# Photonics and Optoelectronics

# Silicon Solar Cell Quantum Yields Approaching 100% Due to Sensitization by Singlet Exciton Fission

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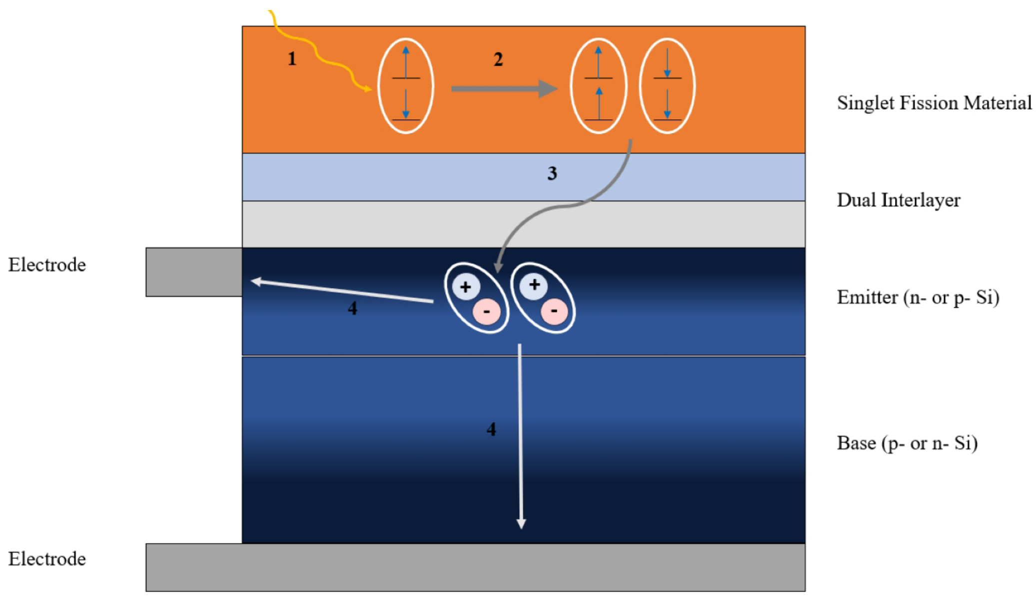
Sponsorship: U.S. Department of Energy, Office of Basic Energy Sciences, and Samsung

Crystalline Silicon based solar cells currently dominate the global industry, but for single junction devices, the efficiencies are approaching the Shockley-Queisser limit. Sensitizing silicon to organic molecules that undergo the carrier multiplication process singlet exciton fission (SF), could provide a facile method to generate two electron-hole pairs per photon and improve efficiencies beyond the industry standard. Surface and bulk charge recombination and surface trap loss pathways have inhibited the transfer of energy from a SF material to silicon and decreased the overall performance. Herein, we employ a dual interlayer system to facilitate interfacial charge transfer states and surface passivation of trap states with a shallow junction device architecture for efficient carrier separation and extraction. We have demonstrated short circuit current from triplet excitons of tetracene and an enhancement to the external quantum efficiency of silicon solar cells.



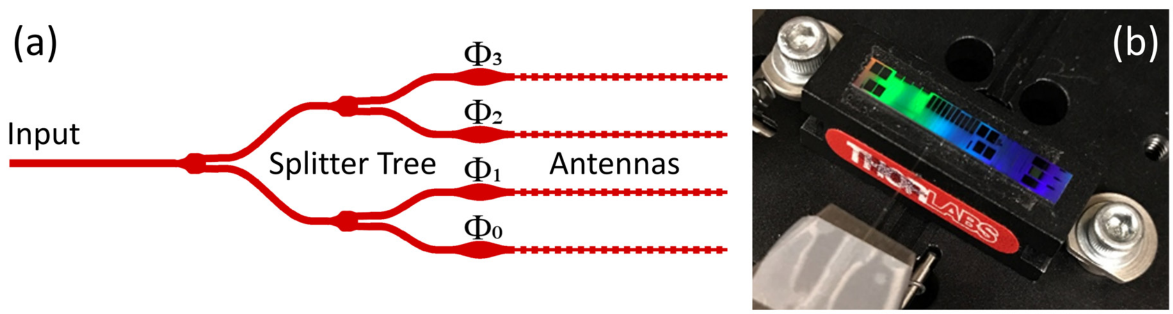

▲ Figure 1: Simplified schematic of a SF sensitized silicon solar cell device: (1) photoexcitation, (2) generation of two triplet excitons, (3) charge transfer into the surface of silicon, and (4) electron and hole separation to the electrodes.

# Integrated Beam-Steering Optical Phased Arrays for Solid-State LiDAR Sensors

B. M. Mazur, D. M. DeSantis, M. R. Torres, M. Notaros, J. Notaros
Sponsorship: SRC JUMP 2.0 CogniSense, MIT Rolf G. Locher Endowed Fellowship, NSF Graduate Research Fellowship

Light detection and ranging (LiDAR) has emerged as a vital and widely-used sensing technology for autonomous systems, such as autonomous vehicles, since it enables 3D mapping with higher resolution than traditional RADAR. However, current commercial LiDAR systems utilize mechanical beam-steering mechanisms that decrease reliability, increase production cost, and limit detection range. To address these limitations, solid-state optical-phased-array-based (OPA-based) LiDAR, which enables low-cost, high-speed, and compact non-mechanical beam steering, has emerged as a promising solution for next-generation LiDAR sensors.

In this poster, we discuss integrated beam-steering OPA architectures and devices for LiDAR sensors, highlighting their design spaces and tradeoffs. Additionally, we propose novel OPA subsystems for spatially-adaptive solid-state LiDAR sensors.



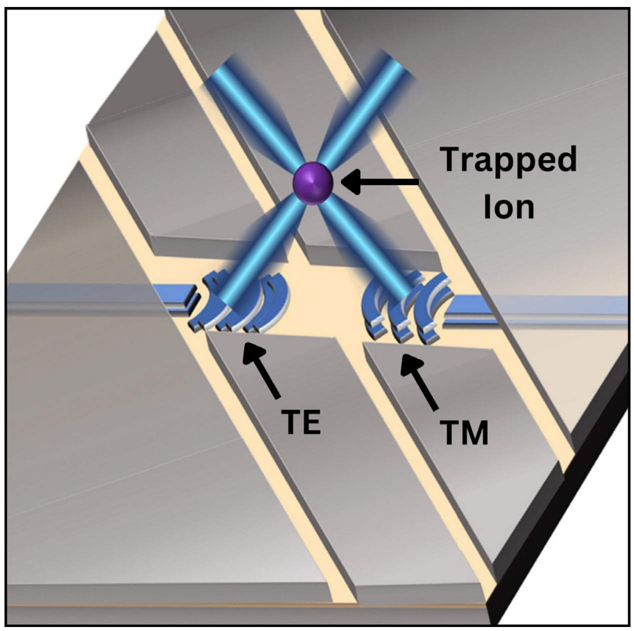

▲ Figure 1: (a) Simplified schematic of an integrated optical phased array. (b) Photograph of a silicon-photonics chip with a large-scale integrated optical phased array.

# Integrated Photonics for Advanced Cooling of Trapped-Ion Quantum Systems

S. Corsetti, A. Hattori, M. Notaros, T. Sneh, R. Swint, P. T. Callahan, F. Knollmann, E. R. Clements, D. Kharas, G. N. West, T. Mahony, C. D. Bruzewicz, C. Sorace-Agaskar, R. McConnell, J. Chiaverini, J. Notaros
Sponsorship: NSF Quantum Leap Challenge Institute Hybrid Quantum Architectures and Networks, NSF Quantum Leap Challenge Institute Quantum Systems through Entangled Science and Engineering, MIT Center for Quantum Engineering, NSF Graduate Research Fellowships Program, Department of Defense National Defense Science and Engineering Graduate Fellowship, MIT Cronin Fellowship, MIT Locher Fellowship

Trapped-ion systems are a promising modality for quantum information processing due to their long coherence times and strong ion-ion interactions, which enable high-fidelity two-qubit gates. However, most current implementations are comprised of complex free-space optical systems, whose large size and susceptibility to vibration and drift can limit fidelity and addressability of ion arrays, hindering scaling. Integrated-photonics-based solutions offer a potential avenue to address many of these challenges.

Motional state cooling is a key optical function in trapped-ion systems. However, to date, integrated-photonics-based demonstrations have been limited to Doppler and resolved-sideband cooling. In this work, we develop and demonstrate integrated-photonics-based systems and associated devices (conceptually depicted in Figure 1) for two advanced cooling schemes, polarization gradient and electromagnetically-induced transparency. This has the potential to improve cooling performance for trapped ions, enabling scalable quantum systems.




▲Figure 1: Conceptual diagram of integrated-photonics-based polarization-gradient-cooling system, demonstrating light of diverse polarizations simultaneously addressing ion positioned over ion-trap chip.

## FURTHER READING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# Spatially-adaptive Solid-state Optical-phased-array-based LiDAR

D. M. DeSantis, B. Mazur, M. R. Torres, M. Notaros, J. Notaros
Sponsors: SRC JUMP 2.0 CogniSense, MIT Rolf G. Locher Endowed Fellowship, and NSF Graduate Research Fellowship (Grant No. 1122374)

Light detection and ranging (LiDAR) has emerged as a vital and widely-used sensing technology for autonomous systems, such as autonomous vehicles, since it enables three-dimensional mapping with higher resolution than traditional radar. However, current commercial LiDAR systems utilize mechanical beam-steering mechanisms that decrease reliability, increase production cost, and limit detection range. To address these limitations, solid-state optical-phased-array-based LiDAR (as shown in Figure 1), which enables low-cost, high-speed, and compact non-mechanical beam steering, has emerged as a promising solution for next-generation LiDAR sensors.

In this work, we propose and develop a novel spatially adaptive solid-state LiDAR system enabled by multiple-beam integrated-optical-phased-array subsystems and integrated optical-processing devices. This multi-beam adaptability enhances spatial awareness and reduces the back-end data processing traditionally associated with beam-rastering LiDAR by enabling the sensing and ranging of multiple targets simultaneously, without the need to scan the sensor's whole environment.


▲ Figure 1: Photograph depicting a large-scale optical-phased-array chip for solid-state beam forming and beam steering.

## FURTHER READING

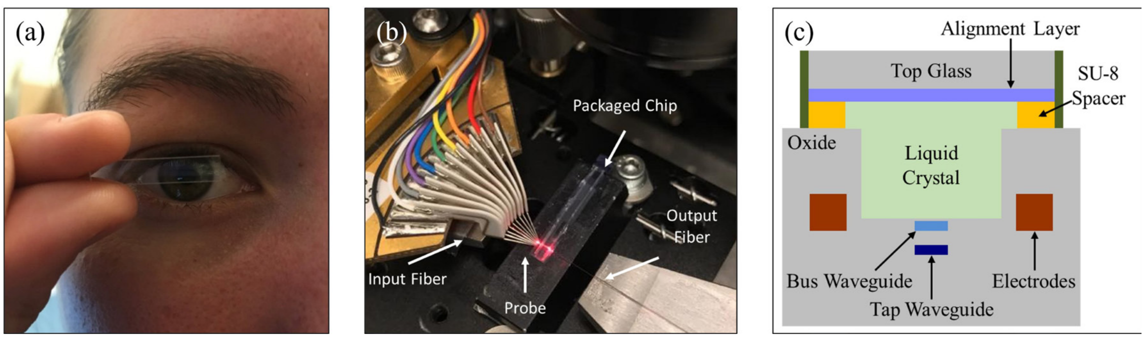
- Y. Liu, C. Zhang, D. DeSantis, D. Hu, T. Meissner, A. Garcia Coleto, B. Mazur, J. Notaros, and J. Klamkin, "High-Resolution Arrayed-Waveguide-Grating-Assisted Passive Integrated Optical Phased Array for 2-D Beam Steering," *Proc. Conference on Lasers and Electro-Optics (CLEO)* (OSA, 2024), paper STu4N.1, pp.1-2.

# Integrated Visible-light Liquid-crystal-based Modulators for Augmented-reality Displays

A. Garcia Coleto, M. Notaros, T. Dyer, M. Raval, C. Baiocco, J. Notaros
Sponsorship: NSF CAREER Program (2239525), Defense Advanced Research Projects Agency (DARPA) Visible Integrated Photonics Enhanced Reality (VIPER) Program (FA8650-17-1-7713), MIT School of Engineering MathWorks Fellowship, NSF Graduate Research Fellowship (1122374)

Augmented-reality head-mounted displays (HMDs) that display information in the user's field of view have many wide-reaching applications in defense, medicine, gaming, etc. However, current commercial HMDs are bulky, heavy, and indiscreet. Moreover, current displays are incapable of producing holographic images with full depth cues; this lack of depth information results in eyestrain and headaches that limit long-term and wide-spread use of these displays.

To address these limitations, we are developing an integrated-photonics-based display that consists of a single transparent chip that sits directly in front of the user's eye and projects holograms that only the user can see. Specifically, we are developing integrated liquid-crystal-based phase and amplitude modulators that enable this integrated-photonics-based display architecture. This work paves the way towards a highly discreet and fully holographic solution for the next generation of augmented-reality displays.




▲Figure 1: (a) Photograph of a transparent integrated-photonics-based holographic display. (b) Simplified cross-sectional schematic of an integrated liquid-crystal-based modulator. (c) Photograph of an integrated photonic chip packaged with liquid crystal on an experimental setup.

## FURTHER READING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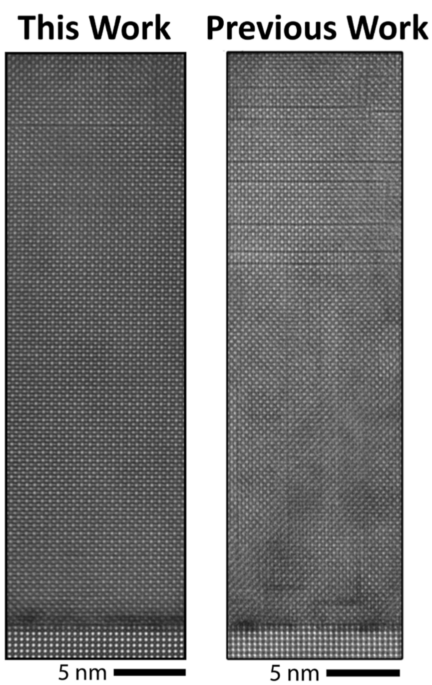
- M. Notaros, T. Dyer, M. Raval, C. Baiocco, J. Notaros, and M. R. Watts, "Integrated Visible-light Liquid-crystal-based Phase Modulators," *Opt. Express* vol. 30, pp. 13790-13801, 2022.

# A Processing Route to Chalcogenide Perovskites Alloys with Tunable Band Gap via Anion Exchange

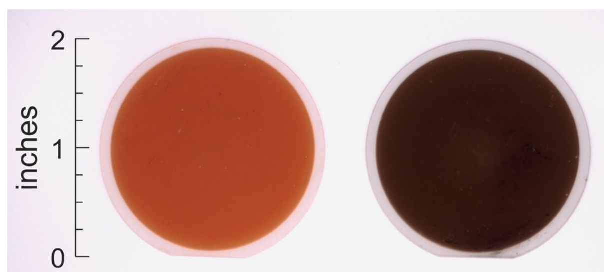
K. Ye, I. Sadeghi, M. Xu, J. Van Sambeek, T. Cai, J. Dong, R. Kothari, J. M. LeBeau, R. Jaramillo
Sponsorship: NSF (Grant Nos. 1751736, 1745302, 2224948)

Chalcogenide (sulfide and selenide) semiconductors in the perovskite crystal structure are anticipated to have favorable structural, optical, and electronic characteristics for solar energy conversion. The most studied compound is $BaZrS_3$, with a band gap of 1.9 eV. Alloying on the anion or cation sites has been explored to lower the band gap into a range suitable for single-junction solar cells. The pure selenide perovskite, $BaZrSe_3$, has been theoretically predicted to have band gap 0.5 eV lower than the sulfide. Experimental efforts from our group in 2023 demonstrated the alloying of $BaZrS_3$ with Se, and we confirmed that this alloy system features a tunable, direct band gap in the range of 1.4 – 1.9 eV.

Now we report an alternative processing route to synthesize these alloyed films. Our measurements on films suggest a reduced defect density and improved optoelectronic material properties compared to those of our previous efforts, as shown in Figure 1. We further showcase the utility of our processing at scale in Figure 2, via a demonstration on a polycrystalline film on a 2" $Al_2O_3$ wafer. More importantly, these results have strong relevance to the future manufacturing prospects of this material class. The gases and processing methodologies are similar to those for other well-known solar cell materials. The present work creates opportunities for research communities to inform the further development of chalcogenide perovskite technology.




▲Figure 1: Atomic-resolution electron microscopy image of a typical film cross section showing a noticeably reduced density of extended defects (left) compared to previous work (right). The images shown here correspond to films with the stoichiometry $BaZrS_{3-y}Se_y$ ($y \approx 2$).




▲Figure 2: Photographs of polycrystalline $BaZrS_3$ thin film samples grown on 2" $Al_2O_3$ wafers before (left) and after (right) selenization.

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# Development of Ultra-Thin Perovskite Solar Module with Slot-die Printing

K. Yang, J. Mwaura, V. Bulović

Sponsorship: Tata Power Company Ltd., U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy

Owing to their solution-processibility, perovskite solar cells (PSCs) promise to offer a flexible, lightweight, and highly efficient alternative to crystalline silicon solar cells (c-Si). PSCs are able to open markets for solar deployment not accessible with c-Si while maintaining price-competitiveness with existing technologies. However, there are technological challenges to be addressed before PSCs are ready for large scale manufacturing.

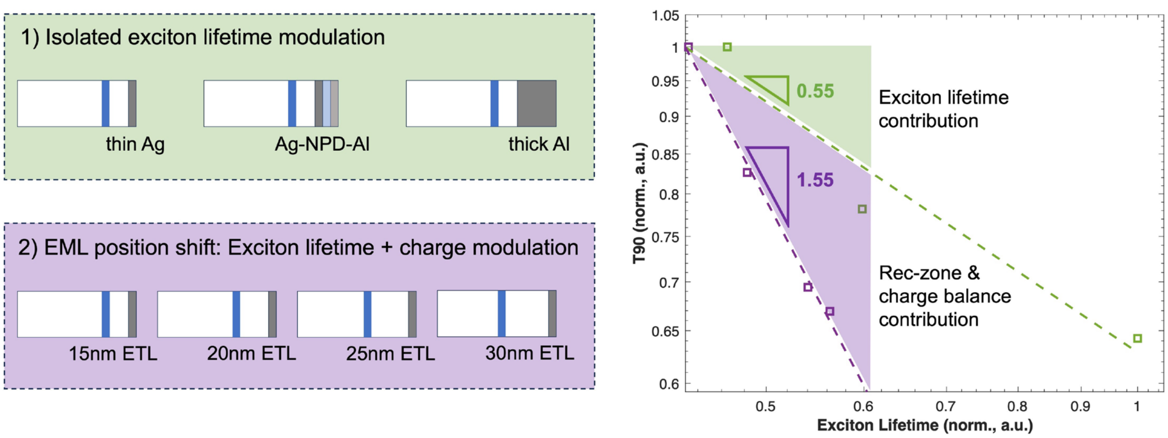
In contrast to the majority of research in PSCs which focuses on improving the stability and efficiency of small, spin-coated devices, this work aims to address challenges on the scaling and manufacturing front. Specifically, there exists a "scaling lag" which is seen when technologies are directly transferred from small devices to large area modules and manifests as decreased module efficiency and increased series resistance. In this work, slot-die coating is used to create large, 45cm$^2$ modules on 125um thick polyethylene terephthalate (PET) substrates with 7.5 cm$^2$ mini-modules exhibiting efficiencies of up to 7.4%. This process is the first working demonstration of a flexible, large-area PSC module fabricated with non-toxic solvents and establishes the baseline for the future transition to a 50μm peelable module which can be laminated onto transparent fabrics. To demonstrate the economic feasibility of commercial production, a techno-economic analysis is performed using Monte-Carlo simulation techniques to ensure price-competitiveness with current established solar technologies. Levelized Cost of Electricity values for flexible PSCs can be as low as 2.24¢/kWh compared to 3.16¢/kWh currently seen with mono-PERC silicon panels.

Successful demonstration of a flexible, large-area perovskite solar cell without toxic solvents will accelerate the industrialization of flexible photovoltaics. This would ultimately shift the solar landscape from mainly utility solar farms to a distributed model, further accelerating solar adoption.

# Decoupling the Role of Exciton Lifetime, Charge Carrier Balance, and Dark Excitons in the Degradation of Blue OLEDs

J. Tiepelt, J. Song, C. Picart, A. Seeglitz, T.-A. Lin, S. Zhu, P. Satterthwaite, J. Li, M. A. Baldo
Sponsorship: U.S. Department of Energy – Office of Energy Efficiency & Renewable Energy

Organic light-emitting diodes (OLEDs) are the predominant technology for mobile display applications. The greatest remaining challenge is the stability of blue OLEDs, caused by long-lived triplet excitons. The effect of key parameters on OLED stability is not well understood to date. Here, we report a characterization technique that decouples an OLED's electronic properties from modulations of its emission layer's exciton lifetime by means of external plasmonic coupling. We show that the device's operational stability shows a much smaller than expected, square-root, dependence on exciton lifetime. As we only modulate emissive excitons here, it is possible that trapped 'dark' excitons dominate stability. In a second experiment, we vary the position of the emissive layer within the OLED, revealing a super-linear dependence of stability on the variation in charge balance and exciton lifetime. Last, we show strong indication of charge carrier imbalance resulting in trapped dark excitons dominating OLED stability.

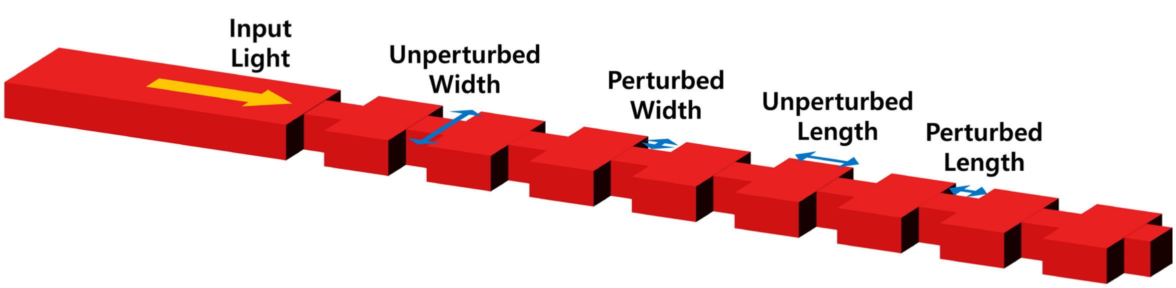



▲ Figure 1: Blue OLED stability in dependence of exciton lifetime variation vs. positional shift of the emitting layer. Device stability shown to be dominated by shifts in the recombination zone and charge carrier balance.

# Integrated Optical Grating-Based Antennas for Solid-State LiDAR Sensors

M. R. Torres, S. Corsetti, D. M. DeSantis, A. G. Coleto, B. Mazur, M. Notaros, J. Notaros
Sponsorship: SRC JUMP 2.0 CogniSense

Light detection and ranging (LiDAR) has emerged as a vital and widely-used sensing technology for autonomous systems, such as autonomous vehicles, since it enables 3D mapping with higher resolution than traditional RADAR. However, current commercial LiDAR systems utilize mechanical beam-steering mechanisms that decrease reliability, increase production cost, and limit detection range. To address these limitations, solid-state optical-phased-array-based (OPA-based) LiDAR, which enables low-cost, high-speed, and compact non-mechanical beam steering, has emerged as a promising solution for next-generation LiDAR sensors. In this poster, we develop integrated optical grating-based antennas, a critical device responsible for light emission in these solid-state LiDAR systems. We develop a device synthesis algorithm, design a suite of antennas with varying operating modalities, and discuss their design tradeoffs when applied to OPA subsystems.




▲ Figure 1: Simplified schematic of an integrated optical grating-based antenna with key design parameters labeled.

# Determining Charge Carrier Transport Parameters from Microscopy Data

T. J. Sheehan, W. A. Tisdale
Sponsorship: Massachusetts Institute of Technology, Department of Chemical Engineering

Time-resolved microscopy techniques are increasingly used to image the transport of excited charge carriers and excitons in materials. Typically, transport parameters such as diffusivity are extracted by generating a spatially localized population of excited charge carriers, then measuring the growth of the spatial charge carrier profile over time. However, current analysis techniques are highly sensitive to the shape of the initial charge carrier profile, and can result in large errors for even small deviations from an assumed profile shape. Additionally, these measurements may be significantly impacted by shot noise at common experimental conditions. Here, we apply conventional analysis techniques to simulated one-dimensional transport measurements to quantify the effects of non-ideal carrier spatial profiles and shot noise on the diffusivities extracted from microscopy data. We show that non-ideal profile shapes can lead to errors almost as large as 50%. Using these results as a baseline, we then propose an alternate analysis technique that uses convolutions of Gaussian functions with the measured charge carrier spatial profiles to both smooth the effects of shot noise and to measure the growth of the spatial profiles. We demonstrate that this algorithm outperforms traditional analysis techniques at recovering diffusivities from simulated data sets, displaying a slightly reduced sensitivity to shot noise and a significantly lower sensitivity to the shape of the initial charge carrier spatial profile. Finally, we apply this technique to experimental data to illustrate different strategies for extending this algorithm to accurately extract parameters for diffusion that occurs in two or more dimensions.

# Understanding Ultrafast Energy Transfer in Mixed-Dimensional Perovskite Heterostructures

M. Chattoraj, W. A. Tisdale
Sponsorship: U.S. Department of Energy, Office of Science, Basic Energy Sciences, award no. DE SC0019345.

Lead halide perovskite nanomaterials are an intriguing class of semiconductors due to their many remarkable optical properties, including long-lived charge carriers and spectrally narrow emission that is synthetically tunable across the visible light spectrum. Perovskites are of interest for many optoelectronic applications ranging from photovoltaics to displays. To increase the efficiency of optoelectronic devices incorporating nanomaterials, a detailed understanding of energy transfer in nanoscale systems is necessary.

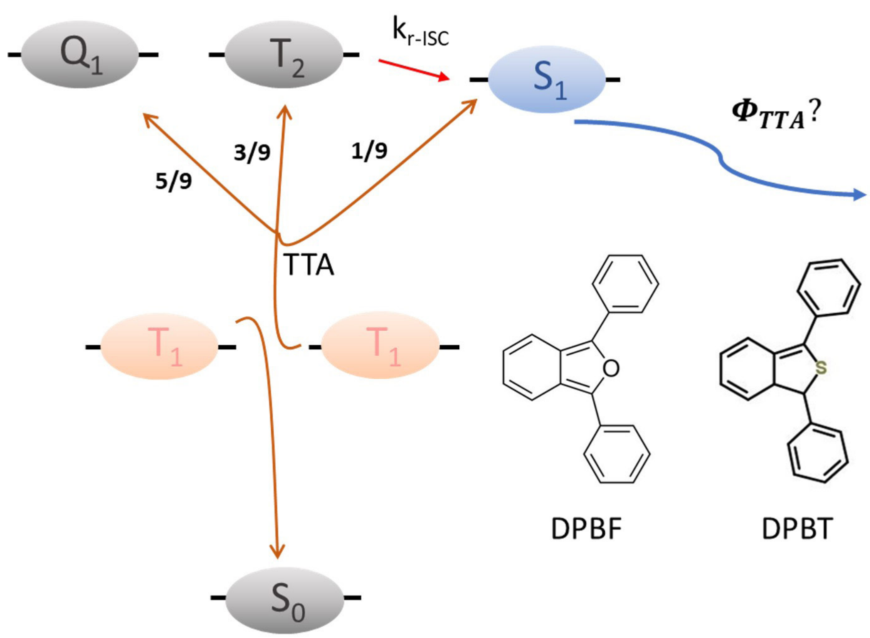
Although exciton transfer in colloidal semiconductors has traditionally been described by Förster resonance energy transfer (FRET), this framework does not fully capture exciton behavior in many novel materials. Lead halide perovskites have been shown to exhibit energy transfer rates far exceeding Förster theory predictions, thus posing an intriguing material platform for establishing a more detailed understanding of exciton dynamics. As devices increasingly incorporate nanomaterials such as quantum dots, understanding energy transfer between materials of varying dimensionality becomes crucial. Rigorous characterization of energy transfer mechanisms in perovskite-based heterostructures requires synthesis of high-quality perovskites. Here, perovskites of various dimensionalities are synthesized and combined into heterostructures. In the future, energy transfer in these heterostructures will be studied using time-resolved photoluminescence (TRPL) and ultrafast transient absorption (TA) spectroscopy. Ultimately, we aim to build a thorough, quantitative understanding of energy transfer mechanisms in novel nanomaterials, which will contribute to the development of highly efficient optoelectronic devices including photodetectors, displays, and solar cells.

# High Level Intersystem Crossing in Triplet-triplet Annihilation Photon Upconversion Materials Diphenylisobenzofuran and Diphenylisobenzothiophene

O. Nix, T.A. Lin, C.A. Kim, C. Perkinson, M. A. Baldo
Sponsorship: U.S. Department of Energy Office of Basic Energy Sciences (DE-FG02-07ER46474)

Triplet-triplet annihilation (TTA) presents a promising photon upconverion (PUC) platform that can improve the efficiency and stability of blue organic light emitting devices. TTA is a spin-dependent process that converts two low energy triplet states to a bright singlet state. However, the TTA process can also form dark high energy triplet states that lead to reductions in efficiency and device stability. There is a fundamental limit on the fraction of singlet states that can be produced through TTA, limiting its PUC efficiency.

In this work, tuning reverse intersystem crossing (r-ISC) from dark triplet states to bright singlet states was probed as a strategy for surpassing this limit. TTA materials diphenylisobenzofuran and diphenylisobenzothiophene were modelled to predict their relative r-ISC rates, and were characterized in solutions and spun cast films. Fast r-ISC was inversely correlated with TTA efficiency, suggesting low level r-ISC is a significant loss pathway to TTA.

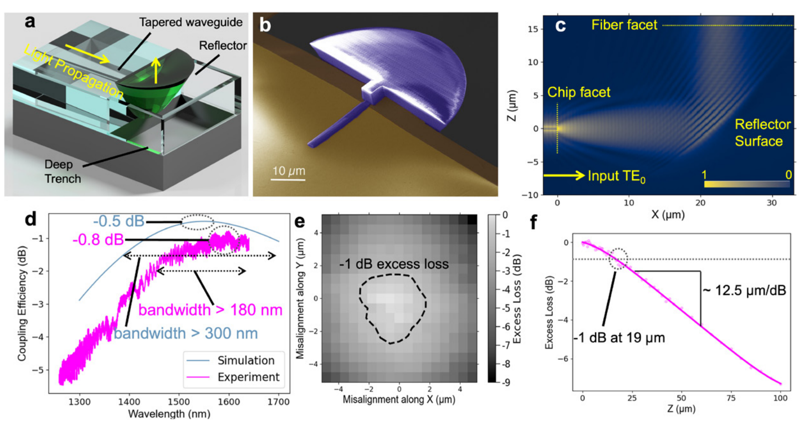



▲Figure 1: Schematic of the triplet-triplet annihilation (TTA) process, where two triplet excitons annihilate to form either a bright singlet or dark triplet or quintet state. Increased formation of the bright singlet through r-ISC is investigated in DPBF and DPBT as a strategy for increasing $\Phi_{TTA}$.

# High-performance Facet-attached 3D Micro-reflectors for Scalable Fiber-to-Chip Coupling

L. Ranno, J. X. B. Sia, C. Popescu, D. Weninger, S. Serna, S. Yu, L. C. Kimerling, A. Agarwal, T. Gu, J. Hu
Sponsorship: NSF Convergence Accelerator (Award Number: DE-AR0000847)

Leveraging the mature fabrication processes developed by the electronics industry, silicon photonics is poised to revolutionize a variety of application spheres, including telecommunications, environmental sensing, and quantum and classical computing. Still, the lack of a scalable and cost-effective packaging solution to interface optically to photonic integrated circuits is proving to be a barrier preventing the wide adoption of photonics. Convergence on a unified optical coupling scheme that meets all the industry requirements is imperative for the success of the field. Among the proposed approaches to address this optical "packaging bottleneck," micro-optics fabricated via two-photon polymerization (TPP) have achieved promising performance metrics. Nevertheless, the research community has primarily focused on uncladded waveguides, which are not the industry standard and require customized cladding removal steps, limiting the scalability of these solutions. We present results on a new scalable coupling scheme that takes advantage of the design freedom enabled by TPP by fabricating 3D printed micro-reflectors directly on wave-guide facets. The shape of the micro-reflector is optimized to both redirect and reshape the beam exiting the waveguide, hence maximizing coupling with a standard flat-cleaved SMF-28 optical fiber positioned vertically above the chip. The deep trenches where the reflectors reside are fabricated during the edge coupling formation step, which is already part of the fabrication flow in photonic foundries. The reflectors can be seamlessly printed onto the waveguide facets at the backend after receiving the fabricated photonic chips. Simulations and experimental results demonstrate the excellent performance of the reflectors, which boast experimentally verified insertion losses of only -0.8 dB, with bandwidths over 180 nm. Additionally, the 1-dB in-plane and out-of-plane alignment tolerances of the devices reach approximately 2 µm and 19 µm, respectively, making the reflectors compatible with high-throughput passive alignment coupling approaches.




▲ Figure 1: (a) Schematic and (b) False-colored scanning electron microscope image of the reflector. (c) Electric field propagating through the system. (d) Waveguide-to-fiber coupling efficiency against wavelength. (e) In-plane and (f) out-of-plane fiber alignment tolerances.

## FURTHER READING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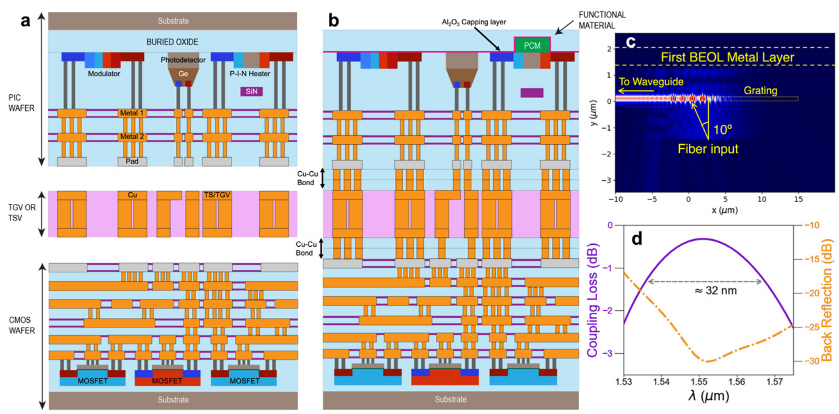
# SuMMIT: A New Platform for Photonic Heterogeneous Integration

L. Ranno, K. P. Dao, J. X. B. Sia, J. Hu
Sponsorship: NSF (Award Number: 2328839)

The exponential growth that silicon photonics has experienced can be primarily attributed to the infrastructure developed by the electronics industry. Leveraging the complementary metal-oxide-semiconductor (CMOS) fabrication processes, photonics foundries have quickly upscaled manufacturing and now commonly offer waveguides with propagation losses on the order of 1~3 dB/cm, modulators with bandwidths of ~40 GHz, and high-efficiency integrated germanium photodetectors. Even though the current toolkit available from foundries is certainly impressive and enables the entire photonics infrastructure of today, a significant number of functionalities, including on-chip light emission and gain, isolation, memory, and electro-optic modulation, is missing as a result of material incompatibilities with the CMOS process. To include these exotic materials in photonic circuits while maintaining good interaction with the waveguide layer, the research community has been forced to either dig trenches in the back end of the line (BEOL) layers of foundry wafers or fabricate custom chips, both of which have significant disadvantages limiting the scalability and technological relevance of such implementations.

We propose a new heterogeneous integration approach that is fully foundry compatible, namely SuMMIT–Substrate Inverted Multi-Material Integration Technology. In SuMMIT, the photonic wafer is bonded to a through-glass or through-silicon via wafer, which acts as a handle wafer and an electrical interface to the photonic wafer. The through-glass via wafer may be bonded to a PCB or CMOS wafer. After bonding, the back of the photonic wafer is removed through a combination of etching and chemical-mechanical polishing, exposing the waveguide layer. At this point, materials can be deposited or bonded as needed. Additionally, the creation of a second interface (back) decouples the electrical and optical input/output and enables new designs that could not be realized before. For instance, the BEOL metal layers can be used to produce highly efficient grating couplers or antennas.




▲ Figure 1: Illustration of the SuMMIT technology stack (a) before bonding and (b) after bonding, back-removal, and material deposition. (c) Electric field of a grating coupler with BEOL metal as a reflector. (d) Performance of the grating implemented in (c).

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# Crown Ether Decorated Lead Silicon Photonic Sensors for $Pb^{2+}$ Environmental Detection

L. Ranno, Z. Xu, J. Hu, J. Xu, B. Sia

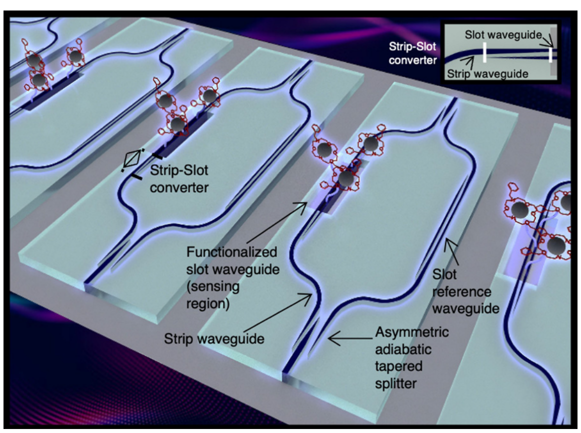
Lead ($Pb^{2+}$) poisoning is a pressing global public health crisis. $Pb^{2+}$ toxification leads to various adverse effects on health, e.g neurological damage or increased infant mortality. Unfortunately, public policies to address this issue have been lackluster.

Here we present the crown ether decorated silicon photonic platform for lead ion detections. Crown ethers are cyclic polyethers with the remarkable ability to selectively bind to specific ions based on their physical and chemical properties. The proposed sensor operates through the means of optical interference. More specifically, ions binding to the crown ether functionalization layer lead to a change in local refractive index, or equivalently a wavelength shift of the interferometer resonance.

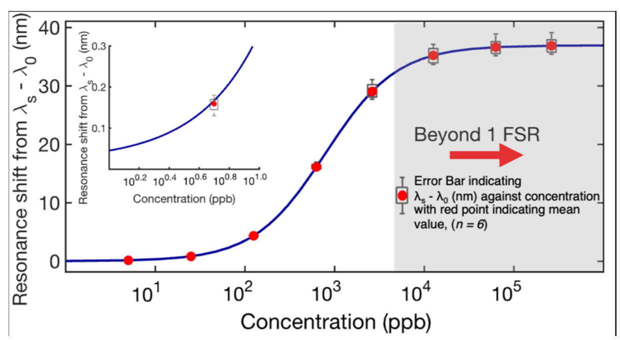
Figure 1 illustrates the integrated $Pb^{2+}$ sensor based on a Mach-Zehnder interferometer. The crown ethers are functionalized on one of the waveguide arms with the other used as reference. During operation, the sensor is first exposed to deionized water to collect a reference spectrum, followed by exposure to the analyte solution and finally flushing with water and measurement of a second optical spectrum. Larger wave-length shifts between the two spectra indicate higher $Pb^{2+}$ concentrations, as shown in Figure 2.

We tested the validity of the calibration curve across different environmentally related samples and verified them with Inductive coupled plasma mass spectrometry prior to the experiment. Performance in environmental performance showed excellent sensitivity and selectivity, indicating the resilience of the proposed solution.

This work innovates on three aspects. First, we demonstrate that applying the Fischer esterification protocol successfully couples carboxylic acid groups with hydroxyl groups on pretreated $SiO_2$ waveguide surfaces. Second, the developed sensor enables swift analyte testing with high detection accuracies, matching the state-of-the-art at a significantly lower price point and greater portability. Third, this integrated platform can leverage high-precision and cost-effective manufacturing techniques for scaling up production.




▲ Figure 1: 3-D illustration of photonic Pb^2+ ion sensor based on crown ether decorated silicon platform. Functionalization performed in sensing region is indicated.




▲ Figure 2: Calibration curve of sensor when exposed to reference Pb^2+ concentrations of 0, 5, 25, 125, 625, 2625, 12625, 62625, and 262625 ppb via cumulative testing approach.

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# Plasmonic Nanoparticle Lattices as Optical Cavities for Thin Film Colloidal QD Lasers

S. Srinivasan, J. Guan, R. Zhang, K. McFarlane-Connelley, M. G. Bawendi, V. Bulović
Sponsorship: Samsung Semiconductor Co., U.S. Department of Energy

Thin film nanoscale lasers have applications ranging from on-chip optical interconnects, virtual and augmented reality displays, and optical wireless communication. To realize these applications, both nanoscale optical cavities and high quantum yield emitters are required. Quantum dots (QDs) are semiconductor nanoparticles with discrete energy levels generated through quantum confinement with size and composition tunable emission. Current thin film lasers utilize molecular beam epitaxy to grow optical cavities and QDs, requiring fabrication with expensive high vacuum systems. To reduce manufacturing costs, both a simple optical cavity and a solution processable gain medium are required. Colloidal QDs are synthesized in solution and are chemically stabilized with organic capping ligands. They have demonstrated synthetically tunable emission and near unity quantum yield. Plasmonic nanoparticle lattices are nanometer spaced arrays of metal nanoparticles that couple local surface plasmon resonance modes of individual nanoparticles with diffraction modes generated by the array. They are fabricated in a single liftoff process, reducing manufacturing complexity. The lattice resonance mode is also easily tunable through control of the lattice geometry, spacing, and surrounding refractive index.

The combination of plasmonic nanoparticle lattices and colloidal quantum dots creates a new paradigm for the fabrication of nanoscale lasers with tunable emission and low pumping thresholds. In this work we demonstrate an optically pumped laser with perovskite colloidal quantum dots integrated into Al-nanoparticle lattices. The lattices were fabricated with a single step electron beam lithography and liftoff process. By varying lattice periodicity, lasing emission directionality was controllable by up to 12 degrees off-normal.

# Optimized design of Vapor Transport Co-Deposited Perovskite Photovoltaics

T. Kadosh Zhitomirsky, S. Srinivasan, W.-J. Hsu, E. Pettit, R. J. Holmes, H. L. Tuller, V. Bulović
Sponsorship: U.S. Department of Energy

Metal-halide perovskites have demonstrated high photo-electrical conversion efficiencies, superior to other thin film semiconductors, hence viewed as promising candidates to replace silicone as solar cell materials. However, popular solution-based processing routes impose a challenge when coming to up-scale. Vapor Transport Deposition (VTD) is a readily scalable and low-cost alternative method for perovskites production. Being solvent-free, they bypass solvent related challenges, namely uniform coverage of large areas, chemical compatibility, and toxicity. As a low-cost alternative to thermal evaporation, VTD has the potential to deposit organic and inorganic perovskite precursor materials either sequentially or via co-deposition. Furthermore, VTD potentially offers higher tunability of deposition parameters, to enable film growth with improved composition and microstructure control. Yet, being a newly developing technique, we still need to prove its viability in producing high-quality perovskite films.

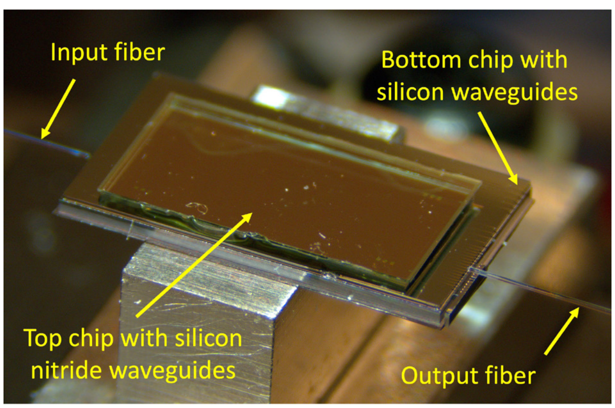
We are currently working with a custom-made VTD system, focused on optimization of co-deposition of lead iodide and methylammonium iodide with the aid of carrier gases. Additionally, we address the design of the device. We conclude that for pristine MAPI, small lead iodide excess leads to higher power conversion efficiencies. We found the n-i-p structure as preferable over the p-i-n one. We also learned the importance of choosing appropriate electrodes and transport layers, as well as applying post-deposition treatments. These findings can serve us in fabricating solar cells utilizing this new technique.

# Inter-chip Optical Couplers for Automated Photonic Integrated Circuit Packaging

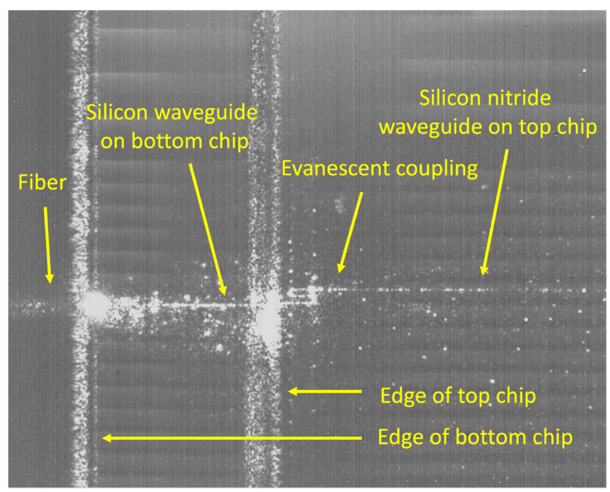
D. M. Weninger, S. Serna, L. Ranno, L. C. Kimerling, A. M. Agarwal
Sponsor: NSF

The use of silicon photonic integrated circuits (Si-PICs) and optical fibers in telecommunications networks offers significant system improvements in terms of latency, energy consumption, and data capacity compared to electrical integrated circuits and copper wiring. However, the manual alignment and bonding of bulky optical fiber arrays to the edge or top of Si-PICs with sub-micron precision create a significant challenge to their widescale adoption. The development of integrated couplers connecting Si-PICs to optical printed circuit boards without using flyover fiber arrays offers an opportunity to advance photonics packaging, as ball grid arrays advanced microelectronics away from wirebonding. Specifically, these couplers can enable automated assembly of Si-PICs using pick-and-place tools readily available through the microelectronics infrastructure.

To this end, studies are investigating several methods for inter-chip coupling such as 3D printed microlenses and mirrors, etched surface gratings, and cantilevers. This work investigates evanescent coupling, a method offering low coupling losses at the expense of alignment tolerances on the order of several hundred nanometers. We fabricated, packaged, and tested prototypes using a novel evanescent coupler design to determine manufacturing feasibility. The resultant prototype was the first demonstration of an inter-chip evanescent coupler between silicon and silicon nitride wave-guides. The measured coupling efficiency for telecommunications wavelengths was approximately 93%--the lowest reported for a silicon-based inter-chip evanescent coupler. Likewise, the measured alignment tolerance was roughly 2.48 micron–an order of magnitude larger than typical evanescent coupling tolerances and large enough to enable automated flip-chip assembly. In addition, the coupler's footprint was roughly a third of the typical length and a tenth of the typical width, versus comparable designs. Developing a high-performance inter-chip coupler using standard complementary metal-oxide semiconductor foundry materials can eliminate the packaging inefficiencies of fiber-to-chip connections to enable mass manufacturing of Si-PICs.




▲Figure 1: Inter-chip evanescent coupling prototype. Light travels through input fiber to bottom chip using edge coupler, couples to top chip using evanescent coupler, couples back down using second evanescent coupler, and is collected at output fiber.




▲Figure 2: Image taken by infrared camera mounted directly above prototype, looking through back of glass top chip. Injected light at 1.55-micron wavelength can be seen coupling from fiber and to top chip using evanescent coupler.

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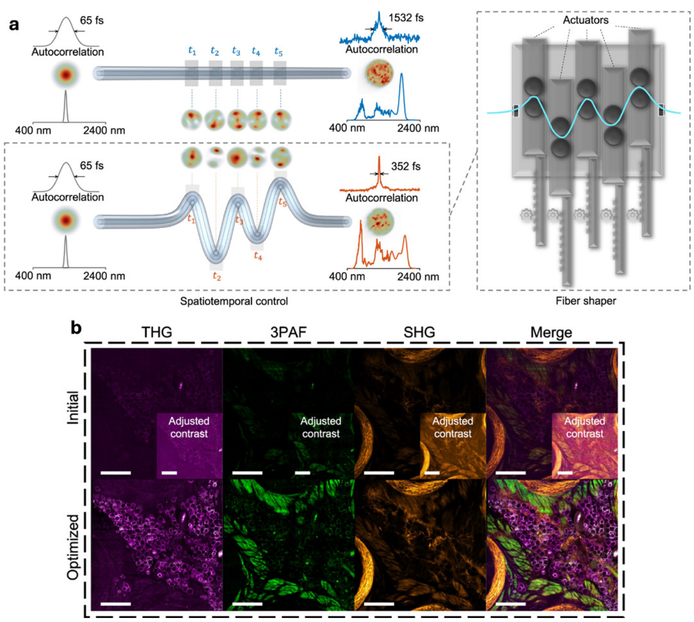
# Tunable Broadband Fiber Source for Multiplexed Nonlinear Microscopy

L. Yu, H. Cao, K. Liu, T. Qiu, S. You
Sponsorship: MIT Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics startup funds, Jameel Clinic, Chan Zuckerberg Initiative, Radon Institute, Koch Institute, Research Corporation for Science Advancement

Nonlinear microscopy is a powerful imaging technology for living, intact biological tissues with the capability of revealing morphological and chemical contrasts at a molecular level in a dynamic environment. Many intrinsic molecules and structures interact with optical fields via various nonlinear processes, including second/third harmonic generation, two-/three-photon autofluorescence, and coherent Raman scattering, offering specificity to endogenous contrasts by which the unperturbed biological activities are discernible. While nonlinear microscopy promises a multiplexed detection scheme for rich biological information, an unsolved challenge remains since the excitation source must cover wavelengths from visible to short-wave infrared with high power density to optimize the sensitivity for each contrast, due to the small nonlinear cross-sections.

To address the unmet need for multiplexed nonlinear microscopy, we demonstrate multimode fiber (MMF) as a compact and cost-effective solution as opposed to the existing techniques such as multi-head lasers and optical parametric oscillators/amplifiers. MMF is an efficient wavelength conversion platform, populating a narrowband pump source to a broadband, high-peak-power, supercontinuum source. While the intermodal coupling and dispersion have long been conceived as detrimental to the pulse duration and beam quality, we demonstrate the spectral, temporal, and spatial properties of the pulses can be tailored toward a better imaging quality by carefully seeding and engineering the pulse propagation. In particular, we developed a device – a fiber shaper–that deforms the MMF via a sequence of motor steppers to introduce programmable disorder to modify the pulse propagation (Figure 1). In addition, we optimized the launching condition by shaping the pump beam for dispersion engineering using a spatial light modulator. By leveraging the programmable disorder and wavefront shaping, we can enhance the spectral density, reduce the pulse duration, or improve the beam quality for diverse imaging modalities in nonlinear microscopy (Figure 2). This study has led to a broadband, high-peak-power, and tunable light source that promises high-content, multiplexed, in vivo imaging technology for a wide array of biological applications.




◀ Figure 1: (a) Spectral-temporal-spatial customization in MMFs by introducing programmable disorders via fiber shaper. (b) Label-free imaging of mouse whisker pad tissue at 1225 nm excitation using fi-ber source with initial and optimized set-tings. Scale bars: 200 μm.

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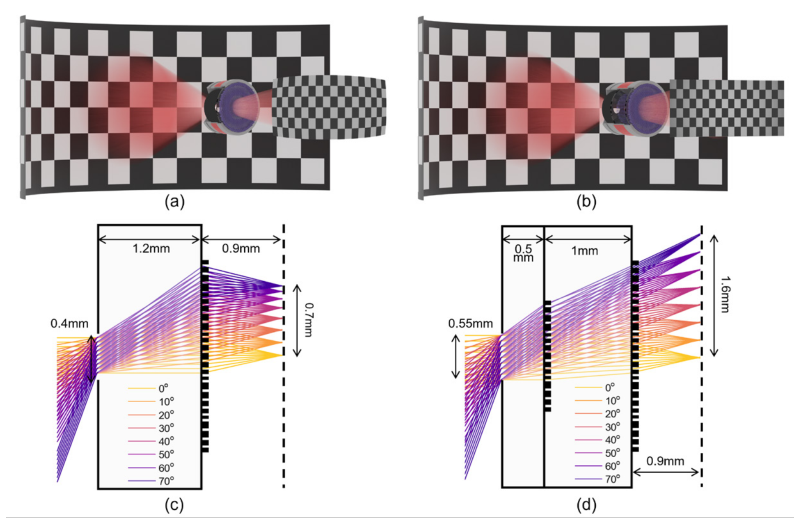
# Compound Metalens Enabling Distortion-free Imaging

H. Zheng, F. Yang, H. Lin, M. Y. Shalaginov, Z. Li, P. Burns, T. Gu, J. Hu
Sponsorship: Defense Advanced Research Projects Agency

Optical metasurfaces comprising sub-wavelength scale meta-atoms provide a versatile platform for wavefront control with a compact form factor. Major advances over the past decade in their design, manufacturing, and integration have catalyzed imminent commercial deployment of functional metasurface components in numerous beachhead markets such as structured light, computer vision, near-eye displays, and beam steering. Optical distortion, deviation from rectilinear projection that deforms images, is an important design specification for these applications involving imaging or image/pattern projection. However, while other image-forming attributes of meta-optics including various other forms of aberrations (spherical, astigmatism, coma, and chromatic aberrations) have been extensively studied, distortion and its compensation remain underexplored.

We propose a generic recipe for designing metalenses with on-demand distortion characteristics, which can customize (or arbitrarily define) the relation between the ray angle of incidence and the corresponding image height for radially symmetric optics. Unlike a single-layer metalens whose distortion is fixed, constrained by its aberration minimization condition, the extra degrees of freedom afforded by a doublet metalens enable concurrent elimination of monochromatic aberrations and specification of custom-tailored distortion. We experimentally validated our design approach through demonstrating a doublet metalens at 940-nm wavelength that simultaneously achieves 140° field-of-view, diffraction-limited performance, and less than 2% distortion (Figure 1). In comparison, a singlet metalens without distortion engineering suffers from distortion as large as 22%.




▲ Figure 1: Comparison of imaging distortion in singlet and compound metalenses. (a) A singlet metalens suffers from large barrel distortion. (b) Compound metalens effectively eliminates the barrel distortion. Ray-tracing modeling of the (c) singlet and (d) compound metalens, respectively. The light incident angles (in air) vary between 0° and 70° with a step of 10°.

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