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Design Method for Optical Phased Arrays that Emit 3D Holograms

J. Zhou, J. Sun, A. Yaacobi, C. V. Poulton, M. R. Watts Sponsorship: Draper Laboratory

Optical phased arrays have garnered a great deal of research attention due to their potential in communications, imaging, and detection. Recent development in the field has shown optical phased arrays can emit 2D patterns and continuously steer in one dimension. Currently, in microwave phased antenna arrays, high resolution is achieved at the expense of size, power, and cost. These drawbacks can be resolved by moving into the optical domain since it maintains high resolution due to a large array size coupled with small optical wavelength. The next step beyond 1D and 2D work is finding a way to extend these optical arrays to be able to tackle issues requiring 3D imaging. The previous 2D emitting phased arrays have produced outputs in the far field, which allows for only a single plane of focus, limiting it to 2D. The near field, on the other hand, allows for multiple patterns to come into focus at different projection distances, creating the framework for generating a 3D hologram. Digital holography techniques can be used to design phased arrays that generate 3D holograms, expanding their potential. In the past, digital binary holograms have been synthesized by superimposing Fourier transforms of output image planes. In the biomedical field, digital 3D holography has shown the ability to detect more information than traditional radiographs and CT images. Digital holography also opens the possibility for 3D displays and TVs without requiring specialized glasses.

This work presents a design technique that attempts to combine the 2D emitting phased array concept with digital holography to generate phased arrays with the capability to emit arbitrary 3D patterns in the near field. The phased array generation is accomplished by backpropagating desired output planes by using Fresnel diffraction to achieve a single electric field realizable by a phased array (Figure 1). This phased array will then tune its individual antennas to amplitudes and phases to match the previously calculated electric field so that it emits the desired 3D pattern when forward-propagated. Additional techniques are applied to improve the output quality of the image by adding both a random and curved phase front to the output planes prior to backpropagation (Figure 2). This technique provides a method to tune phased arrays that are capable of generating near field 3D holograms.



▲ Figure 1: (a) System overview of synthesized and simulated phased array. (b) Concept of 3D hologram design technique by back-propagation of MIT logo.



▲ Figure 2: (a) Back-propagated uniform flat phase front field. (b) Output of the phased array emitting "MIT" using back-propagation of the flat phase front. (c) Addition of circular phase front to back-propagate more accurately to the phased array area. (d) Improved output due to the addition of random and circular phase fronts prior to back-propagation.

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Integrated LIDAR System Based on Frequency-Modulated Continuous-Wave Detection

C. V. Poulton, D. B. Cole, M. R. Watts Sponsorship: DARPA MTO

Light detection and ranging (LIDAR) systems have proven useful in autonomous vehicle, urban mapping, and military applications. However, these systems have traditionally been bulky and expensive, along with utilizing mechanical steering, which is not robust in harsh environments. At the moment, high-performance LIDAR systems cost on the order of \$1,000 to \$10,000, which limits practical applications. Integrated photonics promises a viable path to reduce the cost and form factor of LIDAR systems. The use of standard 300 mm CMOS foundries can reduce the cost of individual chips to under \$10, making LIDAR systems commercially viable for a range of applications. Traditionally, LIDAR systems utilize a time-of-flight measurement technique that requires pulsed lasers with large peak powers, which is difficult to realize in an integrated system.

In this work, we utilize a range detection method based on coherent detection that involves modulating the frequency of a continuous-wave laser (FMCW) and can utilize photodetectors with moderate dark currents. Our recent results have shown ranging measurements with the FMCW method in an integrated optical system consisting of a single-sideband modulator and photodetectors. Edge-coupled waveguides with external collimating optics are used as transmitter and receiver ports. A compact laser diode with modulated injection current for frequency modulation is utilized as an optical input. A distance measurement of 4 m with a range resolution of 2.5 cm is achieved. The addition of large-aperture optical phased arrays will allow for no external optics and beam steering.





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Fast Stochastic Simulation of Silicon Photonic Devices with Non-Gaussian Correlated Process Variations

T. W. Weng, Z. Zhang, Z. Su, L. Daniel Sponsorship: National Science Foundation

Silicon photonics has attracted much attention in recent years thanks to its ability to achieve higher bandwidth, its lower power dissipation compared to electrical interconnects, and its compatibility and easy integration with CMOS process. However, because of the high contrast of the refractive index between silicon and silica, silicon-based optical devices are very sensitive to manufacturing process variations; for example, the geometric variations in silicon width and thickness can result in a fluctuation of the effective phase index, leading not only to degraded performance in devices such as directional couplers and ring resonators but also to serious failures at the system level.

Despite some results for nanometer integrated circuits (IC), there is still a lack of efficient uncertainty quantification techniques for silicon photonics. Monte Carlo (MC) has been the mainstream statistical simulation technique in commercial design software. However, it suffers from a slow convergence rate and long simulation time. Recently, fast stochastic spectral methods have been developed based on generalized polynomial chaos expansions to efficiently approximate a stochastic solution. However, one of the major assumptions in the existing publications is that the input parameters describing the process variations are mutually independent, which is not always necessarily true. Therefore, our goal is to quantify the effects of silicon photonic process variations using a nonintrusive polynomial chaos scheme called stochastic collocation (SC). A directional coupler in Figure 1 is used as an example to show the technique works. In practical fabrications, due to tolerances of the fabrication process, the fabricated waveguide width and the gap between two waveguides of a directional coupler are different from chip to chip and wafer to wafer, and the exterior and interior waveguide sidewall positions are assumed to be correlated random parameters. The simulated power coupling coefficients are shown in Figure 2. It is clearly seen that the probability density function of the power coupling coefficients obtained by 10000 samples MC and 81 quadrature points SC are in good agreement; however, the simulation time of SC is far less than MC, which is around 55 times speed-up in this example.



▲ Figure 1: A silicon directional coupler. W_0 and g_0 are the nominal value of the waveguide width and gap. ΔW_e and ΔW_i are exterior and interior waveguide sidewall positions, which are assumed to be correlated.



▲ Figure 2: The probability density function of power coupling coefficients of a directional coupler under non-Gaussian process variations. The nominal value is designed to be 0.5 at 1550 nm. The dash line and solid line represent Monte-Carlo simulation and stochastic collocation, respectively.

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Irradiation Defects in Germanium

C. Monmeyran, N. Patel, A. Agarwal, L. C. Kimerling Sponsorship: Defense Threat Reduction Agency

Defects in semiconductors, no matter how they arise, control the properties and consequently the performances of a device. Hence, an understanding of bandgap defect states followed by appropriate defect engineering is crucial for obtaining high-performance devices. A systematic study of defects in silicon has been performed, successfully mapping the characteristics of the defect states within the silicon bandgap. But such an investigation has not yet been achieved in germanium, which, in addition to its usage in electronics, is an essential element for Si microphotonics.

⁶⁰Cobalt (⁶⁰Co) gamma irradiation is used to uniformly create elemental defects, vacancies, and interstitials in a controlled fashion in Czochralskigrown 10¹⁵ cm⁻³ Sb-doped germanium. These primary defects and the complexes they form with lattice impurities are then characterized using deeplevel transient spectroscopy (DLTS), leading to the measurement of defect concentrations, energetic positions within the bandgap and capture cross-sections. Isochronal and isothermal annealing of the gamma-irradiated-germanium are also performed for 0 to 400 min and from room temperature to 200°C.

Figure 1 shows a typical DLTS spectrum obtained after ⁶⁰Co irradiation of Ge, and Figure 2 is the Arrhenius plot corresponding to each peak. The peaks are named according to the apparent activation energies shown in the plot relative to the level position below the conduction band. E_{37} dominates the spectrum and has been reported as the E-center, a vacancy group V impurity complex. The other three defects in this figure, however, have not been systematically reported, and their physical identity remains unknown. The purpose of our study is to gain an insight into the nature of these deep states.



▲ Figure 1: DLTS scan of a room temperature gamma irradiated 10^{15} cm $^{-3}$ Sb-doped Ge at a rate window of 200 s⁻¹ with a filling pulse of 500 us, with reverse voltage and pulse voltage of -5 V and OV, respectively.



▲ Figure 2: Arrhenius behavior of the observed peaks in irradiated Ge from which the activation energies and capture cross-sections are extracted.

Light Modulators for Holographic Video Displays

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Sponsorship: MIT Media Lab research consortium, Center for Terrestrial Sensing, AFRL

Side

In this research (a collaboration with Dr. Daniel Smalley of Brigham Young University), we design and fabricate acousto-optic, guided-wave modulators in proton-exchanged lithium niobate for use in holographic and other high-bandwidth displays. Guided-wave techniques make possible the fabrication of modulators that are higher in bandwidth and lower in cost than analogous bulk-wave acousto-optic devices or other spatial light modulators used for diffractive displays and enable simultaneous modulation of red, green, and blue light. In particular, we are investigating multichannel variants of these devices with an emphasis on maximizing the number of modulating channels to achieve large total bandwidths. To date we have demonstrated multichannel full-color modulators capable of displaying holographic light fields at standard-definition television resolution and at video frame rates. New work aims to make larger direct-view panels based on an extension of this technology and different materials. Figures 1 and 2 show a schematic diagram of our device and an image displayed using it.





 Figure 2: Color holographic image displayed using our modulator.

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Electrically Tunable Organic Vertical-Cavity Surface-Emitting Laser

A. Murarka, W. Chang, A. Wang, J. Lang, V. Bulović

Sponsorship: National Science Foundation Center for Energy Efficient Electronics Science

Development of compact tunable lasing devices, using large-area scalable fabrication techniques, would enable many applications in spectroscopy and remote sensing. Additionally, organic semiconducting thin films can be used as spectrally-broad lasing gain materials, with a demonstrated visible lasing wavelength range of over 100 nm using a single organic guest-host gain medium. However, previously demonstrated frequency-tunable lasing devices have required either complex fabrication techniques, external micro-actuated mirror stages, or manual switching between gain media. Tunable air-gap MEMS microcavity structures offer a scalable, integrated solution, but their conventional fabrication processes are incompatible with solvent- and temperature-sensitive organic gain materials.

We demonstrate an electrically tunable organic laser fabricated using a solvent-free composite membrane transfer technique, which allows us to combine the compact form of a MEMS vertical-cavity surface-emitting laser (VCSEL) with spectrally-broad organic gain media to realize large range tunability in compact laser arrays. The device comprises a composite membrane suspended over cavities in a SU-8 spacer layer atop a distributed Bragg reflector. The suspended membrane incorporates an organic laser gain medium, Alq3:DCM, into the microcavity, and the completed capacitive structure can be electrostatically actuated for dynamic tuning of the optical spectra.

Cavity mode emission and lasing in device arrays is measured using a 400 nm wavelength excitation laser as optical pump. Additionally, bias is applied between the composite membrane and the underlying electrode to deflect the membrane and tune the microcavity length. These devices demonstrate a lasing threshold of 200 µJ/cm², as indicated by the integrated emission intensity and the reduction in the full-width half-max (FWHM) spectral linewidth (Figure 1). Electrical actuation and optical characterization of these devices show reversible lasing mode tuning of 10 nm at 6V bias (Figure 2). The membrane deflection and resulting cavity mode shift vary with the square of the applied voltage, as expected. Optimization of device structure and composition to reduce membrane pull-in effects would allow larger ranges of reversible lasing tunability.



▲ Figure 1: Integrated emission intensity (left axis) and FWHM spectral linewidth (right axis) as a function of estimated excitation energy density. The nonlinear increase in intensity and a sudden decrease in mode linewidth are indicative of a lasing threshold of 200 µJ/cm².



▲ Figure 2: VCSEL wavelength shift under applied bias in two consecutive sweeps shows hysteresis below 1 nm. (inset) Normalized spectra of laser emission at various bias voltages.

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Ultra-Compact Low-Threshold Organic Laser

P. B. Deotare, T. S Mahony, V. Bulović, Sponsorship: EFRC Center for Excitonics, MIT

Lasing has been reported under photo-excitation in organic dye devices with distributed Bragg reflectors, distributed feedback structures, whispering gallery resonators, photonic bandgap fiber resonators, and 2D photonic crystals. However, no demonstration of an electrically pumped organic laser has yet been reported. The major limiting factor is attributed to singlet-triplet annihilation leading to unfeasible threshold current densities. A possible way to tackle this problem is to lower the threshold by controlling the device optical properties.

Here, we try to achieve this by controlling the quality factor/mode volume (Q/V) and/or spontaneous emission factor (β), using a photonic crystal nanobeam cavity (PCNC). Lasing was observed with a threshold of 4.2 μ J/cm² when pumped using femtosecond pulses

of λ = 400 nm wavelength light. We also modeled the dynamics of the laser and show good agreement with the experimental data. The devices are fabricated using a top-down approach, which will assist in scalability during manufacturing. These lasers are the smallest organic lasers to be reported, and their waveguide geometry enables on-chip integration with potential application in data communication.

We anticipate that the results will be the launching pad for further work towards achieving an electrically pumped organic laser as well as open up new research areas in optomechanics (due to a suspended structure) and integrated on-chip photonics (due to waveguide geometry) for applications in motion sensing, biochemical sensing and data communication.



▲ Figure 1: (a) SEM image of the fabricated device. (b) Red filled circles denote the output intensity of the optical mode for various absorbed input pulse energy densities. Blue triangles show the corresponding linewidth of the mode. Linewidth narrowing at threshold is observed as a confirmation for lasing. Inset shows log-log plot of the experimental intensity data. The solid line is the numerical fit to the data. (c) Output spectrum of device below (gray line) and above (red line) threshold.

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Integrated Mid-infrared Laser Based on an Er-doped Chalcogenide Microresonator

Z. Han, L. Zhang, L. C. Kimerling, A. M. Agarwal

Mid-infrared (mid-IR) represents a wavelength range that remains less explored in many optics and photonics branches, e.g., in integrated photonics. Recently, significant research effort has been made to develop passive, active and nonlinear integrated devices in the mid-IR. One key benefit of a monolithically integrated mid-IR device is that it enables compact, potentially energy-efficient and cost-effective systems for sensing, signal processing, and communications. For such systems, an integrated on-chip laser source is critical.

The invention of quantum cascade lasers (QCLs) represents a revolutionary development in this area. However, near the short-wavelength end of the mid-IR range, around 2~4 μ m, the availability of QCLs is quite limited. Another technical approach to lasing in the mid-IR, which has also experienced great advances recently, is rare-earth-doped fiber lasers. Bulk Er³⁺-doped GLS shows

mid-IR photoluminescence emission at 3.6 μm through the transition between ${}^{4}F_{9/2}$ and ${}^{4}I_{9/2}$ energy levels. The correlated pumping wavelength is 0.66 μm , which can be realized by a semiconductor laser.

In this work, we numerically demonstrate the feasibility of building a planar room-temperature low-pump-power integrated mid-IR laser, enabled by a high-Q microresonator. Essentially, the cavity acts as a microring resonator at the signal wavelength in the mid-IR range and is similar to a whispering gallery microdisk resonator at the pump wavelength. With a gap of 100 nm, designs with different coupling lengths (L_c) are simulated. A joint consideration of Q factor (at lasing wavelength) and power enhancement factor (at pumping wavelength, $\eta=P_{ring}/P_{bus}$) reveals an optimal L_c of 0.6 µm, η =50.64 and Q=2.2×10⁵. Threshold power is 7.6 µW, and slope efficiency is 10.26%.



Figure 1: (a) Device configuration of a high-Q microresonator-based mid-IR laser, which consists of a ring resonator with a curved bus waveguide. (b) Cross section of a chalcogenide waveguide that is in an Al_2O_3 trench.



▲ Figure 2: Predicted lasing performance for gap=100 nm and LC=0.6 μ m (a) The influence of the power enhancement on the lasing threshold, and (b) the influence of the cavity Q-factor are shown.

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Design and Manufacture of Bio-Inspired Light-Emitting Optical Micro-Cavities

C. Chazot, Y. Kim, M. Kolle Sponsorship: MTL, MISTI

Optical micro-cavities are structures confining light in a small volume by resonant circulation. They can be constructed from two reflective surfaces sandwiching a gain medium to create light-emitting devices and lasers. The quality factor, representing the ratio between the number of round trips that a photon takes in the cavity and the cavity losses, determines the maximum attainable light amplification.

We design and manufacture optical micro-cavities containing light-emitting organic dyes, which were inspired by a structure found on the wings of the *Papilio blumei* butterfly. In the micro-cavities described here, individual reflectors consist of concave half-spherical metal surfaces with 1 μ m-to-10 μ m diameter topped by a Bragg reflector (Figure 1a). Given their micro-scale dimensions, the cavities support a variety of optical resonances in the visible spectrum (Figure 1b). The cavities' bottom reflector is formed from gold or silver with broadband reflectivity. The second light-confining mirror, a flat Bragg reflector, provides high reflectivity for a selected spectral range. The amplifying medium consists of an organic dye stabilized in a polymer matrix.

The manufacturing of the micro-cavities combines a set of procedures, including the assembly of a colloidal template (Figure 1c), the formation of cavities by electrodeposition of metal in the template's interstitial spaces (Figure 1d), template removal, solvent-based spin-casting of the organic dye, and the creation of a Bragg reflector using chemical vapor deposition. The cavities represent periodically arranged micro-scale light sources (Figure 1e) with potential to be selectively switched on and off. Furthermore, they show interesting optical behaviors such as spectral selectivity, polarization rotation effects, and emission in a broad range of angles. The cavities will be incorporated into microfluidic devices and labon- chip assemblies to provide localized chemical sensing and precise cell imaging for applications in microbiology.



◄ Figure 1: a) Schematic of the resonance cavity layout. b) Finite-Difference-Time-Domain simulations of light fields in the cavities for different light wavelengths marked in the image. c) A monolayer of colloidal particles that serves as a template for the formation of the cavities by electro-deposition. d) Half-spherical gold cavities after electro-deposition and removal of the template. e) Optical micrograph of fluorescing organic dye in the optical cavities.

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Enhancement of Colloidal Quantum Dot Luminescence through Photonic Crystal Cavity Modes

T. S. Mahony, P. B. Deotare, V. Bulović

Sponsorship: National Science Foundation, Department of Energy Center for Excitonics

Colloidal quantum dots are semiconductor nanocrystals that can be used as bright light emitters. Their size tunability allows them to emit across the visible spectrum and has enabled their use in LED displays. They are also promising materials for use in generating optical gain for laser applications. Lasing using colloidal quantum dots has been demonstrated using VCSEL and DFB structures, but neither of these devices forms a compact structure, a desirable attribute for an on-chip laser. We are designing a compact laser with a waveguide geometry suitable for an integrated photonic architecture, and we hope to show a further reduction of lasing threshold in our devices.

To create such a laser, we can separate the design process into two pieces: cavity design and fabrication process. The cavity design follows the guidelines found in the literature for creating a deterministically high quality factor nanobeam photonic crystal cavity. These cavities can achieve a theoretical quality factor (Q) of 10⁵-10⁶ with a mode volume approaching the limit of a cubic half wavelength. Nanobeam photonic crystal cavities are suspended structures that have been demonstrated even for very low index contrast systems such as polymers.

The design of the cavity depends on our ability to create nano-patterned suspended structures of

quantum dots. Though demonstrations of nanopatterned quantum dots can be found in the literature, none have been suspended. To overcome this challenge, we mix our quantum dots into a solution with PMMA. We spin coat these solutions on a silicon substrate, leaving behind a thin composite film of PMMA-QDs. At high weight fractions we found that the quantum dots are thermodynamically driven to phase separate from the PMMA, but at low weight fractions, they remain embedded within the polymer matrix. We confirmed our findings by SEM images taken of the surface of devices shown in Figure 1. These films are then patterned with ebeam lithography and undercut to create suspended structures.

We measure the photoluminescence of the cavity structures under pulsed optical excitation. As Figure 2 shows, we observe significant enhancement in the photoluminescence of the quantum dots through the cavity modes. By fitting these peaks to Lorentzian lineshapes, we can estimate the Qs of each mode to be about 1800; however, for the spectra we took, these Q's were limited by the spectrometer resolution. We are hopeful that under power-dependent optical measurements, these cavities will demonstrate the characteristics of lasing.



▲ Figure 1: SEM image showing the surfaces of films with a weight ratio of 15:1 PMMA:QDs on the left and 150:1 on the right. We see that the quantum dots phase separate from the PMMA at higher weight fractions.



▲ Figure 2: Photoluminescence spectrum of a representative device showing enhanced emission through the cavity mode. Inset: Fit of the cavity mode emission spectrum yields a quality factor of 1981.

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Inkjet Printing High-Resolution Patterning of Quantum Dot-LEDs

G. Azzellino, G. J. Supran, V. Bulović

The high luminescence efficiency and uniquely sizetunable color of solution-processable semiconducting colloidal quantum dots (QDs) highlight their potential for use as both optically- and electricallyexcited luminophores in energy-efficient, substrateindependent, high-color-quality solid-state lighting and thin-film display technologies. Recent advances in the design of electrically-driven QD-LEDs have seen their external quantum efficiencies approach 20%, comparable to those of phosphorescent organic LEDs.

We demonstrate high-resolution patterning of quantum dot light-emitting devices (QD-LEDs) by using the droplet-on-demand inkjet printing of colloidal QDs. By tailoring the solvents of QD solutions and by modifying the surface energy of the layer underlying the printed QD films, we obtain "coffee-stain"-free QD structures. We also introduce a surface treatment, applied before printing, which allows us to shrink the lateral dimensions of droplets. In our demonstrations we shrink the size of printed QD features down to 10 μ m, using single-droplet prints. With the latest generation of "hybrid" QD-LED architectures, we show that both visibleand near infrared-emitting QD-LEDs can be patterned, with pixel areas defined by these single printed droplets. This approach definitely paves the way to the highresolution QD-LED displays.

Inkjet printing offers a new, largely unexplored technique for room temperature, maskless pattering of QD-LEDs, yet inkjet printing is often hampered by the formation of "coffee-stains," which can be difficult to overcome solely through optimization of the driving voltage waveform of the printer-head. Here, solvent tailoring enables "coffee-stain"-free, smooth, and uniform inkjet-printing of QD pixels. Since the technique relies on tailoring the solvent, not the solute, it is readily translatable to most QD solutions.



▲ Figure 1: Optical profilometry of an array of infrared core-shell PbS quantum dots inkjet-printed onto pre-treated ZnO (scale bar is 50 µm).



▲ Figure 2: AFM topography of a "coffee stain"-free droplet of core-shell PbS onto pre-treated ZnO.

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Transport of Charge Transfer States in Organic Blends

P. B. Deotare, W. Chang, E. Hontz, D. N. Congreve, P. D. Reusswig, B. Modtland, M. E. Bahlke, V. Bulović, T. Van Voorhis, M. A. Baldo Sponsorship: EFRC Center for Excitonics, MIT

The dynamics of charge transfer (CT) states, bound combinations of an electron and a hole on separate molecules are perhaps the most controversial topic in organic semiconductor devices. CT states, which mediate efficient generation of free charges, are bound in many systems. Consequently, there has been debate over whether charge generation requires mediation by "hot" (non-equilibrium) CT states. Recent studies, including the 2014 Nature Materials paper by Vandewal et al., have shown that the CT states do not need to be hot to efficiently generate photocurrent. These results only deepen the mystery over the generation of photocurrent in such devices. The central question is now: if they are not hot, then what are the dynamics of CT states?

Here, we present the first direct imaging of CT states. Contrary to expectations, we find that the CT states diffuse, and the transport mechanism seems to be neither the conventional Förster nor Dexter

process. Rather, it seems to be a novel exciton-stretching transport analogous to an "inchworm" motion, where the state moves through the blend by repeatedly extending and then contracting into a new position at the donor-acceptor interface.

Given the short exciton lifetimes characteristic of bulk heterojunction organic solar cells, this work confirms the potential importance of CT state transport, suggesting that CT states are likely to diffuse farther than the Frenkel exciton in many donor-acceptor blends. Since donor-acceptor blends typically exhibit rapid conversion from excitons to CT states, it is possible that CT state diffusion distances in many organic devices exceed that of the initial exciton, highlighting the potential importance and impact of CT state transport on device performance. This work will significantly advance the understanding of CT state dynamics with practical implications for organic optoelectronics.



▲ Figure 1: *m*-MTDATA/3TPYMB Charge transfer blend. Schematic of charge transfer state dynamics.

▲ Figure 2: Diffusion imaging. Setup schematic of the optical microscope with a scanning detector for diffusion imaging measurements.

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Quantum-Spillover Enhanced Surface-Plasmonic Absorption at the Interface of Silver and High-Index Dielectrics

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Surface plasmons (SPs), known as collective oscillations of conduction electrons at a metal-dielectric interface, have attracted interest for several decades. Nanomaterials that strongly absorb visible light through plasmonic effects could be very important for solar-energy devices. It is normally assumed that classical theory, with prescribed frequency-dependent bulk permittivities, reliably captures the SP properties. Quantum effects, despite their academic interest, are usually considered to have negligible effect in practical systems.

We demonstrate an unexpectedly strong surfaceplasmonic absorption at the interface of silver and

1.2(a) +4.0 $\mu_{\rm F} ({
m eV})$ 1.0 \bar{u}_{\prime} -2.0Electron Density n_{-} 0.8Fermi Level Potential $V_{\rm eff}$ -Ag Dielectric 0.6 Air -2.0 SiO_2 0.4 $E_{\rm F}$ Dielectric Ag Dielectrie Al₂O₃ Effective HfO_2 -4.0-d0 TiO 0.2-6.00 -10-5510 0 Position z (Å) 30 4 Response g (arb. u.) 0 00 00 02 Density Variation $\epsilon_{\rm D} \, \delta n_- / \, \bar{n}$ (b) (c) Aiı 3 SiO_2 Ag Dielectric Al_2O_3 HfO-2TiO₂ = 0.05 a₀ (q1 Surface 0 2.53.0 3.54.0-10202.0-200 10 Excitation Energy $\hbar\omega$ (eV) Position z (Å)

▲ Figure 1: (a) Calculated ground-state electron-density profiles and effective-potential profiles for silver in contact with varied dielectrics. (b) Calculated dynamic surface response. (c) Calculated induced density variation.

high-index dielectrics. We show, from first-principles, that due to the lowered metal-to-dielectric workfunction at such interface, conduction electrons display a drastic quantum spillover, causing the interfacial electron-hole pair production to become the predominant dissipation channel (Figure 1). The theoretical prediction is supported experimentally by the electron-energy loss spectroscopy and ultravioletvisible spectrophotometry (Figure 2). This finding can be of fundamental importance in understanding and designing quantum nano-plasmonic devices, which utilize metal-high-index contacts.



▲ Figure 2: (a) Electron energy-loss spectra for 20 nm dielectrics on 20 nm silver. (b) Experimentally measured and theoretically calculated reflection spectra for 20 nm dielectrics on 200 nm silver. The grey curve is the measured reflectance of the bare 200 nm silver as a reference.

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Integrated Graphene-Based Photonic Devices

R. Shiue, J. Goldstein, C. Peng, D. Efetov, D. Englund Sponsorship: Office of Naval Research

Graphene is a single-atom-thick 2D material consisting of a single layer of graphite. Its high carrier mobility, extremely broadband and uniform optical properties, high surface area, CMOS compatibility, and potentially low cost of manufacture make it a promising material for optoelectronic applications (among many others). In particular, graphene's high mobility and extremely fast carrier dynamics make it suitable for applications that require high speed operation, e.g., telecommunications, where digital signals must be modulated onto light using optical modulators and detected using photodetectors. Typically, these optical signals use wavelengths of around 1550 nm, which coincides with the absorption minimum of glass optical fibers. We aim to demonstrate fast, CMOS-compatible waveguide-integrated graphene-based photodetectors and modulators that outperform the state-of-the-art germanium photodetectors and silicon modulators in terms of speed and, ideally, size.

Previously, we reported a waveguide-integrated graphene photodetector (shown in Figure 1) with a high responsivity of up to 0.1 A/W and a bandwidth of above 20 GHz at zero bias operating at wavelengths between 1450 and 1590 nm. In this device, the gold contacts pin the Fermi level of the graphene channel, which, being a 2D material, has a very low density of electronic states. The gold contacts create a jump in the Fermi level near the contacts, which in turn yields a jump in the graphene's Seebeck coefficient. Combining the Fermi level profile with the electron temperature bump from the absorption of light passing through the waveguide, we obtain a measurable thermoelectric voltage, just as in a thermocouple. We are continuing to improve upon these types of devices and to combine them in optical networks.

More recently, we demonstrated an optical reflection modulator involving a silicon photonic crystal cavity transferred on top of a boron nitride (BN)-graphene-BN-graphene-BN stack (a so-called Van der Waals heterostructure) as shown in Figure 2. In this device, a voltage applied between the two graphene layers shifts their Fermi levels, preventing them from absorbing light below a certain frequency due to Pauli blocking. The photonic crystal cavity on top of the graphene "sandwich" supports an optical mode that overlaps with the graphene sheets, allowing absorption of the mode to be controlled by the input voltage. This device shows a 3.2-dB modulation depth and a cutoff frequency of 1.2 GHz.



▲ Figure 1: This graphene photodetector's photoresponse is caused mainly by the photothermoelectric effect, whereby charge carriers heated by the absorbed radiation interact with a nonuniform Seebeck coefficient to generate a photovoltage.



▲ Figure 2: This image depicts a graphene-based reflection modulator. Applying a voltage between the two graphene sheets changes their optical absorption, while a photonic crystal cavity concentrates light in the vicinity of the sheets.

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Free-Space Coupled Superconducting Nanowire Single-Photon Detectors for Mid-IR Optical Communications

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Mid-IR optical communication represents an important technology for naval and astronomical applications. A transmission window in the atmosphere at 10-um-wavelength (λ) allows mid-IR light to travel unperturbed for hundreds of kilometers. In addition, optical communication based on single-photon transmitters and receivers enables secured, high-speed, and low-power communication protocols if the receiver can detect more than 30% of the signal from the transmitter at a data rate of 100 Mbit/s. The superconducting nanowire single-photon detector (SNSPD) is the only existing technology that combines high-speed with single-photon sensitivity in the mid-IR; in order to couple more than 30% of the signal from the transmitter in the mid-IR, free-space optics is necessary. Our goal is to design an experimental apparatus that maximizes the mid-IR light coupled in free-space to an SNSPD.

Figure 1 shows a prototype of a cryogenic system that we designed and built with free-space optical access that couples on the detector more than 50% of the light from a source at λ = 1550 nm, dampens the vibration amplitude at the sample stage to < 400 nm, and has the potential for multiple channel communication. Commercially available cryostats could not meet those characteristics or were either too expensive or based on cryogens. We tested an SNSPD with an active area of 8 × 7.3 μ m² at λ = 1550 nm, and we extrapolated from data that 56.5% of the light from the source hit the detector. An SNSPD can easily be fabricated with an active are of 10 × 10 μ m², which would allow us to couple 76% of the light. Figure 2 shows the oscillation in the count rate of the detector that we used to extrapolate the vibration amplitude of the stage. Knowing the dimensions of the SNSPD and the beam diameter, we extrapolated vibration on the order of 400 nm.

This cryogenic system will be upgraded to work at mid-IR wavelength and to host 4 separate communication channels. Our coupling demonstration was performed at λ = 1550 nm because of our familiarity at that wavelength. Moving to mid-IR optics should simply be a matter choosing lenses with the correct focal length to allow high coupling on the SNSPD. The use of free-space components allows us to add multiple channels at the transmitter without changing the optics. Based on this idea, we will upgrade from single channel to four channels to improve the data rate capabilities of the system.



▲ Figure 1: Free-space coupled mid-IR optical communication system. On the top, we show a schematic of the final system for long distance communication. On the bottom, we show a picture of the prototype that we built and that operates at λ = 1550 nm.



Figure 2: Count rate from an $8 \times 7.3^{\circ} \mu m^2$ area NbN SNSPD as a function of time. The signal beam was positioned at 4.6° μm° from the center of the detector.

FURTHER READING

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Measuring the Timing Jitter of WSi SNSPDs with Integrated nTron Readout

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Superconducting nanowire single photon detectors (SNSPDs) based on tungsten silicide (WSi) have been used to demonstrate the highest reported system detection efficiency at 1550 nm with a single device. However, WSi devices lag behind niobium nitride (NbN) SNSPDs in terms of timing performance, as both the reset time and the timing jitter are one order of magnitude larger in WSi than in NbN devices. WSi SNSPDs have higher jitter than NbN devices due to their lower switching current and lower signal-to-noise ratio (SNR). In order to decrease the jitter of WSi SNSPDs, a nanocryroton (nTron) could be used to increase the output signal after photodetection and thus reduce jitter. The nTron is a three-terminal superconducting device that allows a small gate current to switch a channel current that is orders-of-magnitude larger. The reduction of the jitter of NbN SNSPDs using NbN nTrons has been demonstrated recently.

We designed and fabricated SNSPDs and nTrons on a single layer of 5-nm-thick WSi deposited on SiO_x. We used electron-beam lithography with hydrogen silsesquioxane resist to fabricate devices. This process was shown to yield superconducting WSi devices, and we have demonstrated that the addition of a DC bias current at the nTron gate can strongly suppress the switching current of the nTron channel as shown in Figure 2. Additionally, an off-chip coupling circuit was designed and built to couple the SNSPD output signal into the nTron gate. We used an electro-thermal model of superconducting nanowires contained in SPICE circuit simulation software to design the coupling circuit and ensure that both the SNSPD and the nTron could self-reset while operating at full speed. This work should enable the reduction of noise-related-jitter in WSi SNSPD systems via readout with integrated nTrons.



▲ Figure 1: Helium ion microscope image of WSi nTron fabricated by electron beam lithography. Current sourced into the nTron gate from the right can cause the narrow superconducting section that connects the gate and channel to switch to the normal state. Joule heating in this region reduces the channel's ability to carry current and can lead to switching.



▲ Figure 2: The zero voltage state of the superconducting IV curves of a WSi nTron channel, as a function of the gate current. The channel switching current is strongly suppressed as the gate current is increased above 1.2 microamperes.

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Ionic Conduction Studies in TIBr Radiation Detector Materials

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Detection of high-energy radiation (e.g., γ -rays) is key in nuclear non-proliferation strategies. When a wideband gap semiconductor detector intercepts a γ -ray, electron-hole pairs are formed, resulting in an increase in electrical conductivity, facilitating their detection. As in any photodetecting device, sensitivity is maximized if the conductivity in the non-illuminated (dark) state is very low. While current semiconductor-based technologies require cooling to very low temperatures, adding to cost and reducing portability, TlBr is an attractive detector material given its low room temperature dark conductivity, as well as its high mass density, leading to high radiation absorption. In TlBr the dominant conduction mechanisms when non-illuminated are ionic. This ionic conduction therefore presents itself as a source of leakage current during operation and its minimization is valuable to produce higher performance detectors. A schematic illustrating operation and the presence of the leakage current is shown in Figure 1.

In this project, we characterize the ionic conduction properties of TlBr, dopant association, and exsolution using impedance spectroscopy. Through doping techniques, we have determined that TlBr is primarily a Schottky type ionic conductor, meaning that Tl and Br move through the material by vacancy motion. These measurements have led us to predict a doping strategy to minimize dark conductivity. We take advantage of the detailed defect model that we have established in the investigation of the origin of this long-term performance degradation and its relation to electrode chemistry.



▲ Figure 1: The operating principle of TIBr radiation detectors showing the ionic species contributing to current leakage.