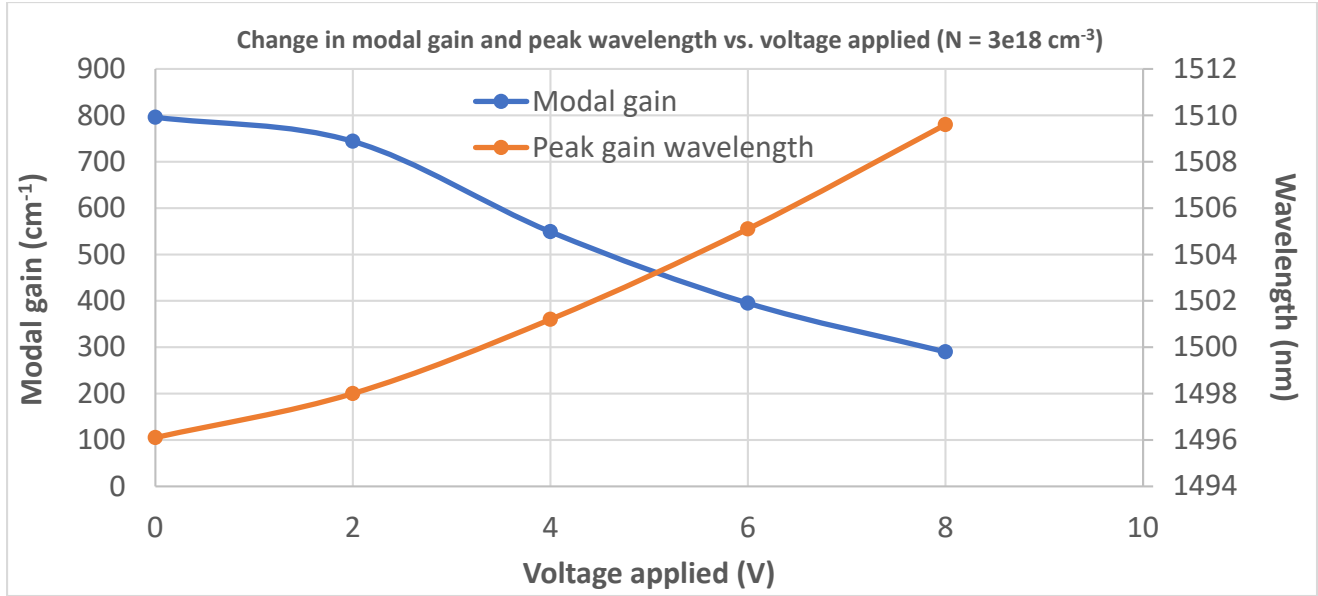


Fig. 15. The change in modal gain and peak gain wavelength as a function of applied voltage across the capacitive structure.

Having quantified the QCSE effect numerically, we then started fabrication of the actual device. Fig. 16 shows a schematic of the intended design mirroring the structure simulated in SILVACO.

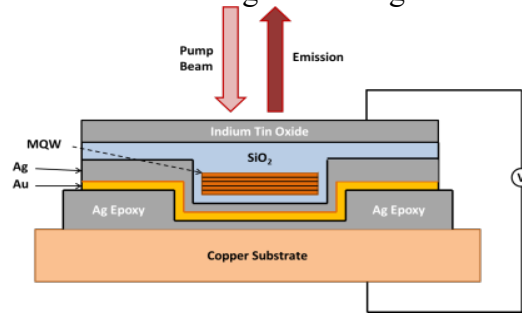


Fig. 16. The schematic of the device to be fabricated

The photoluminescence of the devices was measured at each step of the fabrication process and even after the final step of depositing ITO, a sharp lasing peak along with spatial coherence as viewed on an IR camera were observed as shown in Fig. 17.

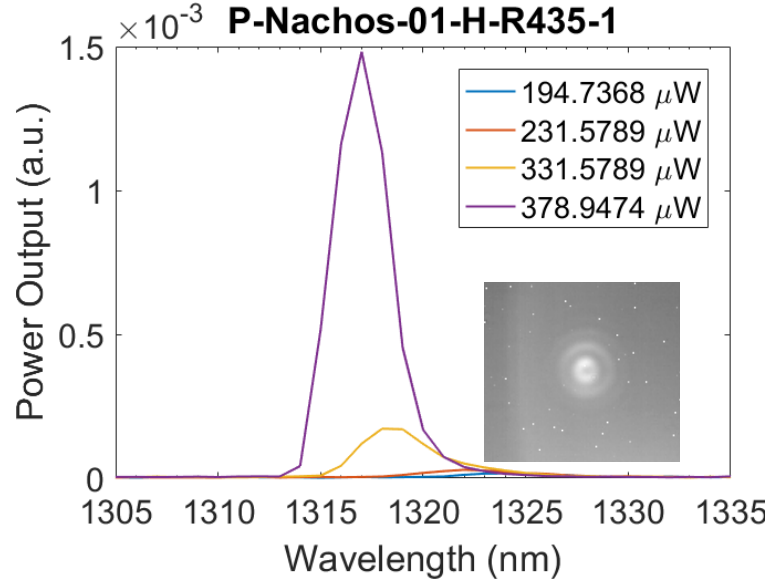


Fig. 17. The spectral evolution of a representative device as the pump power is increased shows emergence of a narrow lasing peak

The main problem encountered in the project so far has been that the dielectric layer seems to be easily penetrated by the electrical probes that apply the external field. Ideally, the layer should be insulating enough that the field can be applied at the electrodes without any current leakage. With leakage, however, it would not be possible to maintain a field across the capacitive design.

One way that is being tested currently to combat this issue includes improving the method of contacting the surface by using point probes with high precision. Additionally, increasing the dielectric thickness that is deposited could also reduce chances of any conductance current being measured. If these issues in this final phase of applying external field are resolved, we are confident that the devices can perform as intended since they have been already shown to exhibit lasing behavior even after the completion of the fabrication procedure.

Appendix B1. Dynamics of nanolasers

B1.1 Dynamics vs. β for a single nanolaser

Before using multiple cross-coupled nanolasers for integration into on-chip computing networks, it is imperative to understand in-depth the dynamics of a single such device. Previously, we demonstrated that by measuring the second-order intensity correlation, $g^2(\tau)$, of a single metallo-dielectric nanolaser, the different operational regimes of the device can be distinguished clearly based on both the value of $g^2(0)$ approaching 1 for the lasing regime as well as the evolution of the $g^2(\tau)$ pulse width [1]. This capability becomes especially important when the traditional marker for lasing – the kink in the output light vs. input light curve (LL curve) – becomes less and less pronounced as β is increased to the theoretical limit of 1. Although in [1], the results we obtained were for a fixed value of $\beta \sim 0.25$, the technique of using the $g^2(\tau)$ pulse width is applicable for any value of the parameter.

To better understand how varying β can specifically alter the dynamics observed for the nanolaser, we considered two extreme cases – one where $\beta = 10^{-5}$ and the other with the maximum possible value for β of 1 [7]. For each case, we numerically simulated the rate equations for photon and carrier densities as shown below, with the parameter values and descriptions listed in Table 1. Doing so allows us to observe the transient output photon density representing a single emission

pulse of the nanolaser under nanosecond pulse pumping, the results of which are depicted on the left-hand sides of Fig. 18 and Fig. 19 for $\beta = 10^{-5}$ and for $\beta = 1$ respectively. The right-hand sides of Figs. 18 and 19 show the $g^2(\tau)$ for these two β cases.

$$\frac{dS}{dt} = \Gamma g_0 (N - N_0) S - \frac{S}{\tau_p} + \frac{\Gamma \beta N}{\tau_{rr}}$$

(1)

$$\frac{dN}{dt} = I_{peak} \exp\left[-\frac{(t-t_0)^2}{\Delta^2}\right] - \frac{N}{\tau_{rr}} - \frac{N}{\tau_{nr}} - g_0 (N - N_0) S$$

(2)

Symbol	DESCRIPTION	Value
S	photon density	
N	carrier density	
P_{peak}	peak pump (injected) carrier density	
$FWHM$	full width at half maximum of optical pump pulse	
Δ	$FWHM/(2\sqrt{\ln 2})$	6.65 ns
t	time	0 to 80 ns
t_0	time when the Gaussian pump pulse reaches maximum	30 ns
Γ	energy confinement factor	0.6
G	linear gain coefficient	$5 \times 10^{-16} \text{ cm}^2$ [54]
n_g	group refractive index for InGaAsP	3.5 [19], [54], [55]
c	speed of light	$3 \times 10^8 \text{ m/s}$
v_g	group velocity	$v_g = c/n_g = 8.57 \text{ cm/ns}$
g_0	$v_g \times G$	$4.285 \times 10^{-15} \text{ cm}^3/\text{ns}$
N_0	transparency carrier density	$2 \times 10^{18} \text{ cm}^{-3}$ [19], [55]
Q	cavity quality factor	3474
β	spontaneous emission factor	$10^{-5}, 0.1, 0.25, 0.5, 0.7, 1$
λ	emission wavelength	1550 nm
τ_p	photon lifetime	$(Q\lambda n_g)/(2\pi c) = 0.01 \text{ ns}$
τ_{rr}	radiative recombination lifetime	1 ns [19]
τ_{nr}	Nonradiative recombination lifetime	1 ns [19]
τ_c	total carrier recombination lifetime	$\tau_{rr} + \tau_{nr}$

Table 1: Parameter descriptions and values used to numerically simulate the coupled rate equations for photon and carrier density. β is varied [Ref 7].

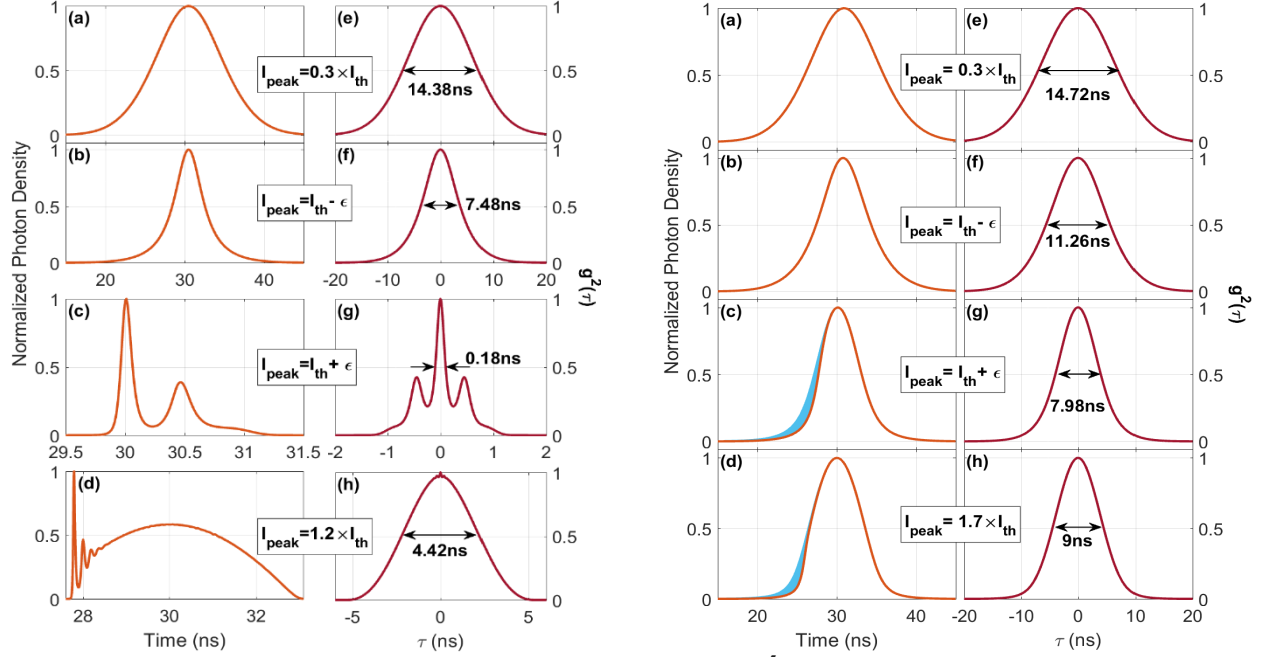


Fig 18 (left) and Fig. 19 (right): Output photon pulses for $\beta = 10^{-5}$ (left-hand side of Fig. 18) and $\beta = 1$ (left-hand side of Fig. 19) along with $g^2(\tau)$ for these cases (right-hand sides of Fig. 18 and Fig. 19 respectively). The pulse width is broadest below threshold (a), shrinks as the pump intensity increases (b) and reaches a minimum slightly above threshold (c) for both values of β . Finally, as the pump intensity continues to increase above threshold, the width starts broadening again (d). Interestingly, the photon density for the low- β case exhibits a shorter pulse and exhibits multiple pulses (Fig. 19(c) due to faster photon decay and relaxation oscillations respectively. The oscillations are highly damped for the unity- β case [Ref 7].

From the left-hand sides of Figs. 18 and 19, it is evident that akin to the results in [1], the output photon pulse is broadest below threshold, shrinks as the pump intensity is increased reaching a minimum slightly above threshold and finally, broadens as the pump intensity continues to increase above threshold. The $g^2(\tau)$ pulse width, shown on the right-hand side of Figs. 18 and 19 mirrors the pulse width of the output photon pulses. More interestingly, however, the $g^2(\tau)$ pulse width for the $\beta = 10^{-5}$ case is approximately 44 times smaller than that of the unity- β device. The reason for the shorter pulse is that when $\beta = 10^{-5}$, the last term in equation (1) for the photon density can be neglected. As a result, the photon decay is faster due to less contribution of photons from spontaneous emission.

Additionally, multiple photon pulses can be observed for the low- β case in Fig. 18(c) which is also reflected in the autocorrelation of the output pulse in Fig. 18(g). These additional pulses are observed due to relaxation oscillations (RO) that result from a time-varying pump. When the carrier lifetime, τ_c , is longer than the photon lifetime, τ_p , as is the case for class-B lasers such as the nanolasers shown here (see Table 1 for values), such RO are an expected occurrence. Though both low- β and unity- β lasers are similarly affected by this phenomenon, the oscillations are rapidly damped in the latter case.

To illustrate this, we analytically solved equation (1) assuming a small perturbation in the pump intensity and using the small-signal modulation transfer function (SSMTF). Doing so yielded the following solution for the photon density:

$$\Delta S(t) \propto 1 - \frac{e^{-\omega_n \xi}}{\sqrt{1 - \xi^2}} \sin\left(\omega_n \sqrt{1 - \xi^2} t + \varphi_p\right) \quad (3)$$

where $\phi_p = \arctan[(\sqrt{1-\xi^2})/\xi]$, $\Delta S(t)$ is the time-varying photon density fluctuation, ω_n is the relaxation frequency and ξ is the damping factor. As can be seen from equation (3) above, there is an exponential dependence of the photon density on the damping factor. Therefore, when equation (3) is plotted for varying values of β , as shown in Fig. 20, the increased damping with higher values of β can be clearly seen.

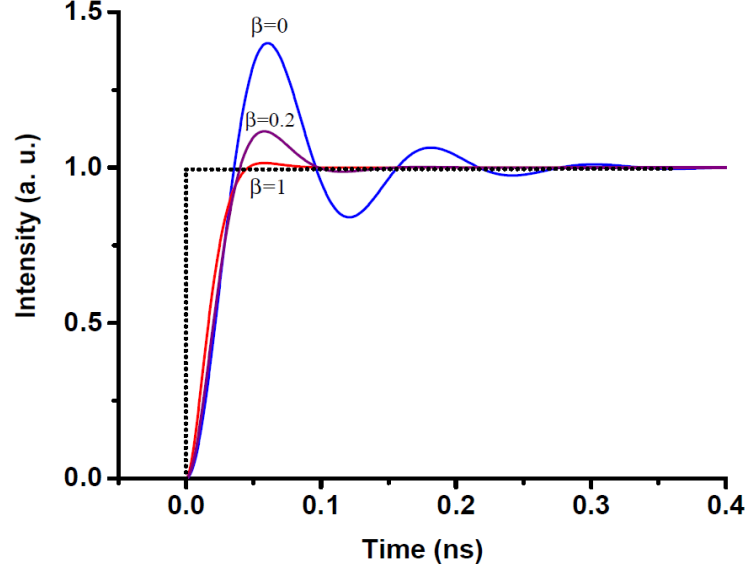


Fig. 20: The time-varying photon density for a small perturbation in the pump intensity for three different values of β . Due to an exponential damping term in front of the sinusoidal RO affecting the density, the higher the β , the more pronounced is the damping of the RO [Ref 7].

Due to the multi-pulse behavior of low- β nanolasers, it becomes problematic to unambiguously define and use the $g^2(\tau)$ pulse width to demarcate operational regimes of the device. In such a scenario, a more appropriate metric to use would be to integrate the total area underneath the $g^2(\tau)$ function. Figure 21 shows the $g^2(\tau)$ pulse area for varying values of β for a nanolaser along with the area for the pump laser. The evolutionary trend in the $g^2(\tau)$ area exhibited by the pulses (except for the pump laser) mirrors the results found in [1] for the $g^2(\tau)$ pulse width evolution – narrowing in the spontaneous emission regime, a minimum slightly above threshold in the amplified spontaneous emission regime and broadening in the lasing regime. Additionally, from Fig. 21, it appears that even a unity- β laser exhibits a minimum in the area under the $g^2(\tau)$ function, suggesting that there exists a threshold for such a laser – at least under nanosecond pulse pumping conditions - despite the absence of a kink in the LL curve.

These recent results, detailed in [7], have helped us to better understand and characterize a single nanolaser, which is essential if we are to use multiple such, densely packed nanolasers to realize a tunable, chip-scale optical network.

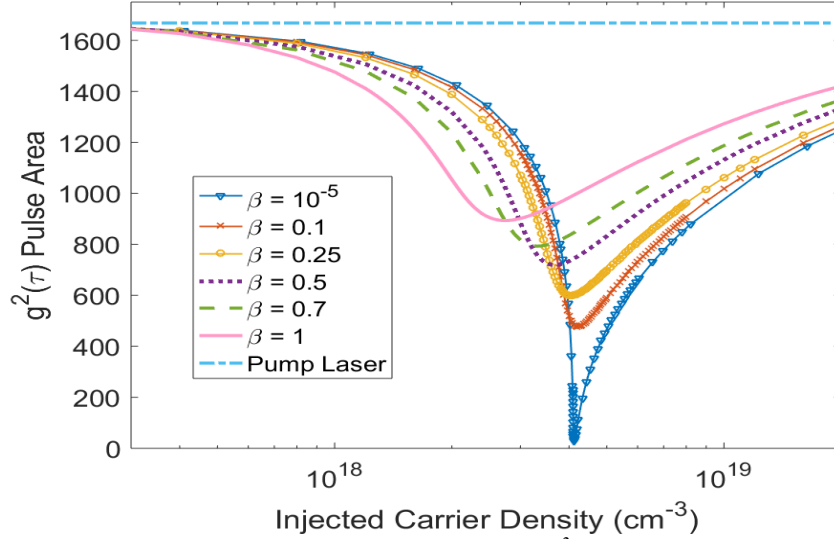


Fig. 21: The total integrated area underneath the $g^2(\tau)$ function as the pump intensity is increased for various values of β as well as for the pump laser. The evolution in the area is similar to what is observed in the width in [1] – shrinks below threshold until it reaches a minimum slightly above threshold and then broadens as the pump intensity continues to increase above threshold. A minimum is also observed for the $\beta = 1$ case [Ref 7].

Appendix B2. Coupling in two metallo-dielectric nanolasers

If multiple, on-chip closely spaced coherent sources such as nanolasers are to be used for WDM-based optical networks, it is necessary to investigate and understand coupling. Such a study is required for both applications that require each source to be operated and/or modulated independently without cross-talk (in which case coupling is undesirable) as well as those that rely on the tunable dynamics that may be observed in a coupled system. Though evanescent coupling between closely spaced optical cavities has been widely reported, whether the same phenomena is induced for metal-clad cavities had not been explored. Recently, we investigated this question by performing some FEM simulations on a dual metallo-dielectric cavity system, a schematic of which is shown in Fig. 22 [8].

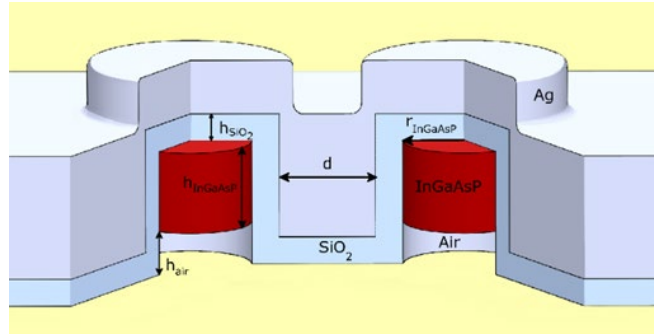


Fig. 22: Schematic of the dual cavity system with constituent materials labelled. The distance, d , between the dielectric shields is the parameter changed to probe the characteristics of the modes [Ref 8].

First, the electric field intensity was recorded for two extreme cases – when the resonators are far apart from one another and when they are in contact. When far enough apart, the two cavities support independent modes albeit at the same resonant frequency due to their identical size as seen in Fig. 23(a). When the dielectric shields contact each other, however, the emergence of two new

supermodes is observed due to increased evanescent coupling. Fig. 23(b) and (c) correspond to these two new coupled states – the anti-bonding and the bonding state respectively.

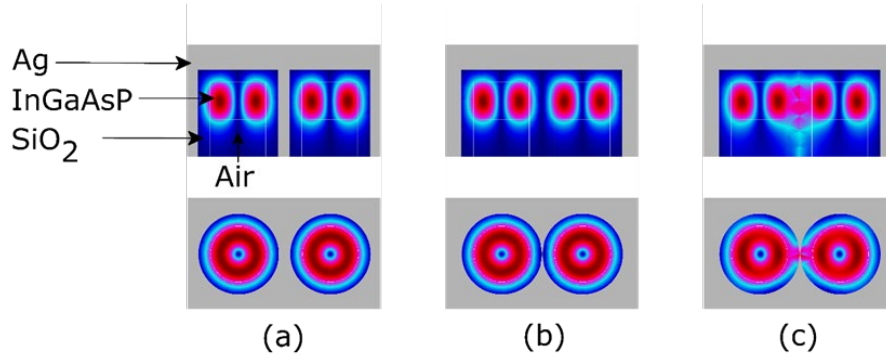


Fig. 23: Electric field intensity profile across side (top row) and top (bottom row) cross-sections of the dual cavity system. (a) The distance between dielectric shields is 90 nm and two identical but independent modes are supported. (b) The shields are now in contact and an anti-bonding supermode with strong confinement of the mode to the gain medium is created. (c) A new bonding mode is created for the same separation as in (b) but with poor confinement of electromagnetic mode to gain medium [Ref 8].

To better elucidate the effect of coupling, the separation between the two cavities, d , was varied in an eigenfrequency solver module of COMSOL Multiphysics. For each inter-cavity distance, the resonant wavelength, λ , and quality factor, Q , for the modes supported by the system are calculated. Akin to what has been reported for both micron and nanoscale structures, a split in these quantities is observed as shown in Fig. 24(a) and (b) respectively. Additionally, to gain insight on the likelihood for lasing, the gain threshold, g_{th} , is calculated in Fig. 24(c). As the two cavities are brought closer together, increased evanescent interaction between the electromagnetic fields of each resonator gives rise to the bonding mode – which demonstrates a lower Q and longer λ than an individually isolated mode – and an anti-bonding which exhibits a higher Q and shorter λ than the same parameters for an isolated cavity mode. Due to the higher loss of the bonding state, it is therefore much less likely to exhibit lasing than its anti-bonded counterpart as seen by the high and low g_{th} values for both modes, respectively, in Fig. 24(c).

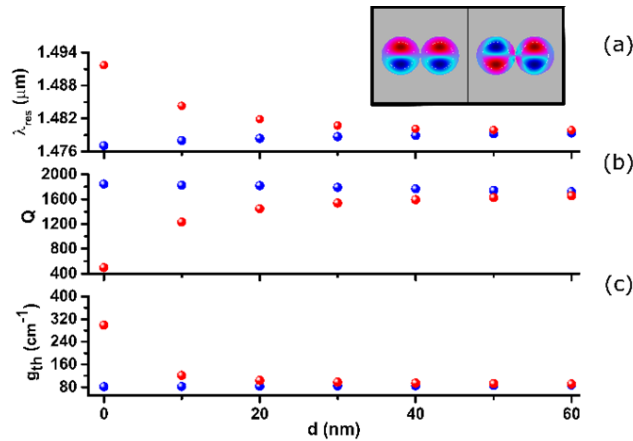


Fig. 24: Resonance wavelengths (a), Q -factors (b) and gain thresholds (c) for each of the two modes at different inter-cavity separations. Red represents the bonding and blue the anti-bonding state at lower separations. Inset: Electric field distribution of the anti-bonding (left) and bonding (right) supermode. An exponential splitting of the quantities is observed as d is reduced to 0 nm [Ref 8].

If the application demands that the independence of each source is preserved, then methods must be introduced to inhibit coupling from occurring. We did so by detuning the resonant frequencies of the two nanolasers by introducing a slight change in radius (5 %) for one of the cavities relative to its neighbor. Doing so and calculating the same parameters as shown in Fig. 24 yields the results shown in Fig. 25. As is evident, there is no longer a bifurcation in the Q and λ of the two modes as the inter-cavity distance d is reduced to 0 nm. The two disparate wavelengths, due to the dissimilar cavity sizes, can now be individually programmed or controlled without cross-talk.

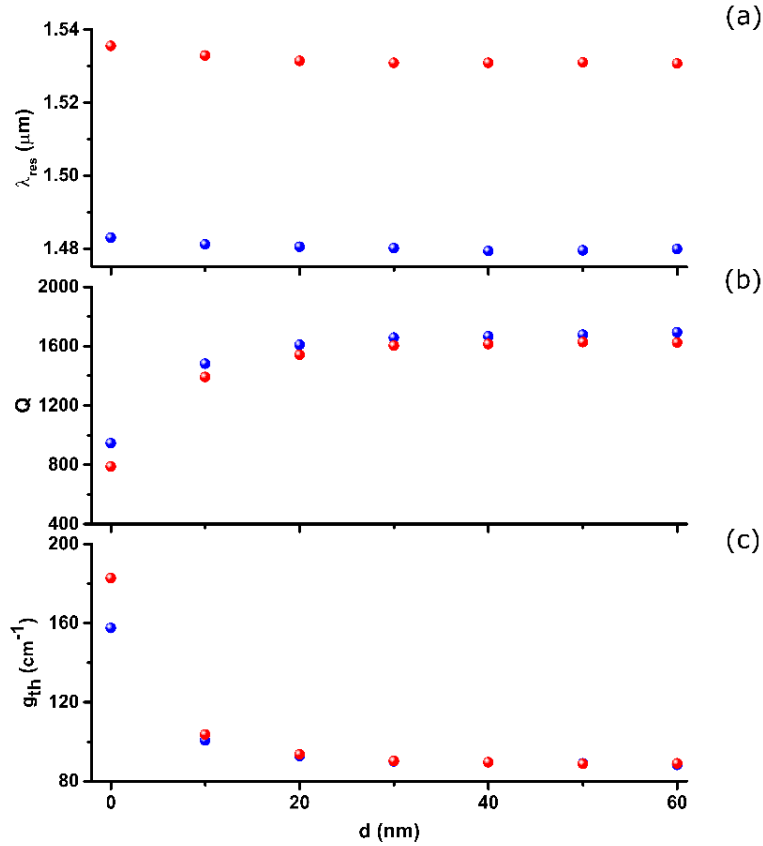


Fig. 25: Resonance wavelengths (a), Q-factors (b) and gain thresholds (c) for each of the two modes at different inter-cavity separations for dissimilar cavity sizes. Red represents the bonding and blue the anti-bonding state at lower separations. There is no longer a split in the quantities observed as d is reduced [Ref 8].

An alternative method to impede coupling is to design all the nanolasers in the system to be larger. These larger-sized cavities support higher order modes which are better confined than lower-order ones and hence, less likely to couple evanescently. An example of this can be seen in Fig. 26 which illustrates the Q -factors of the modes supported by the dual nanolaser system when the radius of each cavity is increased to 275 nm from the original 225 nm studied in [8]. Due to the increase in the radii, more than just two modes, as is the case for the smaller-sized cavities shown in Fig. 25, can be observed for the enlarged-cavity system. Additionally, the Q -factors of all the modes except one stay relatively constant or increase slightly as d is reduced. Only one mode exhibits a higher loss (lower Q) with decreasing d [7].

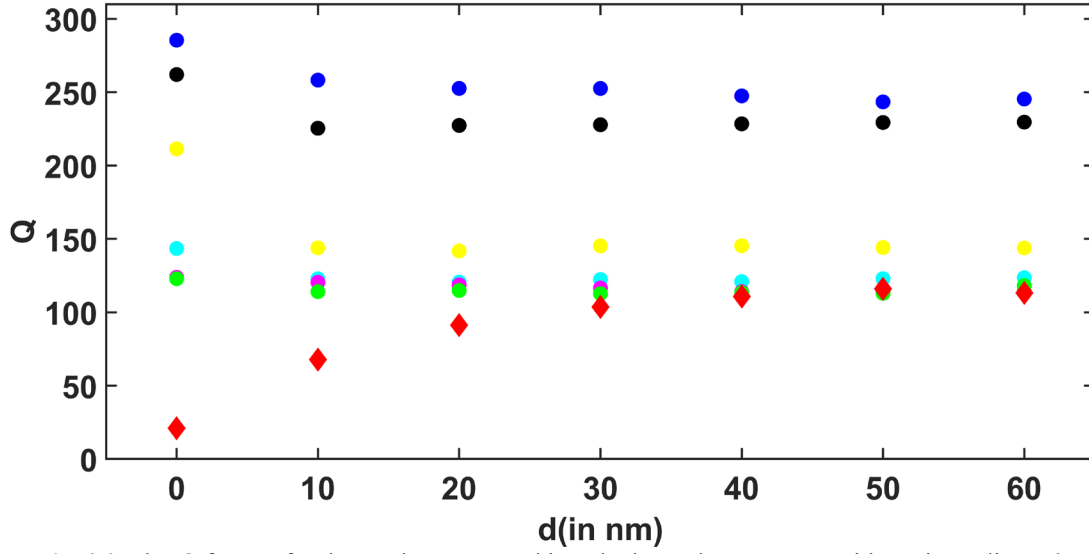


Fig. 26: The Q -factors for the modes supported in a dual nanolaser system with cavity radius = 275 nm for different values of d . Only one of the modes, shown in red, experiences higher losses as d is decreased down to 0 nm; the Q for the rest of the cavity modes either stays constant or increases only slightly [Ref 7].

Taking only this coupled mode and calculating the difference in its Q - $\Delta Q_{coupled}$ - for when the nanolasers are designed far apart ($d = 100$ nm) and when their shields are in contact ($d = 0$ nm) for different sized cavities yields the plot in Fig. 27. As shown in the figure, with increased radius, the coupled mode exhibits reduced fluctuation in its Q despite the continual decrease in d . This is due to reduced coupling experienced by the higher-order modes of the larger resonators.

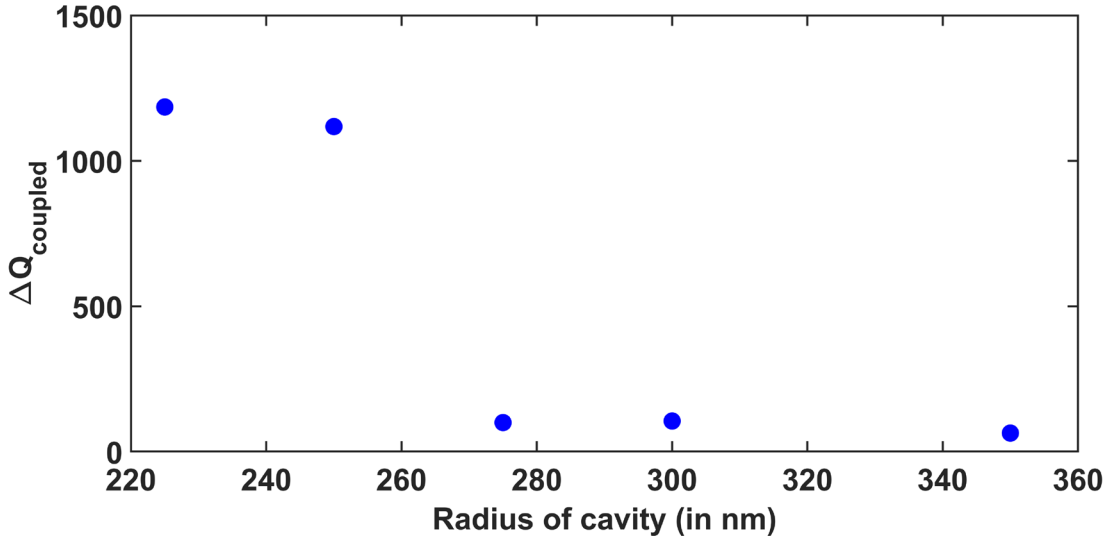


Fig. 27: Difference in Q -factor for the coupled mode - $\Delta Q_{coupled}$ - for $d = 100$ nm and $d = 0$ nm for varying radii of the cavities. As radius is increased, there is less loss experienced by the mode as d is reduced since coupling becomes less pronounced. [Ref 7].

Appendix B3. Switching based on second-order nonlinearities

B3.1 Tunability with a metal-semiconductor-metal (MSM) metamaterial

One of the essential elements of a low-cost, scalable and energy efficient photonic-integrated circuit would be an optical switch. In addition to developing subwavelength nanolasers and studying their fundamental properties, it is necessary to have materials that can be switched in a fast and efficient manner. One way to implement such switches is to make use of tunable optical nonlinearities. In a recent work, we experimentally demonstrated an asymmetric MSM metamaterial that exhibits a significant and electronically tunable effective second-order optical susceptibility ($\chi^{(2)}$) which originates from the interaction between the third-order optical susceptibility of the semiconductor ($\chi^{(3)}$) and the engineered internal electric field that arises due to the dissimilar work functions of two metals on either side of the semiconductor [9].

As shown in the Fig. 28(c), TCAD Silvaco simulation tools were first used to study the magnitudes and spatial distributions of the built-in electric fields inside the MSM metamaterial structures and a high value of effective $\chi^{(2)}$ can be expected due to the large $\chi^{(3)}$ ($\chi^{(2)} \sim 3 \chi^{(3)}$) [9].

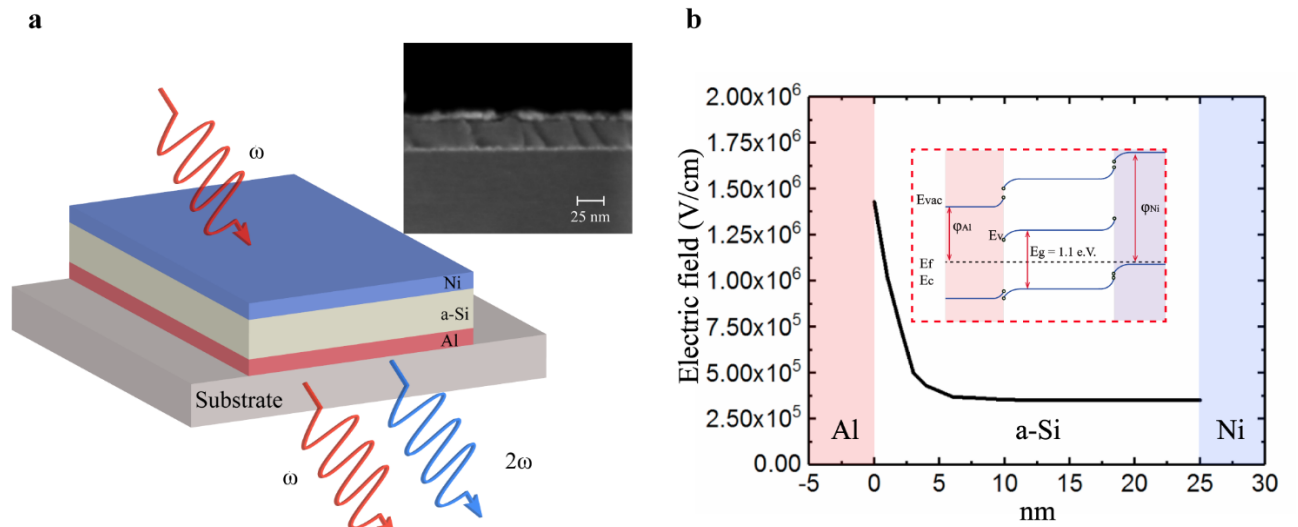


Fig. 28. (a) Schematic and SEM image of a 5 nm Ni / 25 nm a-Si / 5 nm Al MSM metamaterial for second-harmonic generation process. (b) The reduced band diagram and the simulated distribution of built-in electric field for the Ni / a-Si / Al metamaterial. The induced electric field decreases from $\sim 1.5 \times 10^6$ to $\sim 3 \times 10^5$ across the bulk of a-Si [Ref 9].

These structures were then experimentally realized on fused silica substrates using magnetron sputter deposition at room temperature. The Maker fringes method was then used to characterize the polarization dependence of the second harmonic generation (SHG) for extracting the $\chi^{(2)}$ tensor coefficients. The measured p- and s- polarized second-harmonic responses as a function of the polarization angle of the input pump are shown for the MSM metamaterial along with single layers of the cladding metals Al and Ni on fused silica substrates in Fig. 29(b) and (c), respectively. For both polarizations, the SHG intensities from the MSM are clearly much larger than that generated from a combination of Al and Ni layers on fused silica substrates, since the second-order nonlinear response is dominated by the a-Si layer due to the existence of the non-zero built-in electric field. This experimental result was in line with the theory and simulations.

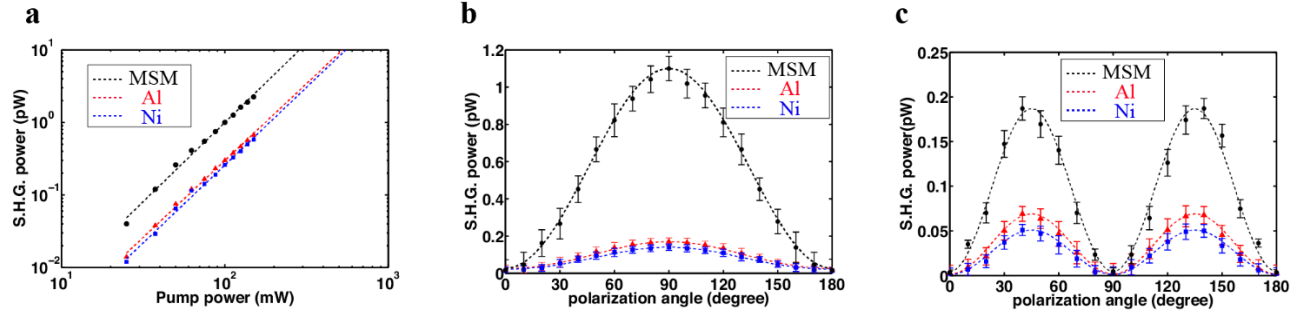


Fig. 29. (a) The log-log plot of measured SHG signal versus pump power for a single layer of Al (red triangles), Ni (blue squares) film and MSM metamaterial (black circles) grown on silica substrates for a fixed pump-beam incident angle of 45° . (b) The generated p-polarized and (c) s-polarized SHG intensity versus polarization angle for a 100 mW pump [Ref 9].

Additionally, the active control of the second-order nonlinear optical response of MSM metamaterials can also be achieved by applying an external electric field using the constituent metals as electrodes. To illustrate this, experiments were carried out on a MSM metamaterial sample fabricated with a thicker a-Si layer, the schematic of which is shown in Fig. 30(a). An external DC voltage is then applied across the a-Si layer, and the generated SHG signal is measured for a range of bias voltages, spanning both positive and negative voltages. The minimum and maximum values of the measured SHG intensity are then used to determine that a wide tunable range of 2.8 to 15.6 pm/V is achievable for the effective $\chi_{zzz}^{(2)}$ tensor in this MSM metamaterial which makes it suitable for on-chip optical switching and modulation [9].

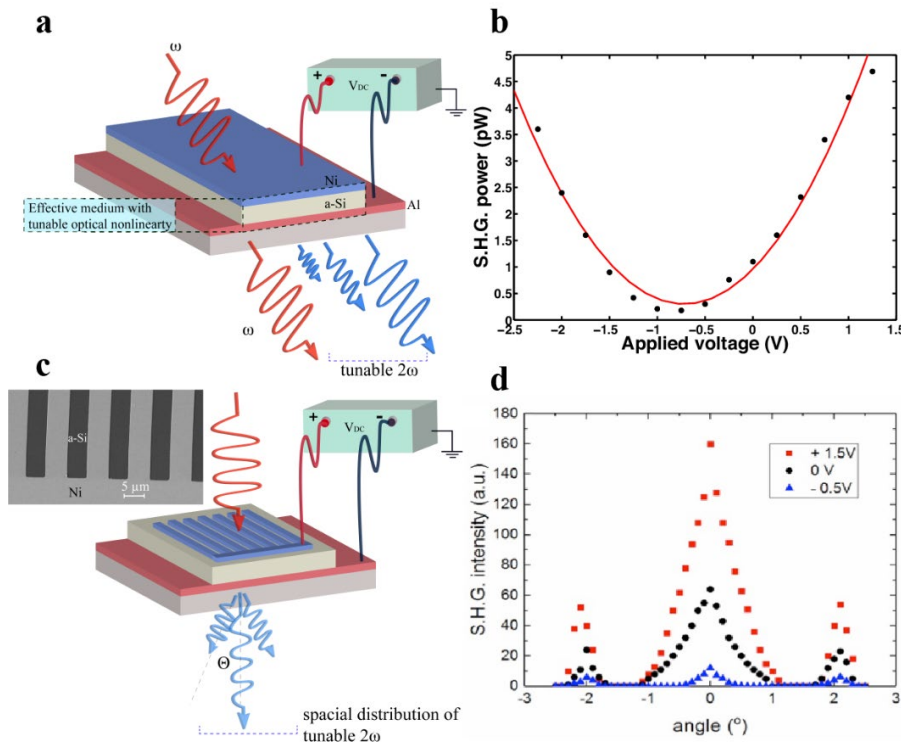


Fig. 30. (a) Schematic of an active MSM metamaterial. (b) Measured SHG intensity under variant DC voltage (dots), and the red fitting curve showing the quadratic dependency. (c) Schematic representing the design for creating spatial nonlinear responses, and the top-view SEM image of the fabricated metal grating. (d) The SHG intensity from the patterned MSM structure detected under different angles and external electrical biases [Ref 9].

B3.2 Second-order nonlinearity in silicon-rich nitride thin films

Another promising material for in-waveguide applications on-chip is non-stoichiometric silicon-rich nitride (SRN) films. Although bulk nonlinearities in silicon nitride films are not as pronounced, changing the stoichiometry of the compound by increasing the silicon content can lead to an enhancement of $\chi^{(2)}$. We explored this in a recent study by comparing the SHG signal for three different SRN thin-film samples – S1, S2 and S3 - where the quantity of silicon was varied from 41-56 % (S1 – S3) [10]. As can be seen in Fig. 31(b), measuring the SHG signal as a function of the pump polarization angle at 800 nm reveals that the silicon content is directly proportional to the strength of the SHG signal from the sample.

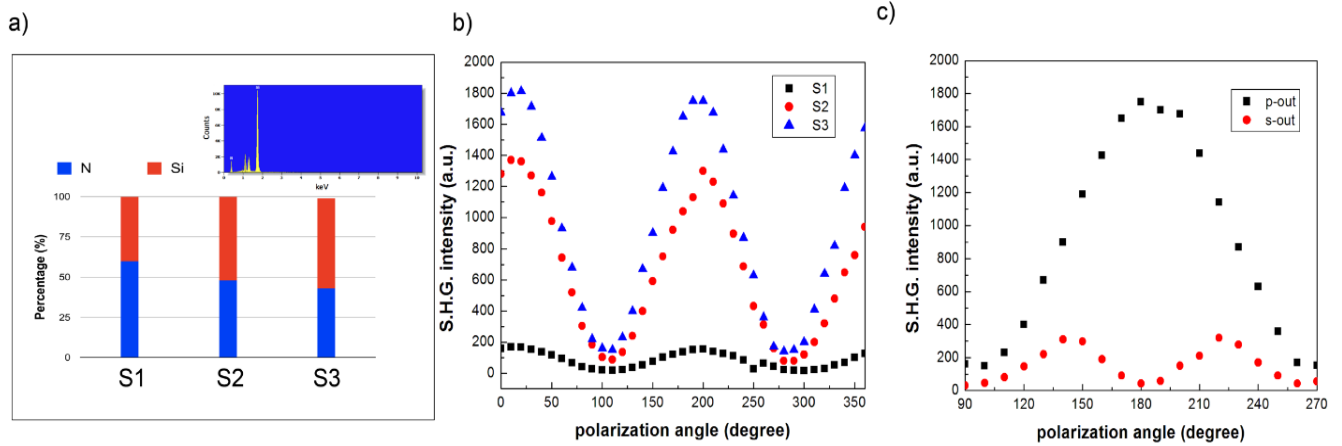


Fig. 31. (a) Composition of the samples, S1, S2 and S3, extracted using EDX spectroscopy, inset figure shows the EDX data as obtained for the SRN samples, S3. (b) Second-harmonic signal generated from the three-films as a function of polarization angle for p- polarization. (c) SHG signals from the SRN film (S₃) for both s- and p-polarized input pumps [Ref 5].

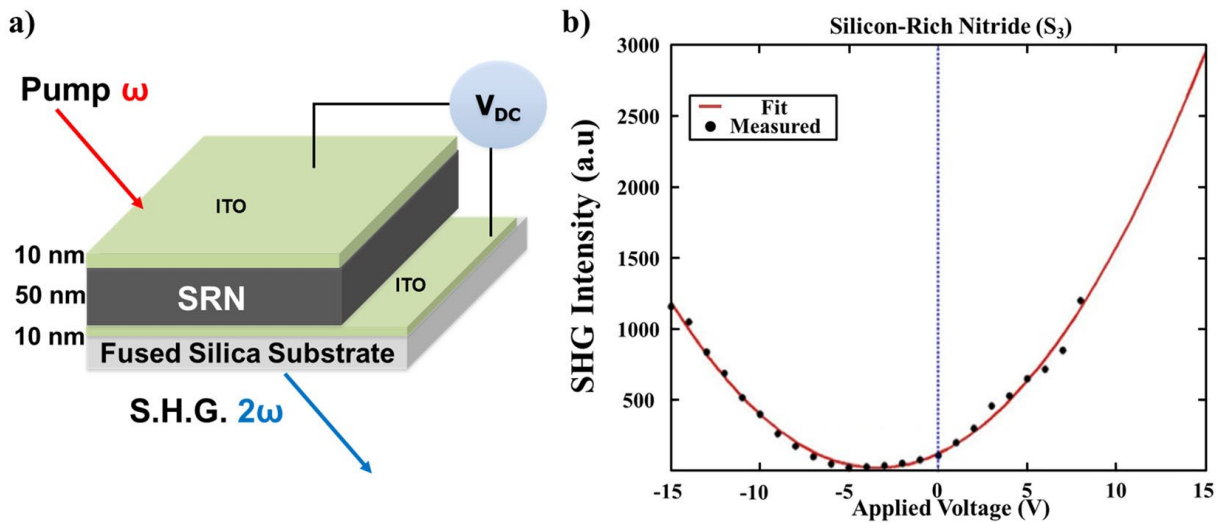


Fig. 32. (a) Schematic illustration of the SHG response from a 50nm silicon nitride film sandwiched between two 10nm ITO films on a fused silica substrate. (b) Experimental (black dots) and quadratic fitting (red) curve showing the SHG response from a SRN sample as a function of the external voltage applied across the layer [Ref 10].

In addition to increasing the silicon content, the nonlinear response of these SRN thin films can also be enhanced via the electric-field induced second-harmonic (EFISH) effect. In essence, an external electric field can interact with the third-order nonlinearity of the thin films, resulting in a higher effective second-order response and therefore, a resulting increase in the overall SHG intensity from the waveguides. To analyze the tunability of the nonlinear response in SRN films, ITO electrodes on a fused silica substrate (shown in Fig. 32(a)) were used to sandwich the silicon nitride films. As the voltage across the electrodes was swept, The SRN film demonstrated a wide range of effective $\chi^{(2)}$ from $\sim 3\text{pm/V}$ to as high as 22pm/V as illustrated in Fig. 32(b). This wide tunability range demonstrates the promising potential of devices based on SRN films since they may be used for switching and/or modulation.

Another additional degree of control over the nonlinear response of SRN films arises from the inherent dispersive nature of the as-deposited films. This was made evident by measuring the SHG intensity for the samples mentioned earlier – S1, S2 and S3 – with two different pump wavelengths of 1064 nm and 1550 nm. The setup and results, depicted in Fig. 33, show a reduction of ~ 5 times in the effective $\chi^{(2)}$ as the pump wavelength is increased from 1040 nm to 1550 nm.

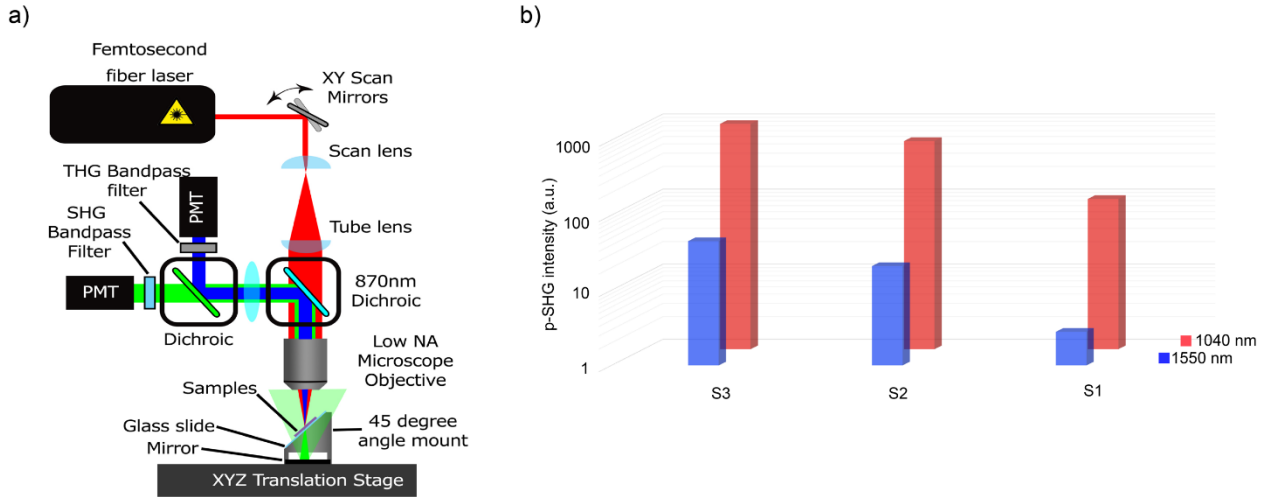


Fig. 33. (a) Schematic of the reflective second-harmonic generation setup. (b) The generated reflective p-polarized SHG signals from the three samples, corresponding to pump wavelengths of 1040 nm (red bars) and 1550 nm (blue bars), respectively [Ref 10].

Appendix C1. Noise properties of nanolasers

Before using multiple cross-coupled nanolasers for integration into on-chip computing networks, it is imperative to understand in-depth the noise properties of a single such device. Noise attributes of a high-speed nanolaser are essential to on-chip communication. However, the noise characterization in nanolasers remains a challenge because of their low power emission, which is on the order of pico- to micro-watts [2,11]. The low emission power in nanolasers precludes the use of well-established noise measurement techniques, requiring a noise probing technique suited for nanoscale emitters.

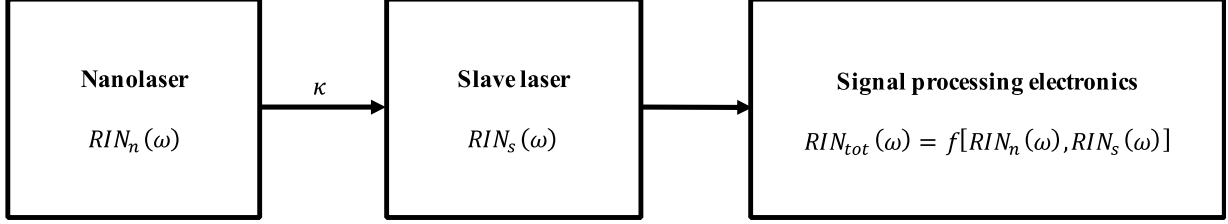


Fig. 34. The block diagram of an optical injection scheme. RIN: the intrinsic relative intensity noise; κ : the injection strength; $f[\cdot]$: an arbitrary function that is under investigation.

We realized that the intensity noise of a nanolaser can be extracted in an injection locking scheme [12]. The scheme shown in Fig. 34 is based on optical injection of emission from a nanolaser, serving as a master oscillator, transferring its intensity fluctuations to a low-noise semiconductor laser serving as a slave oscillator. The inheritance of noise characteristics is utilized to estimate the relative intensity noise (RIN) of a nanolaser. To better understand the photon-carrier dynamics of the coupled oscillators, small signal analysis is used to analyze the corresponding stochastic rate equations. We demonstrated with our assumptions that the total RIN of the coupled laser oscillators is a weighted superposition of the RIN of individual lasers,

$$RIN_{tot}(\omega) = H_f(\omega)RIN_n(\omega) + RIN_s(\omega).$$

Here, H_f is the filtering function, RIN_n is the intrinsic RIN of the isolated nanolaser, and RIN_s is the intrinsic RIN of the semiconductor laser. Additionally, numerical studies were carried out with laser parameters shown in Table 1 below.

Table 1

	Symbols	Nanolaser	Slave laser [12]	unit
Modal confinement factor	Γ	0.6	0.4	-
Photon lifetime	τ_p	2.88	3	ps
Radiative carrier lifetime	τ_r	1	1	ns
Nonradiative carrier lifetime	τ_{nr}	1	1	ns
Round-trip time	τ_{rt}	-	8.63	ps
Differential gain coefficient	g_0	4.29×10^{-6}	2.14×10^{-6}	cm^3/s
Lasing wavelength	λ	1550	1550	nm
Carrier density at transparency	N_0	2×10^{18}	1×10^{18}	$1/\text{cm}^3$
Modal volume	V_p	9.82×10^{-14}	3.75×10^{-10}	cm^3
Volume of the active region	V	5.89×10^{-14}	1.50×10^{-10}	cm^3
Spontaneous emission factor	β	0.2	3×10^{-5}	-
Purcell factor	F	67.22	1	-

As shown in Fig. 35, when the injection strength κ is changed from 1% to 25%, the total RIN increases by modifying the intrinsic RIN of the slave laser. This observation supports that one can extract the nanolaser's RIN directly from the total RIN, given that the injection strength κ is appropriately chosen. The disadvantage incurred in this process is that the additional poles due to the cascaded laser cavities are retained in the total RIN. Such approach limits the degree to which the nanolaser's RIN can be directly estimated with the total RIN consisting of a -40 dB/Hz per decade roll-off. Moreover, mutual correlation is used as a mathematical tool to quantify the degree of resemblance between the injected and extracted intensity fluctuations. As shown in Fig. 36, we theoretically confirm that the nanolaser's RIN and the system RIN are at least 97% correlated within the 3-dB bandwidth at an injection strength of 25%.

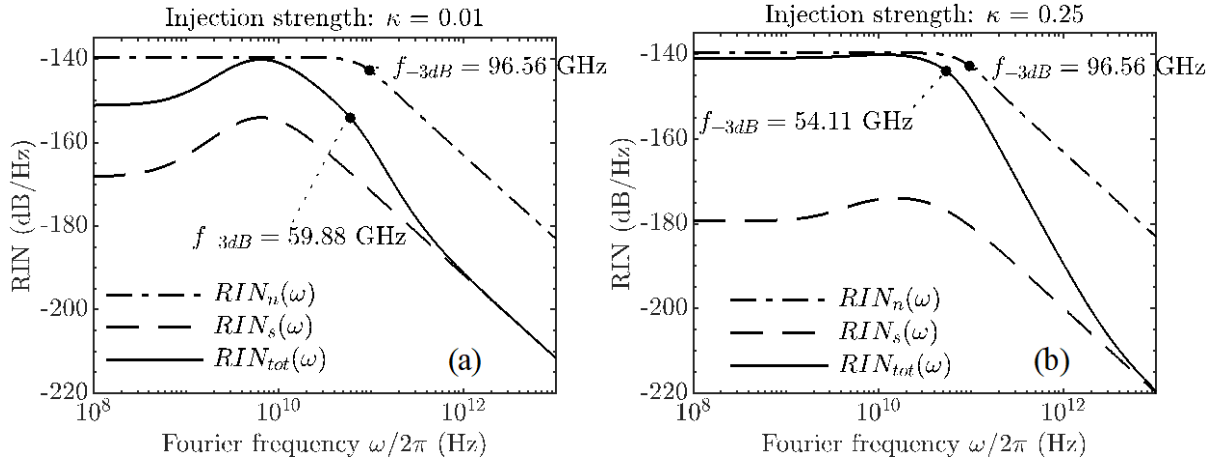


Fig. 35. Total RIN at two selected injection strength (a) $\kappa = 0.01$ and (b) $\kappa = 0.25$. The master and the slave are pumped at thrice and twice of their respective threshold levels. In determining the threshold of the nanolaser, the carrier density is first calculated as a function of pump rate.

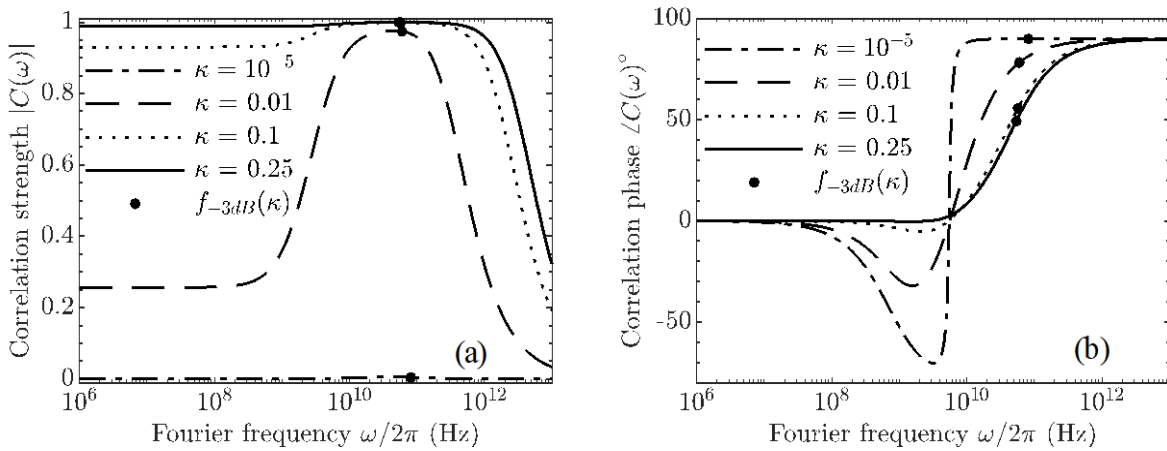


Fig. 36. (a) Correlation strength and (b) phase of the complex mutual correlation function. The 3-dB points correspond to the 3-dB bandwidth of the total RIN spectra. The pump levels are identical to that of Fig. 2.

Appendix C2. Linewidth broadening in nanolasers due to fundamental thermal fluctuations

The capability of nanolasers to generate coherent light in ultra-small volume have established them as attractive light sources for future ultra-dense on-chip integration. However, nanolasers also exhibit broad linewidths, that are usually on the order of 1nm. Therefore, before engineering nanolasers to be employed in applications where narrow linewidth is desired, evaluating the linewidth broadening effect inside nanolasers is of great importance. While it is a known fact that the broad spectral linewidths are generated by the noises inside nanolasers, in this work, we specifically study the impact of fundamental thermal fluctuations (FTF) on a nanolaser's spectral linewidth [13]. FTF is an intrinsic thermodynamic noise and is expected to be more pronounced inside nanocavities. The variance of such fundamental temperature fluctuation ΔT is inversely proportional to the optical mode volume V , which is shown as:

$$\langle \Delta T^2 \rangle = \frac{k_B T^2}{\rho c V} \quad (1)$$

In semiconductor lasers, the temperature fluctuation perturbs the refractive index of the resonator through the thermo-refractive effect, and hence causes the resonance frequency to fluctuate around its mean. Consequently, it imposes a limitation on the frequency stability of the nanolasers. As we can see from (1), the temperature fluctuations ΔT are more pronounced with increasing ambient temperature and decreasing mode volume. Therefore, in this work, we numerically investigate the effect of mode volume and ambient temperature on the linewidth broadening of nanolasers due to FTF. In this work, ΔT is obtained by solving the stochastic heat transport equation. This equation includes a Langevin noise source $F(\vec{r}, t)$ to account for the randomness of the thermal fluctuations, and is expressed as:

$$\frac{\partial \Delta T(\vec{r}, t)}{\partial t} - D_T \nabla_{\vec{r}}^2 \Delta T(\vec{r}, t) = F(\vec{r}, t) \quad (2)$$

A rigorous analysis in spectral domain is conducted. Frequency noise $S_f(w)$ and linewidth broadening are evaluated by using the following formulas:

$$S_f(w) = \frac{4Ak_B T^2}{\rho c V} \int_V \int_V \left(-\frac{2\pi v_0}{n} \frac{dn}{dT} \right)^2 \text{Re}[G(r, r'; iw)] |E(r)|^2 |E(r')|^2 r r' dr dr' \quad (3)$$

$$S_{\Delta v}(\Delta v) = I_0 \int_{-\infty}^{\infty} \exp(j2\pi \Delta v \tau) \exp \left(-\frac{\tau^2}{2\pi} \int_0^{+\infty} S_f(w) \frac{\sin^2 \left(\frac{w\tau}{2} \right)}{(w\tau/2)^2} dw \right) d\tau \quad (4)$$

where $G(r, r'; iw)$ is the Green's function solutions of Eq. (2), $E(r)$ is the electric field solution of the eigenmode, ν_0 is the center frequency, A is the area of the cross-section of gain medium, T is the ambient temperature, k_B is Boltzmann constant, ρ is the density, c is the specific heat capacity. To elucidate the impact of the optical mode volume on the linewidth broadening effect, we studied and compared two devices, that are N-250 and N-750. Their geometry parameters are given in Table. 2.

TABLE 2
DIMENSION PARAMETERS OF THE NANOLASERS FOR CALCULATION

Parameter (unit)	N-250	N-750
R_1 (nm)	250	750
R_2 (nm)	350	900
H (nm)	300	300

First, in Fig. 37(a), we present the power spectral density (PSD) of the frequency noise $S_f(f)$ of N-250 under ambient temperature 300K, 77K and 4K. The frequency noise $S_f(f)$ spectra behave as a low-pass filter with a 3-dB bandwidth of ~ 6.1 MHz. As we can see, a higher frequency noise is generated due to FTF at higher ambient temperatures. We then present the single-sided PSD of the frequency shift $S_{\Delta\nu}(\Delta\nu)$ in Fig. 37(b). The linewidth can be read out as twice of the 3-dB bandwidth value. For N-250, the linewidth broadening caused by FTF are estimated to be 1.14nm, 0.31nm and 5.4nm at 300K, 77K and 4K, respectively. As we can see for N-250, due to the ultra-small optical cavity, FTF imposes a large limitation on the resonance stability via the thermo-refractive effect and induces a pronounced spectral linewidth under room temperature.

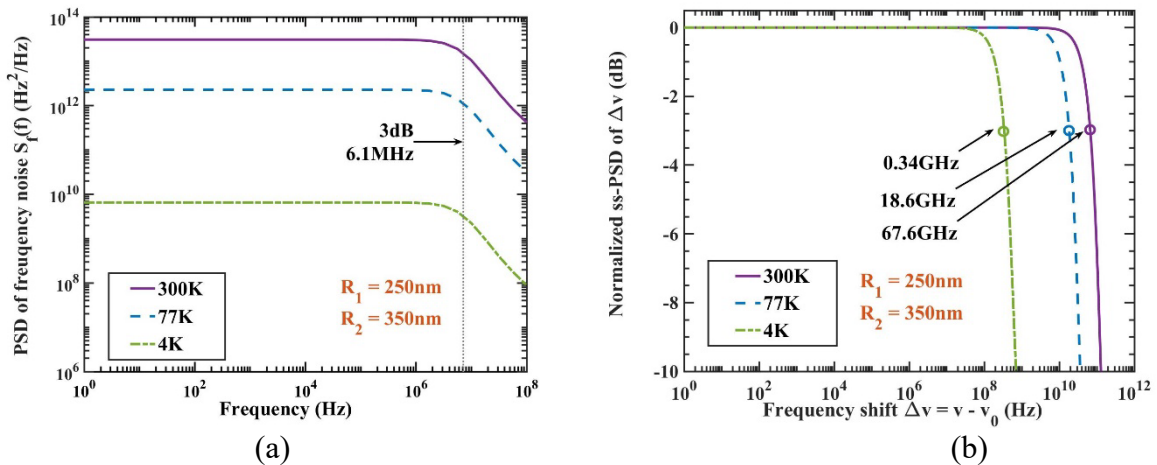


Fig. 37. (a) PSD of the frequency noise $S_f(f)$ due to FTF at different ambient temperatures 300K (purple solid line), 77K (blue dashed line), and 4K (green dash-dotted line) in N-250. The grey vertical dotted lines are the 3-dB cut-off frequency. (b) The normalized single-sided PSD $S_{\Delta\nu}(\Delta\nu)$ of the frequency shift to the central frequency $\Delta\nu = \nu - \nu_0$ (Hz) due to FTF under different ambient temperatures 300K,

77K, and 4K for N-250. The 3-dB are 67.6GHz, 18.6GHz, and 0.34GHz, that correspond to linewidth broadenings of 1.14nm, 0.31nm, and 5.4pm under 300K, 77K, and 4K, respectively [Ref 13].

To elucidate the impact of the decreasing mode volume, we investigate and compare the frequency noise and linewidth broadening in a larger cavity N-750 at the same ambient temperatures. Similarly, we can read out the linewidth for N-750 as twice of the 3-dB bandwidth of $S_{\Delta\nu}(\Delta\nu)$, as shown in Fig. 38. We have the spectral linewidth due to FTF as 0.16nm, 0.04nm and 2pm at ambient temperatures of 300K, 77K, and 4K, respectively. By comparing the values of N-250 and N-750 at same temperature, significantly larger linewidth broadening is observed in N-250. This corroborates that nanoscale optical cavities are more prone to FTF than lasers with larger mode volumes, and thus exhibit broader linewidths due to the parasitic frequency noise.

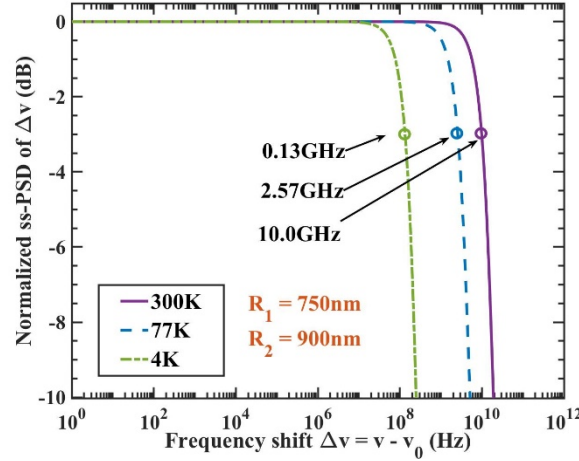


Fig. 38. The normalized single-sided PSD $S_{\Delta\nu}(\Delta\nu)$ of the frequency shift to the central frequency $\Delta\nu = \nu - \nu_0$ (Hz) due to FTF under different ambient temperatures 300K, 77K, and 4K for N-750. The 3-dB are 10.0GHz, 2.57GHz, and 0.13GHz, that correspond to linewidth broadenings of 0.16nm, 0.04nm, and 2pm under 300K, 77K, and 4K, respectively [Ref 13].

Other than nanolaser's dimension, the ambient temperature is also a crucial factor in determining the finite linewidth generated by FTF. Figure 39 shows the trend of the linewidth broadening with increasing temperature for N-250 and N-750. An almost linear relation between linewidth broadening caused by FTF and ambient temperature can be seen for both N-250 and N-750. For the purpose of practical implementation, the fitting curves shown in Fig. 39 provide a good estimation for the finite linewidths generated due to FTF at any other temperature. This work was published in [13].

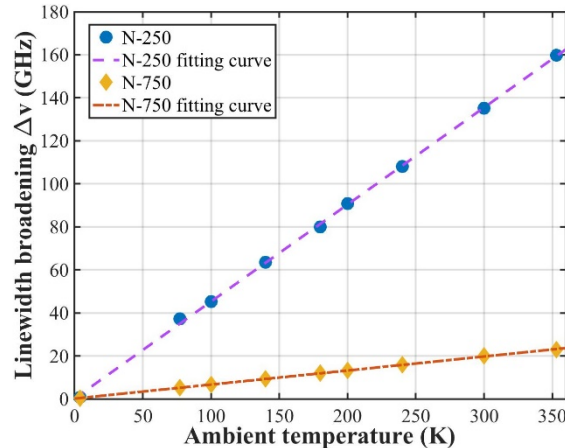


Fig. 39. Linewidth broadening of N-250 and N-750 caused by FTF at ambient temperatures of 4K, 77K, 100K, 140K, 180K, 200K, 240K, 300K, and 353K.

Appendix C3. Development of low-resistance nanolasers based on tunnel junctions

The challenges in construction of nanolasers lie in co-design of optical cavity and electrical injection. Most of the reported studies on nanolaser structure designs use optical pumping. However, it is evident that electrical pumping is an essential step to make nanolasers useful for practical applications. We have in the past developed metallo-dielectric nanolasers [14,15] where current injection through contacts to heavily p- and n-doped InP and InGaAsP layers. However, their small physical dimensions and critical requirements for achieving low resistance p++ contacts still make current injection a major challenge. In turn, these issues lead to prohibitively high threshold voltage and current density, ultimately. Joule heating setting a barrier for the development of more efficient nanolasers. To address this issue, we experimentally demonstrate lasing action in electrically pumped metallo-dielectric nanolasers featuring heavily doped tunnel junctions for current injection [16]

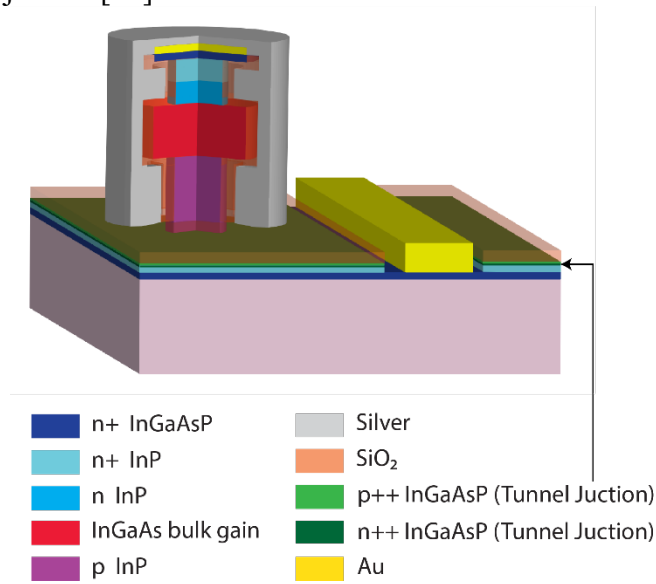


Fig. 40. Schematic of tunnel junction incorporated nanolaser (the position of the tunnel junction is indicated by the arrow).

The schematic diagram of the nanolaser is shown in Fig. 40. The nanolaser is based on an InP/InGaAs/InP double heterostructure grown on an InP wafer. The epitaxial heterostructures are grown by molecular beam epitaxy (MBE). The gain material is a 320nm thick intrinsic bulk InGaAs layer lattice matched to InP. The top and bottom layers where the metal ohmic contacts are deposited are n-InGaAsP. The tunnel junction, which consists of heavily doped 20nm p-InGaAsP (dopant: Be) and 12nm n-InGaAsP (dopant: Si) lies beneath the p-InP layer. The tunnel junction doping concentrations for p-InGaAsP and n-InGaAsP are $4 \times 10^{19} \text{ cm}^{-3}$ and $4.7 \times 10^{19} \text{ cm}^{-3}$, respectively. InP layers between gain and InGaAsP layers serving as electron and hole transport layers are under-cut to achieve better vertical mode confinement.

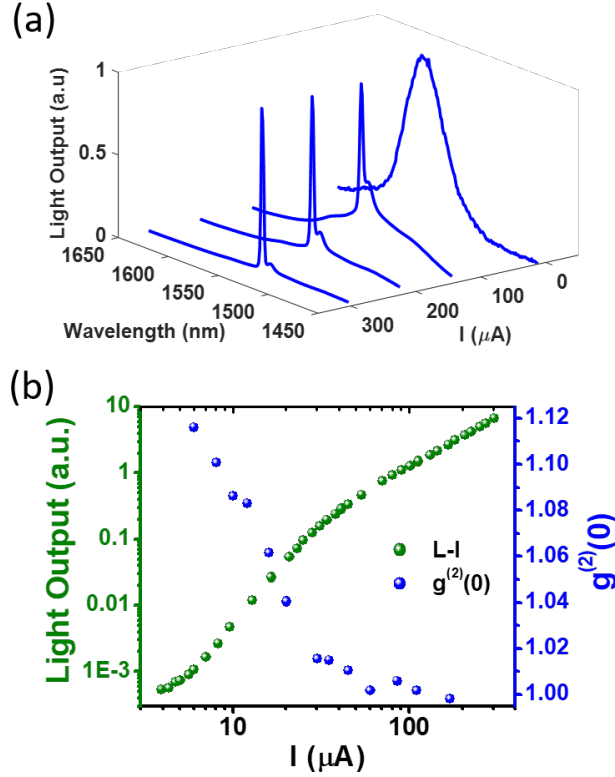


Fig. 41. (a) Normalized emission spectral evolution of the nanolaser with increasing inject current at 77 K. (b) (Green) The Light-current curve of the nanolaser. (Blue) The evolution of the nanolaser's second-order coherence function at zero delay $g^{(2)}(\tau=0)$.

Fig. 41(a) shows the normalized emission spectrum of a nanolaser (radius of 0.95 μm) at an ambient temperature of 77 K with respect to different CW pumping current. Broadband spontaneous emission can be observed when the injection current is less than 5 μA . As the injection current increases beyond 20 μA , spectra narrowing can be observed. Above threshold, the lasing peak is located around 1540 nm which is within the telecommunication wavelength regime.

To further validate lasing action, we conducted the light output versus injection current (L - I) characterization and measured the second-order coherence function $g^{(2)}(\tau) = \langle I(t)I(t+\tau) \rangle / \langle I(t) \rangle^2$ with a Hanbury Brown-Twiss (HBT) interferometer [1]. The measurement results are presented in Fig. 42(b). The solid green dots show the L - I curve in log-log scale. The threshold current I_{th} , defined by the inflection point of the kink in the L - I curve, is approximately 20 μA . Furthermore, the second-order coherence function at zero delay, $g^{(2)}(\tau=0)$, at various pump current is represented in Fig. 42(b) by the blue dots. At pump current less than 20 μA , the measured $g^{(2)}(\tau=0)$ value is greater than 1, indicating that the device emission is incoherent. As the pump current increases toward 20 μA , $g^{(2)}(\tau=0)$ monotonically decreases correspondingly, signifying that the emission becomes more and more coherent. At pump current above 20 μA , $g^{(2)}(\tau=0)$ fluctuates around unity, suggesting that the emission is coherent and therefore, the device is operating in the lasing regime. Hence, the threshold current is also approximately 20 μA according to our $g^{(2)}(\tau)$ measurement results. Therefore, the $g^{(2)}(\tau=0)$ and L - I -curve measurements are fully consistent with each other, which unambiguously confirms the lasing characteristics of our device [17].

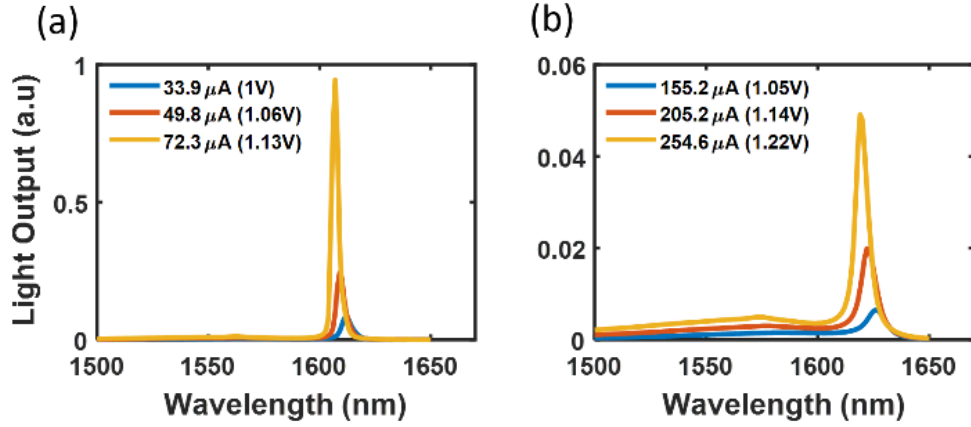


Fig. 42. Emission spectrum of nanolaser ($r=0.7 \mu\text{m}$) with different applied voltage and current at (a) 77 K, (b) 180 K.

To further demonstrate that tunnel junction is capable of making nanolasers operational at higher temperature, we studied another nanolaser with a radius of $0.7 \mu\text{m}$ and a pillar height of $1.6 \mu\text{m}$ and a total device volume of $\sim 0.59 \lambda^3$. The spectra, L - I curve and linewidth evolution are shown in Fig. 42. Here Fig. 42(a) shows the emission spectrum at an ambient temperature of 77 K. The lasing peak is located at 1605 nm and its linewidth is getting narrower as the current pumping increases. The temperature is then raised to 180 K (Fig 42(b)). The linewidth narrowing is also observed at higher current with applied voltage less than 1.2 V. The emission peak is located at 1610 nm which means there is no mode hopping as the temperature increases. This work was published in [16].

Appendix D1. Wavelength Tunability and Intensity Modulation of a Metallo-dielectric Nanolaser

In this work, we report on simultaneously tuning the emission wavelength as well as altering the intensity of output light from a metallo-dielectric nanolaser. The mechanism is based on applying an external electric field to the nanolaser device which induces modifications in both the overlap of the electron and hole wavefunctions as well as the bound state energies via the quantum-confined Stark effect (QCSE).

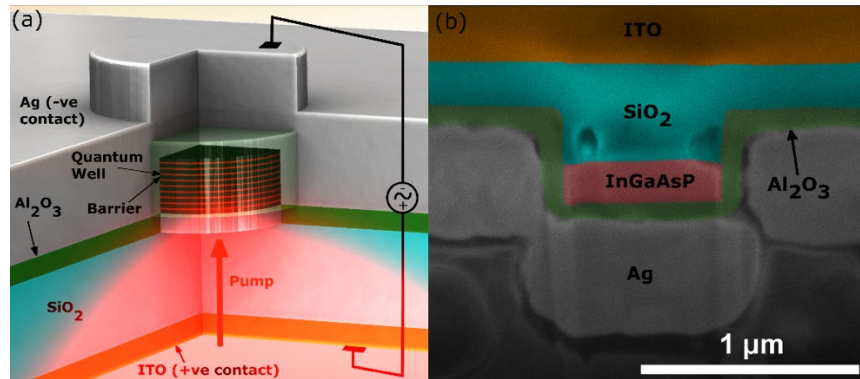


Fig. 43: (a) Device schematic of the metallo-dielectric nanolaser with constituent materials labelled. The gain comprises 10 nm thick InGaAsP quantum wells (shown in red) and 20 nm thick barriers (shown in black). The device is pumped from the bottom and emits in the same direction (shown via the red beam). The ITO thin film and Ag cladding serve as the bottom and top electrodes respectively, across which voltage is applied to the device (b) FIB cross-section image of a representative device with false color and constituent materials labelled.

The design and fabrication of the metallo-dielectric nanocavity used in this study builds onto the device first reported by Nezhad *et al.* [18] with modifications to enable external E-field to be applied to the device. Firstly, the gain in this work comprises of 300 nm of InGaAsP multiple quantum wells (MQWs) with wells and barriers of 10 and 20 nm thickness, respectively. Secondly, Al₂O₃ serves as the dielectric shield for the devices presented here instead of SiO₂ owing to better thermal properties of the former [14]. In order to apply an electric field to tune/modulate the emission of the cavity, two additional fabrication steps were added as depicted in the device schematic in Fig. 43(a). A layer of SiO₂ (~500 nm) was deposited to function as the insulator and then a thin film of ITO (~20 nm) was deposited on top of this dielectric layer and used as the bottom electrode. Although ITO is transparent at the NIR wavelengths of the nanolaser emission, it is still optically lossy and therefore, the film was chosen to be as thin as possible. Fig. 43(b) is an FIB cross-section image post-completion of all fabrication steps depicting a representative device with a gain radius of 455 nm.

D1.1 Wavelength Tuning

In order to tune the nanolaser wavelength in real-time, an external electric field was applied perpendicular to the MQWs. A Cu substrate connected to the Ag-metal cladding was chosen as one electrode while the thin film of ITO functioned as the other. A voltage source (Keithley 2400) was then used to apply the voltage across the device while it was optically pumped at an input optical intensity of $\sim 2 \cdot P_{th}$, where P_{th} denotes the device's lasing threshold intensity. The emitted output spectra of the nanolaser were subsequently recorded with a high-resolution monochromator. Fig. 44(a) illustrates the results of applying varying amounts of DC voltage on a typical nanolaser device shown in Fig. 43(a) and (b). To provide better intuition, values of the electric field are reported as voltage instead. From Fig. 44(a), it can be observed that with increasing voltage, the nanolaser spectra are affected in two clear ways. First, the output intensity of the emitted light decreases monotonically till the emission is nearly suppressed at the highest values of the applied voltage. Secondly, the emission wavelength of the device redshifts, also monotonically, with increased voltage.

To better quantify these effects induced by the E-field, the nanolaser's peak output intensity, P , for each applied voltage is plotted in Fig. 44(b) as a percentage of the peak intensity, P_0 , in the absence of the E-field/voltage. An almost linear drop in the peak output intensity can be observed with the attenuation in intensity as high as ~89% at the highest electric field/voltage value. Similarly, the alteration of the peak wavelength, $\Delta\lambda$, plotted on the right axis of Fig. 44(b) is also significant and exhibits a redshift of around 8.35 nm with increased voltage. Redshifts in peak wavelength smaller than 150 pm can be achieved with only slight increments in the applied voltage (~0.65 V). This fine control also extends to the output intensity which can be attenuated by lower than ~2% as the voltage is varied. Such nuanced tuning of the emission along with the dynamical nature of the alterations themselves can prove to be invaluable if nanolasers are to be used for on-chip applications [19].

D1.2 Intensity Modulation

For practical applications, high-speed modulation of nanolasers is desirable and in some cases such as for communication purposes, even imperative. To demonstrate the high-speed modulation capability of our devices under an external E-field, a small-signal modulation experiment was carried out where the device was pumped optically while an AC electric field was applied across the device's contacts. The output emission from the nanolaser was collected using a low-noise, high-gain APD (Thorlabs APD430C) which was then connected to an electrical spectrum analyzer

(ESA, Keysight N9181A). If the device emission follows the AC signal of the voltage source, a peak would be registered in the ESA at the exact frequency of the AC input signal applied to the device via a function generator. Fig. 44(c) illustrates the result of applying a 400 MHz sinusoidal AC voltage to the nanolaser which registers a clear AC signal amplitude on the ESA at the exact frequency of the applied input signal. This confirms that our nanolaser can be modulated at a high speed of up to 400 MHz under external E-field modulation.

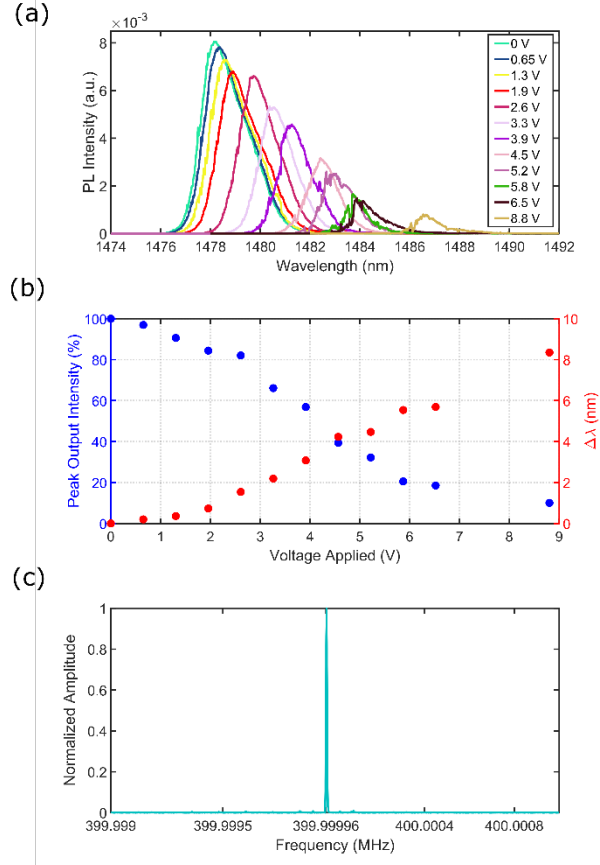


Fig. 44: (a) Real-time dynamic tuning of lasing wavelength by applying DC electric field/voltage across the device while pumping with an optical pulsed pump. (b) Peak output intensity percentage (blue) and change in peak wavelength - $\Delta\lambda$ (red) – plotted as a function of the voltage applied to the device. The intensity is attenuated by $\sim 89\%$ and the wavelength is red shifted by ~ 8.35 nm when about 8.8 V is applied across the device. (c) 400 MHz modulation of the output intensity of the device as measured by a high-speed APD connected to an electrical spectrum analyzer. The span of the window is 2 kHz and the voltage applied is ~ 6.5 V.

Theoretically, emission alterations of nanolasers based on electronic effects can reach high speeds up to even the THz regime [20]. In practice, however, further demonstrations at higher modulation speeds were impeded by the response of the APD used in this study, which had a 3-dB bandwidth of 400 MHz. Nevertheless, as a proof-of-concept demonstration, the modulation speed at 400 MHz indicates that our modulation mechanism is due to electronic instead of thermal effects, the latter of which would have limited the upper modulation speed to the few megahertz regime [21]. Future efforts to attain high speeds in the gigahertz regime and beyond would involve altering the electrode design in order to minimize noise and realize planarized contacts more appropriate for handling high-speed signals. The manuscript based on the results presented in this section has been published in [22].

Appendix D2. Optical Nonlinearities for Switching

D2.1 Effective Second Order Nonlinearities – The DC-Induced Pockels effect

In continuation of our work exploring novel platforms for energy efficiency, low-cost optical switching we have focused our efforts expanding upon our work on the DC-Induced Pockels effect. Previously we have demonstrated the electric field induced second harmonic effect (EFISH) [10] for developing effective second order nonlinearities in second harmonic generation in a thin film silicon rich nitride platform. We then showed initial results using the DC-Induced Pockels effect for developing effective second order nonlinearities for in-waveguide switching. In continuation of this on-going work we continue to fully explore silicon-rich nitride as a platform for optical switching using effective second order nonlinearities through the DC-Induced Pockels effect.

As previously, it is helpful to begin from an expansion of the polarizability. Shown below in equation 2.1 is an expansion of the nonlinear portion of the polarizability including up to the third order terms.

$$\begin{array}{c} \bar{P}_{NL} \\ = \epsilon_0 \{ \underbrace{\chi^{(2)} [2EE^* + E_{dc}^2]}_{\text{Kerr effect and DC-Induced Pockels}} + \underbrace{\chi^{(2)} [2E_{dc}Ee^{-j\omega t} + 2E_{dc}E^*e^{j\omega t}]}_{\text{Pockels}} + \underbrace{\chi^{(2)} [E^2e^{-j2\omega t} + E^{*2}e^{j2\omega t}]}_{\text{SHG}} + \underbrace{\chi^{(3)} [E_{dc}^3 + 6EE^*E_{dc}]}_{\text{THG}} \\ + \underbrace{\chi^{(3)} [(3E_{dc}^2E + 3E^2E^*)e^{-j\omega t} + (3E_{dc}^2E^* + 3EE^{*2})e^{j\omega t}]}_{\text{Kerr effect and DC-Induced Pockels}} + \underbrace{\chi^{(3)} [3E_{dc}E^2e^{-j2\omega t} + 3E_{dc}E^{*2}e^{j2\omega t}]}_{\text{EFISH}} + \underbrace{\chi^{(3)} [E^3e^{-j3\omega t} + E^{*3}e^{j3\omega t}]}_{\text{THG}} \} \end{array}$$

Equation 2.1: An expansion of the nonlinear portion of the polarizability out to the third order contributions. Take special note of how the EFISH term is a third order nonlinearity but contributions to the second harmonic term and compare this to the similar between the Kerr and DC-Induced Pockels effect and the Pockels Effect.

If we take the DC-Induced Pockels terms and relate them to an effective linear susceptibility we can derive equation 2.2(a) below for the change in refractive index (Δn_i) based on an applied electric field. It is important to note that for silicon-rich nitride's material class only certain tensor components can be non-zero. Therefore, to uniquely attribute our experiment to the two contributing tensor components separately we will impose some field and symmetry conditions based on our electrode design in order to simplify equation 2.2(a) into equation 2.2(b)

$$(a) : \Delta n_i = \frac{3 \Gamma_{SRN}}{2} \sum_{j,k,l} \frac{\chi_{ijkl}^{(3)}}{n_{i,eq}} E_j^{dc} E_k^{dc} \quad (b) : \Delta n_i = \frac{3 \Gamma_{SRN}}{2} \sum_{l,j} \frac{\chi_{ijji}^{(3)}}{n_{i,eq}} E_j^{dc^2}$$

Equation 2.2: (a) The generic form of the induced change in refractive index for an applied field with components along $\hat{j}$ and $\hat{k}$ based on the DC-Induced Pockels Effect. (b) Reduced form based on symmetry and imposed field conditions.

Our electrode design is very important for this study as we wish to be able to uniquely attribute our measurements to the two contributing tensor components separately. In order to properly model the applied field distribution, capacitance versus voltage and current versus voltage measurements were performed in order to determine the RF permittivity and breakdown field of our silicon-rich nitride thin films. From these measurements, shown below, we determined the RF permittivity to be 9.0578 and the breakdown field to be greater than 1.2E8 v/m post annealing.

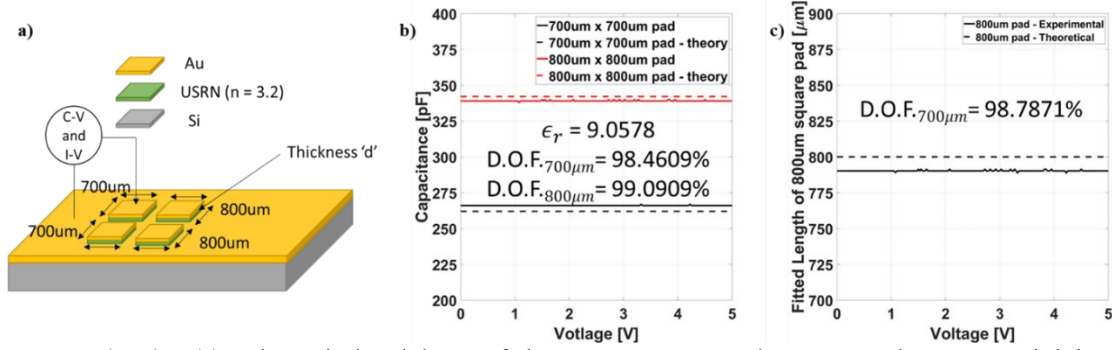


Fig. 45: (a) Schematic breakdown of the test structure used to extract the RF permittivity. Capacitance vs voltage measurements are performed using an Agilent B1500A semiconductor device analyzer. Thickness 'd' = 150nm. (b) Capacitance [pF] vs Voltage [V] at 100 kHz along with a fitting for the relative permittivity showing a value of 9.0578. (c) Confirmation of the fitting where the effective length [μm] of one pad is extracted based on fitting the other pad for its relative permittivity. As can be seen the fitting is good using either method and show similar results.

Using this we designed the electrode configuration, shown below in Fig. 46(a)-(c), to maximize the difference between the in-plane and out-of-plane components of the applied field achieving a 3 order of magnitude difference. We then chose to utilize this electrode design in a racetrack ring resonator, placing 220um long electrodes in each of the two 250um long straight sections of the racetrack ring, see Fig. 46(a).

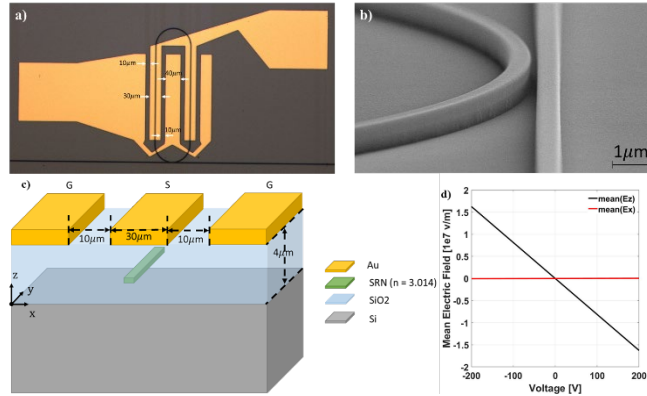


Fig. 46: (a) Optical microscope image of our point coupled micro-ring resonator with electrode width and spacing marked with white arrows and text overlay. (b) Scanning Electron Microscope image of the point coupler region. (c) Schematic breakdown of the phase shifter design shown as a cutout. (d) Plot of the mean value of the Applied Field E_x and E_z components versus voltage inside the waveguide core.

The design of our electrodes, and the decision to utilize a racetrack ring resonator allows us to uniquely attribute electro-optic measurements of the TE- and TM- polarized optical modes to the tensor components $\chi_{1331}^{(3)}$ and $\chi_{3333}^{(3)}$ respectively. This is the importance of the electrode design as these two tensors being the only two contributing non-zero tensors allows us to give a proper tensorial treatment of the DC-Induced Pockels effect using our measurements of these racetrack ring resonators operating in TE- and TM- modes.

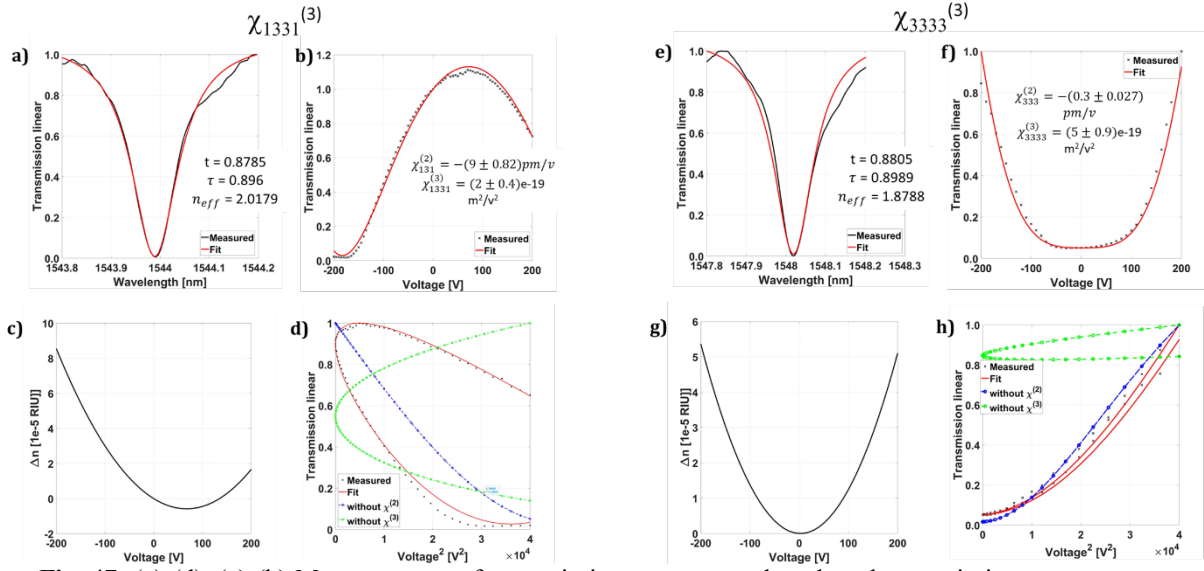


Fig. 47: (a)-(d), (e)-(h) Measurements of transmission versus wavelength and transmission versus applied voltage for the case of the TE- and TM- polarized optical modes respectively. (a) Plot of transmission versus wavelength for one resonance of TE- polarized optical mode fit for t , τ , and effective refractive index. (b) Plot of transmission versus applied voltage operating at a fixed wavelength of 1544.02 nm in the TE- polarized optical mode case normalized to the transmission at 0 volts applied and fit for $\chi_{131}^{(2)}$ and $\chi_{1331}^{(3)}$ as well as the overlap factor. (c) Plot of the extracted change in effective refractive index versus applied voltage for the TE case (d) Plot of transmission versus applied voltage squared at a fixed wavelength of 1544.02 nm in the TE- polarized optical mode case normalized to the maximum transmission. (e) Plot of transmission versus wavelength for one resonance of the TM- polarized optical mode fit for t , τ , and effective refractive index. (f) Plot of transmission versus applied voltage operating at a fixed wavelength of 1548.02 nm in the TM- polarized optical mode case normalized to the maximum transmission and fit for $\chi_{333}^{(2)}$ and $\chi_{3333}^{(3)}$ (g) Plot of change in effective refractive index versus applied voltage for the TM case extracted from (f). (h) Plot of transmission versus applied voltage squared at a fixed wavelength of 1548.02 nm in the TM- polarized optical mode case normalized to the maximum transmission.

For characterization, we use a combination of optical and electro-optic measurements to fully extract the material parameters of interest and in doing so demonstrate electro-optic switching based on the quadratic electro-optic effect. We use a fiber coupled input and a free-space output setup with a tunable Agilent 8164B CW source with a wavelength span of 1465nm to 1575nm [10]. Electrical probes are used to contact the electrode pads (see Fig. 46(a)) applying voltage from a Keithly SourceMeter 2400 with a maximum voltage range of ± 210 V with the sample placed on a thermally controlled stage. Note that although this range may seem large the actual field within the waveguide core is $1.6\text{E}7$ v/m at 200 volts, and that due to the electrode design, as discussed below, large voltages are needed to achieve these field strengths. Note, that more optimized electrode design will significantly reduce the required voltage to few volts.

Two measurements are performed in our experimental characterization: we first measure the passive transmission spectra of our racetrack resonators, followed by a second measurement of the transmission spectra as a function of the applied voltage at a fixed wavelength. These two measurements are repeated for TE- and TM- polarizations. Fig. 47(a) – (d) and Fig. 47(e) – (h) show the measured results for the TE- and TM- polarizations, respectively. We achieve a maximum extinction ratio of $\sim 16\text{dB}$ and $\sim 13\text{dB}$ for the TE and TM cases, respectively. In both cases, the transmission versus wavelength results are first fit to extract the self-coupling

coefficient, t , the single pass retention factor, τ , and the effective refractive index in accordance with [23, 24], the results of which can be seen in Fig. 47(a) and (e). These parameters are then used to fit for the $\chi^{(2)}$ and $\chi^{(3)}$ by fitting for the change in effective refractive index as a function of applied field utilizing Lumerical Mode Simulations to solve for the effective refractive as a function of change in material index, which is in turn derived from modelling of the applied field within the waveguide in Lumerical Device. The results of a best fit optimization can be seen in Fig. 47(b) and (f). Corresponding change in effective refractive index can be seen in Fig. 47(c) and (g).

In this work we present and discuss ongoing results of a low-loss PECVD silicon-rich nitride film with a refractive index of 3.0 or higher and use it to undertake a systematic evaluation of the DC-induced Pockels effect or electro-optic switching. Further optimization of the electrode design is needed to maximize field strength rather than linearity as shown here; however, electro-optic switching in silicon-rich nitride is a promising avenue of exploration for a low-cost energy efficient optical switch.

References

- [1] S. H. Pan, Q. Gu, A.E. Amili, F. Vallini, and Y. Fainman, "Dynamic hysteresis in a coherent high- β nanolaser." *Optica* 3, no. 11 (2016): 1260-1265.
- [2] M. Khajavikhan, A. Simic, M. Katz, J. H. Lee, B. Slutsky, A. Mizrahi, V. Lomakin, and Y. Fainman. "Thresholdless nanoscale coaxial lasers." *Nature* 482, no. 7384 (2012): 204-207.
- [3] P. Antonik, M.C. Wicks, H.D. Griffiths, and C.J. Baker. "Frequency diverse array radars." *In 2006 IEEE Conference on Radar*, pp. 3. IEEE, 2006.
- [4] S. Jiang. S.S. Deka, S.H. Pan, and Y. Fainman. "Effects of high- β on phase-locking stability and tunability in laterally coupled lasers", submitted.
- [5] T. Erneux and P. Glorieux, "Slow passage," in *Laser Dynamics* (Cambridge Univ. Press, 2010), pp. 155-171.
- [6] C. Y. Fang, F. Vallini, A. El Amili, J. S. T. Smalley and Y. Fainman, "Low Resistance Tunnel Junctions for Efficient Electrically Pumped Nanolasers," *IEEE Journal of Selected Topics in Quantum Electronics* 23(6), pp. 1-6 (2017).
- [7] S.H. Pan, S.S. Deka, A. El Amili, Q. Gu, and Y. Fainman, "Nanolasers: Second-order intensity correlation, direct modulation and electromagnetic isolation in array architectures," *Progress in Quantum Electronics* (2018).
- [8] S.S. Deka, S. H. Pan, Q. Gu, Y. Fainman, and A. El Amili, "Coupling in a dual metallo-dielectric nanolaser system," *Optics Letters* 42, 4760-4763 (2017).
- [9] H. Lin, F. Vallini, M. Yang, R. Sharma, M. W. Puckett, S. Montoya, C. D. Wurm, E. E. Fullerton, and Y. Fainman, "Electronic Metamaterials with Tunable Second-order Optical Nonlinearities," *Scientific Reports* 7(9983) (2017).

- [10] Lin, Hung-Hsi, Rajat Sharma, Alex Friedman, Benjamin M. Cromeey, Felipe Vallini, Matthew W. Puckett, Khanh Kieu, and Yeshaiahu Fainman. "On the observation of dispersion in tunable second-order nonlinearities of silicon-rich nitride thin films." *APL Photonics* 4, no. 3 (2019): 036101.
- [11] C.-Y. A. Ni and S. L. Chuang, "Theory of high-speed nanolasers and nanoleds," *Optics Express* 20, 16450–16470 (2012).
- [12] Z. Chen S. S. Deka, S. H. Pan, S. Jiang, C.-Y Fang, Y. Fainman, and A. El Amili, "Intensity Noise and Bandwidth Analysis of Nanolasers Via Optical Injection", *Optics Express* 27 pp. 8186-8194 (2019).
- [13] S. Jiang, S.H. Pan, S.S. Deka, C.Y. Fang, Z. Chen, Y. Fainman, and A. El Amili, "Impact of Fundamental Temperature Fluctuations on the Frequency Stability of Metallo-Dielectric Nanolasers", *IEEE Journal of Quantum Electronics*, 55(5), pp.1-10 (2019).
- [14] Q. Gu, J. Shane, F. Vallini, B. Wingad, J. S. T. Smalley, N. C. Frateschi, and Y. Fainman, "Amorphous Al₂O₃ Shield for Thermal Management in Electrically Pumped Metallo-Dielectric Nanolasers," *IEEE J. Quantum Electron.* 50, 499–509 (2014).
- [15] J. H. Lee, M. Khajavikhan, A. Simic, Q. Gu, O. Bondarenko, B. Slutsky, M. P. Nezhad, and Y. Fainman, "Electrically pumped sub-wavelength metallo-dielectric pedestal pillar lasers," *Optics Express* 19, 21524 (2011).
- [16] C.Y. Fang, S.H. Pan, , F. Vallini, A. Tukiainen, J. Lyytikäinen, G. Nylund, B. Kanté, M. Guina, A. El Amili, and Y. Fainman, "Lasing action in low-resistance nanolasers based on tunnel junctions", *Optics letters*, 44(15), pp.3669-3672 (2019).
- [17] R. Loudon, *The Quantum Theory of Light* (OUP Oxford, 2000).
- [18] M. P. Nezhad, A. Simic, O. Bondarenko, B. Slutsky, A. Mizrahi, L. Feng, Vitaliy Lomakin, and Y. Fainman. "Room-temperature subwavelength metallo-dielectric lasers." *Nature Photonics* 4, no. 6 (2010): 395-399.
- [19] R.M. Ma, and R.F. Oulton. "Applications of nanolasers." *Nature Nanotechnology* 14, no. 1 (2019): 12-22.
- [20] D.A.B. Miller. "Device requirements for optical interconnects to silicon chips." *Proceedings of the IEEE* 97, no. 7 (2009): 1166-1185.
- [21] D. Massoubre, J.L. Oudar, A. O'Hare, M. Gay, L. Bramerie, J.C. Simon, A. Shen, and J. Decobert. "Analysis of thermal limitations in high-speed microcavity saturable absorber all-optical switching gates." *Journal of lightwave technology* 24, no. 9 (2006): 3400.
- [22] S. S. Deka, S. H. Pan, S. Jiang, A. El Amili, F. Vallini, Q. Gu and Y. Fainman, "Real-Time Dynamic Wavelength Tuning and Intensity Modulation in Metal-Clad Nanolasers," *Optics Express* 28(19), 27346-27357 (2020).

[23] R. Sharma, M. W. Puckett, H. Lin, A. Isichenko, F. Vallini, and Y. Fainman, *Opt. Lett.* 41, 1185 (2016).

[24] W. Bogaerts, P. D. Heyn, T. V. Vaerenbergh, K. D. Vos, S. K. Selvaraja, T. Claes, P. Dumon, P. Bienstman, D. V. Thourhout, and R. Baets, *Laser & Photonics Reviews*, 6, 47 (2012).