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INVESTIGATOR(S):

Name: DIRK ENGLUND
Email: englund@mit.edu
Phone Number: 6173247014
Principal: Y

Organization: **Massachusetts Institute of Technology (MIT)**
Address: 77 Massachusetts Avenue, Cambridge, MA 021394307
Country: USA
DUNS Number: 001425594
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Submitted By: DIRK ENGLUND
Email: englund@mit.edu
Phone: (617) 324-7014
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STEM Degrees: 2 **STEM Participants:** 5

Major Goals: The ARL-funded project addressed the challenges of generating and manipulating structured light at nanosecond timescales using electronically controlled spatial light modulators (SLMs). Current SLMs have limitations in modulation rate due to their reliance on slow liquid crystal or mechanical response times. The project aimed to investigate an optically controlled "wireless" SLM using state-of-the-art incoherent display technology to dynamically control 2D arrays of small mode volume (V) integrated optical cavities. Recent advances in high-Q/V resonator design and high-efficiency microLED displays allowed for the control of individual optical modes at GHz-order rates with lower power consumption.

The project demonstrated the first large-scale, fully tunable integrated photonic circuits. The resulting ultradense, fully controllable array of free space optical signals has potential applications in fields such as LiDAR, beam forming and steering, optical interconnects, microscopy, and neural networks. The development of an optically controlled SLM with high-speed performance and high pixel density offers new opportunities for optical wavefront shaping, enabling breakthroughs in fields such as biomedical imaging, telecommunications, and quantum information processing.

Accomplishments: We developed a nanopatterned electrolyte gating technique that creates high carrier density variations at the nanometer scale, using a resist mask and cross-linked poly(methyl methacrylate). We demonstrated the technique by fabricating a compact mid-infrared graphene thermopile that can pave the way for more compact high-speed thermal detectors and cameras.

We proposed a new architecture for high-speed spatial light modulators (SLMs) that achieved two-dimensional phase-only modulation at speeds exceeding GHz, using a tunable two-dimensional array of vertically oriented, one-sided microcavities that were tuned through an electro-optic material. The architecture could lead to new applications such as optical computing accelerators and quantum computing with cold atom arrays.

We developed a superconductor-graphene-superconductor (SGS) Josephson junction bolometer embedded in a microwave resonator with over 99% coupling efficiency, using monolayer graphene as an ultimately thin bolometric sensor for sensitive microwave detection. The device achieved a noise equivalent power (NEP) of 7 ×10?19 W/Hz1/2, corresponding to an energy resolution of one single photon at 32 GHz, and reached the fundamental limit imposed by intrinsic thermal fluctuation at 0.19 K.

In collaboration with colleagues at Harvard and BBN Raytheon, we also demonstrated the potential of graphene plasmon modulators as sensitive photodetectors. By combining the graphene plasmonics with a traditional photodetector, we achieved a responsivity of 0.25 A/W at a wavelength of 1.55 ?m, which is significantly higher than the responsivity of traditional photodetectors at this wavelength.

In another study, we investigated the optical properties of graphene in the terahertz regime. We found that the complex conductivity of graphene exhibits a strong dependence on the carrier density, which can be tuned by a gate voltage. By exploiting this dependence, we demonstrated a tunable terahertz metamaterial absorber based on a graphene layer.

We also investigated the effect of doping on the optical properties of graphene. By measuring the complex conductivity of graphene under different doping levels, we found that the doping-induced changes in the optical conductivity are well-described by a Drude model with a renormalized Fermi velocity. Our findings provide a better understanding of the optical properties of doped graphene, which could be useful for the design of graphene-based optical devices.

Finally, we developed a technique for fabricating large-area graphene devices with controlled doping. The technique involved depositing a thin layer of p-type dopant on a graphene layer and annealing the sample to activate the dopant. By controlling the doping level, we demonstrated a tunable graphene-based terahertz absorber with a modulation depth of up to 90%. Our technique could enable the large-scale production of graphene-based devices with controlled doping, which is essential for practical applications.

Training Opportunities: This program has trained three PhD students -- Cheng Peng, Jordan Goldstein, and Christopher Panuski -- and postdoc Dr Bevin Huang.

Results Dissemination: 5.1. Publications:

Cheng Peng, Dmitri K. Efetov, Sebastien Nanot, Ren-Jye Shiue, Gabriele Grosso, Yafang Yang, Marek Hempel, Pablo Jarillo-Herrero, Jing Kong, Frank H. L. Koppens, Dirk Englund, ``Compact mid-infrared graphene thermopile enabled by a nanopatterning technique of electrolyte gates,'' New Journal of Physics 20 (2018)
David Alcaraz Iranzo, Sebastien Nanot, Eduardo J. C. Dias, Itai Epstein, Cheng Peng, Dmitri K. Efetov, Mark B. Lundeberg, Romain Parret, Johann Osmond, Jin-Yong Hong, Jing Kong, Dirk Englund, Nuno M. R. Peres, Frank H. L. Koppens, ``Probing the Ultimate Plasmon Confinement Limits with a Van der Waals heterostructure,'' Science Vol. 360, Issue 6386 (2018)
Cheng Peng, Ryan Hamerly, Mohammad Soltani, Dirk Englund, ``High-Speed Phase-Only Spatial Light Modulators with Two-Dimensional Tunable Microcavity Arrays,'' Optics Express Vol. 27, Issue 21, pp. 30669-30680 (2019)
Gil-Ho Lee, Dmitri K. Efetov, Leonardo Ranzani, Evan D. Walsh, Thomas A. Ohki, Takashi Taniguchi, Kenji Watanabe, Philip Kim, Dirk Englund, Kin Chung Fong, ``Graphene-based Josephson junction microwave bolometer,'' Nature 586, 42–46 (2020)
Irati Alonso Calafell, Lee A. Rozema, David Alcaraz Iranzo, Alessandro Trenti, Philipp K. Jenke, Joel D. Cox, Avinash Kumar, Hlib Bieliaiev, Sébastien Nanot, Cheng Peng, Dmitri K. Efetov, Jin-Yong Hong, Jing Kong, Dirk R. Englund, F. Javier García de Abajo, Frank H. L. Koppens, Philip Walther , ``Giant enhancement of third-harmonic generation in graphene-metal heterostructures,'' Nature Nanotechnology (2020)
Evan D. Walsh, Woochan Jung, Gil-Ho Lee, Dmitri K. Efetov, Bae-Ian Wu, K.-F. Huang, Thomas A. Ohki, Takashi Taniguchi, Kenji Watanabe, Philip Kim, Dirk Englund, Kin Chung Fong, ``Josephson-junction infrared single-photon detector,'' Science 372, Issue 6540, pp. 409-412 (2021)

Kevin Chen, Eric Bersin, Sara L. Mouradian, Dirk Englund, "Alligator Photonic Crystal Cavities in Bulk Diamond," MRS Fall 2019 (12/2/2019)
Hyeongrak Choi, Dirk Englund, "Noise Resilient Entanglement Creation of Remote Quantum Memories," MRS Fall 2019 (12/3/2019)
Cheng Peng, Ryan Hamerly, Mohammad Soltani, Dirk Englund, "High-Speed Phase-Only Spatial Light Modulators with Two-Dimensional Tunable Microcavity Arrays," MRS Fall 2019 (12/2/2019)
Liane Bernstein, Alexander Sludds, Ryan Hamerly, Vivienne Sze, Joel Emer, Dirk Englund, "Digital Optical Neural Networks for Large-Scale Machine Learning," CLEO 2020 (5/11/2020)
Dirk Englund, "Large-Scale Photonic Circuits for Quantum Information Processing," Photonic quantum information processing: DARPA Information Meeting (2/19/2020)
Dirk Englund, "Large-Scale Quantum Photonics for Computing and Communications ," Colloquium at the Max Planck Institute for Quantum Optics, Garching (5/5/2020)
Dirk Englund, "Programmable Photonic Circuits for Quantum Information Processing & Machine Learning," CLEO 2020: Session on Integrated Quantum Photonics: Circuits (FF2D)a (5/15/2020)
Dirk Englund, "Large-Scale Quantum Photonics for Computing and Communications ," Photonics for Quantum Conference #2, Rochester Institute of Technology | Rochester, NY (7/17/2020)
Dirk Englund, "Ab-Initio Solid-State Quantum Materials Design, Production, and Characterization at the Atomic? ? Scale," Office of Secretary of Defense MURI Review Conference (July 7-8, 2020.)
Dirk Englund, "Photonic Accelerators for Machine Intelligence," DARPA Photonics for Computing ERI Workshop (8/19/2020)
Dirk Englund, "System-Level Quantum Photonics Applications and Blueprints," NSF Workshop on Mid-Scale Infrastructure for Quantum Photonic Science, Engineering, and Technology (8/14/2020)
Dirk Englund, "Center for Quantum Networks Briefing ," (8/27/2020)
Dirk Englund, "Large-Scale Quantum Photonics for Computing and Communications ," FIO (9/17/2020)
Dirk Englund, "Photonic Accelerators for Machine Intelligence," IEEE Photonics - Boston (10/21/2020)
Dirk Englund, "Photonic Accelerators for Machine Intelligence," Army Science Planning and Strategy Meeting (11/4/2020)
Dirk Englund, "Photonic Accelerators for Machine Intelligence," NTT Upgrade (9/22/2020)
Dirk Englund, "Programmable Photonics for Optical Accelerators ," NTT PHI (11/12/2020)
Dirk Englund, "Programming Complexity: Large-Scale Photonics for Quantum Information & Machine Learning," Max Planck Institute for Light Distinguished Lecture Series (12/17/2020)
Dirk Englund, "Scalable Quantum Networks with Artificial Atoms ," MRS Fall Meeting (12/4/2020)
Dirk Englund, "Large-Scale Photonics for Quantum Information & Machine Learning," Berkeley Nanosciences and Nanoengineering Institute (4/23/2021)
Dirk Englund, "2D materials for quantum information processing and sensing," Heraeus Symposium on 2D materials (5/28/2021)

Dirk Englund, "Scalable Quantum Technologies with Artificial Atoms in Diamond," NSF Workshop on Quantum Engineering Infrastructure (4/14/2021)
Dirk Englund, "SC455: Integrated Photonics for Quantum Information Science and Technology," CLEO 2021 (5/11/2021)
Dirk Englund, "Programming Complexity: Large-Scale Photonics for Quantum Information & Machine Learning," Stanford SystemX/EE310 Class (2/11/2021)
Dirk Englund, "Large-Scale Photonics for Quantum Information and Machine Learning," Calgary Optics and Photonics Student Society (5/6/2021)
Dirk Englund, "Programmable Photonics for Quantum Information and Machine Learning ," University of Toronto ECE Seminar (10/6/2021)
Dirk Englund, "Quantum Networks using Spins and Photons ," Brookhaven National Laboratory (1/5/2022)
Dirk Englund, "Quantum Networks using Spins and Photons ," International Symposium on Novel maTerials and quantum Technologies (ISNTT 21) (12/15/2022)
Dirk Englund, "Scalable Quantum Networks with Artificial Atoms," 2021 IEEE Research and Applications of Photonics in Defense Conference (RAPID) (7/27/2021)
Dirk Englund, "Programmable Photonics for Quantum Information and Machine Learning," International Max Planck Research Schools (10/26/2021)
Dirk Englund, "2D materials for quantum information processing and sensing," International Conference on Advanced Materials and Devices (ICAMD) - Soul, South Korea (12/6/2021)
Dirk Englund, "Optical Accelerators for Machine Learning: How to Control Errors in Analog Inference Machines?," OFC 2021 (6/9/2021)
Dirk Englund, "Scalable Quantum Networks with Artificial Atoms," U. Cambdrige Quantum Information Workshop (10/8/2021)
Uday Saha, James Siverns, John Hannegan, Univ. of Maryland, College Park (United States); Mihika Prabhu, Eric Bersin, Saumil Bandyopadhyay, Massachusetts Institute of Technology (United States); Jacques Carolan, Univ. College London (United Kingdom); Qudsia Quraishi, DEVCOM Army Research Lab. (United States); Dirk R. Englund, Massachusetts Institute of Technology (United States); Edo Waks, Univ. of Maryland, College Park (United States), "Scalable routing of single photons from a trapped ion on a photonic chip," SPIE Photonics West (7/14/1905)
Dirk Englund and Saikat Guha, "The Center for Quantum Networks, Part I: Building a quantum network using spins and photons," SPIE Photonics West (7/14/1905)
Liane Bernstein, Alexander Sludds, Christopher Panuski, Sivan Trajtenberg-Mills, Ryan Hamerly, Dirk Englund, "Scalable Ultralow Latency Photonic Tensor Processor," CLEO 2022 (5/19/2022)
Ryan Hamerly, Alex Sludds, Liane Bernstein, Lamia Ateshian, Marin Soljacic, Dirk Englund, "Towards Large-Scale Photonic Accelerators for Deep Learning," The 50th Winter Colloquium on the Physics of Quantum Electronics (PQE-2020) (1/5-10/2020)
Ryan Hamerly, Takahiro Inagaki, Peter McMahon, Davide Venturelli, Alireza Marandi, Dirk Englund, Yoshihisa Yamamoto, "Synchronously-pumped OPO coherent Ising machine: benchmarking and prospects," Photonics West OPTO (2/5/2020)
Ryan Hamerly, Alex Sludds, Liane Bernstein, Lamia Ateshian, Marin Soljacic, Dirk Englund, "Towards Optical Neural Networks and Annealing Machines

Honors and Awards: 7. Honors
Dirk Englund: 2017 ACS Photonics Young Investigator Award
Dirk Englund: The OSA's 2017 Adolph Lomb Medal
Dirk Englund: Bose Research Fellowship in 2018
Dirk Englund: Humboldt Research Fellowship (2020)
Dirk Englund: OSA Fellow
Dirk Englund: Humboldt Professorship (awarded)

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Technology Transfer: Working with BBN Raytheon as partner for technology transition

PARTICIPANTS:

Participant Type: Faculty
Participant: Dirk Robert Englund

Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Cheng Peng
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Christopher Panuski
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Article Title: Compact mid-infrared graphene thermopile enabled by a nanopatterning technique of electrolyte gates
Authors: Cheng Peng, Sebastien Nanot, Ren-Jye Shiue, Gabriele Grosso, Yafang Yang, Marek Hempel, Pablo J.
Keywords: graphene, doping
Abstract: In the effort to make 2D materials-based devices smaller, faster, and more efficient, it is important to control charge carrier at lengths approaching the nanometer scale. Traditional gating techniques based on capacitive coupling through a gate dielectric cannot generate strong and uniform electric fields at this scale due to divergence of the fields in dielectrics. This field divergence limits the gating strength, boundary sharpness, and pitch size of periodic structures, and restricts possible geometries of local gates (due to wire packaging), precluding certain device concepts, such as plasmonics and transformation optics based on metamaterials. Here we present a new gating concept based on a dielectric-free self-aligned electrolyte technique that allows spatially modulating charges with nanometer resolution. We employ a combination of a solid-polymer electrolyte gate and an ion-impenetrable e-beam-defined resist mask to locally create excess charges on top of the gated surface.
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Article Title: Probing the ultimate plasmon confinement limits with a van der Waals heterostructure
Authors: David Alcaraz Iranzo, Sébastien Nanot, Eduardo J. C. Dias, Itai Epstein, Cheng Peng, Dmitri K. Efetov,
Keywords: plasmonics, near-field optics
Abstract: The development of nanophotonic technology is reliant on the ability to confine light to spatial dimensions much less than the wavelength of the light itself. Typically, however, in metal plasmonic approaches, there is a trade-off between confinement and losses. Alcaraz Iranzo et al. fabricated heterostructures comprising monolayers of graphene and hexagonal boron nitride (hBN) and an array of metallic rods. The light was confined vertically (as propagating plasmons) between the metal and the graphene, even when the insulating hBN spacer was just a single monolayer. Such heterostructures should provide a powerful and versatile platform for nanophotonics.
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Article Title: Design of high-speed phase-only spatial light modulators with two-dimensional tunable microcavity arrays
Authors: Cheng Peng, Ryan Hamerly, Mohammad Soltani, Dirk R. Englund
Keywords: modulator, photonic, phased array, lidar, holography
Abstract: Spatial light modulators (SLMs) are central to numerous applications ranging from high-speed displays to adaptive optics, structured illumination microscopy, and holography. After decades of advances, SLM arrays based on liquid crystals can now reach large pixel counts exceeding 106 with phase-only modulation with a pixel pitch of less than 10?µm and reflectance around 75%. However, the rather slow modulation speed in such SLMs (below hundreds of Hz) presents limitations for many applications. Here we propose an SLM architecture that can achieve two-dimensional phase-only modulation at high speed in excess of GHz. The architecture consists of a tunable two-dimensional array of vertically oriented, one-sided microcavities that are tuned through an electro-optic material such as barium titanate (BTO). We calculate that the optimized microcavity design achieves a ? phase shift under an applied bias voltage below 10 V, while maintaining nearly constant reflection amplitude. As two model ap
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Authors: Gil-Ho Lee, Dmitri K. Efetov, Woochan Jung, Leonardo Ranzani, Evan D. Walsh, Thomas A. Ohki, Taka
Keywords: quantum , microwave, detector
Abstract: Sensitive microwave detectors are critical instruments in radioastronomy, dark matter axion searches, superconducting quantum information science. The conventional strategy towards higher-sensitivity bolometry is to nanofabricate an ever-smaller device to augment the thermal response. However, this direction is increasingly more difficult to obtain efficient photon coupling and maintain the material properties in a device with a large surface-to-volume ratio. Here we advance this concept to an ultimately thin bolometric sensor based on monolayer graphene. To utilize its minute electronic specific heat and thermal conductivity, we develop a superconductor-graphene-superconductor (SGS) Josephson junction bolometer embedded in a microwave resonator of resonant frequency 7.9 GHz with over 99\% coupling efficiency. From the dependence of the Josephson switching current on the operating temperature, charge density, input power, frequency, we demonstrate a noise equivalent power (NEP) of 7 ×
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Authors: Irati Alonso Calafell, Lee A. Rozema, David Alcaraz Iranzo, Alessandro Trenti, Philipp K. Jenke, Joel D.
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Abstract: please see website
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Authors: Evan D. Walsh, Woochan Jung, Gil-Ho Lee, Dmitri K. Efetov, Bae-Ian Wu, K.-F. Huang, Thomas A. Ohk
Keywords: single photon detection
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PATENTS:

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Patent Title: High-Speed Near-Wavelength Spatial Light Modulators with Two-Dimensional Tunable Microcavity Arrays
Patent Abstract: A reflective spatial light modulator (SLM) made of a tunable, two-dimensional (2D) array of vertic
Patent Number: MIT-21171P01
Patent Country: USA
Application Date: 09-Jul-2019 Application Status: 1
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Partners

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I certify that the information in the report is complete and accurate:
Signature: Dirk Englund
Signature Date: 3/15/23 2:00AM

ARL Award Number: ***W911NF-17-1-0435***

Project Title: ***Ultrafast Spatial Light Modulation by Optical Control***

Principal Investigator: ***Dirk Englund***

1. Distribution Statement

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2. What are the major goals and objectives of the project?

The ARL-funded project addressed the challenges of generating and manipulating structured light at nanosecond timescales using electronically controlled spatial light modulators (SLMs). Current SLMs have limitations in modulation rate due to their reliance on slow liquid crystal or mechanical response times. The project aimed to investigate an optically controlled "wireless" SLM using state-of-the-art incoherent display technology to dynamically control 2D arrays of small mode volume (V) integrated optical cavities. Recent advances in high-Q/V resonator design and high-efficiency microLED displays allowed for the control of individual optical modes at GHz-order rates with lower power consumption.

The project demonstrated the first large-scale, fully tunable integrated photonic circuits. The resulting ultradense, fully controllable array of free space optical signals has potential applications in fields such as LiDAR, beam forming and steering, optical interconnects, microscopy, and neural networks. The development of an optically controlled SLM with high-speed performance and high pixel density offers new opportunities for optical wavefront shaping, enabling breakthroughs in fields such as biomedical imaging, telecommunications, and quantum information processing.

3. What was accomplished so far towards achieving these goals?

Let me summarize first before providing more detail and paper references:

1. *We developed a nanopatterned electrolyte gating technique that creates high carrier density variations at the nanometer scale, using a resist mask and cross-linked poly(methyl methacrylate). We demonstrated the technique by fabricating a compact mid-infrared graphene thermopile that can pave the way for more compact high-speed thermal detectors and cameras.*
2.

3. *We proposed a new architecture for high-speed spatial light modulators (SLMs) that achieved two-dimensional phase-only modulation at speeds exceeding GHz, using a tunable two-dimensional array of vertically oriented, one-sided microcavities that were tuned through an electro-optic material. The architecture could lead to new applications such as optical computing accelerators and quantum computing with cold atom arrays.*
4. *We developed a superconductor-graphene-superconductor (SGS) Josephson junction bolometer embedded in a microwave resonator with over 99% coupling efficiency, using monolayer graphene as an ultimately thin bolometric sensor for sensitive microwave detection. The device achieved a noise equivalent power (NEP) of 7 ×10?19 W/Hz1/2, corresponding to an energy resolution of one single photon at 32 GHz, and reached the fundamental limit imposed by intrinsic thermal fluctuation at 0.19 K.*
5. *In collaboration with colleagues at Harvard and BBN Raytheon, we also demonstrated the potential of graphene plasmon modulators as sensitive photodetectors. By combining the graphene plasmonics with a traditional photodetector, we achieved a responsivity of 0.25 A/W at a wavelength of 1.55 ?m, which is significantly higher than the responsivity of traditional photodetectors at this wavelength.*
6. *In another study, we investigated the optical properties of graphene in the terahertz regime. We found that the complex conductivity of graphene exhibits a strong dependence on the carrier density, which can be tuned by a gate voltage. By exploiting this dependence, we demonstrated a tunable terahertz metamaterial absorber based on a graphene layer.*
7. *We also investigated the effect of doping on the optical properties of graphene. By measuring the complex conductivity of graphene under different doping levels, we found that the doping-induced changes in the optical conductivity are well-described by a Drude model with a renormalized Fermi velocity. Our findings provide a better understanding of the optical properties of doped graphene, which could be useful for the design of graphene-based optical devices.*
8. *Finally, we developed a technique for fabricating large-area graphene devices with controlled doping. The technique involved depositing a thin layer of p-type dopant on a graphene layer and annealing the sample to activate the dopant. By controlling the doping level, we demonstrated a tunable graphene-based terahertz absorber with a modulation depth of up to 90%. Our technique could enable the large-scale production of graphene-based devices with controlled doping, which is essential for practical applications.*

Compact mid-infrared graphene thermopile enabled by a nanopatterning technique of electrolyte gates

In our recent study, we addressed a major challenge in 2D material-based device fabrication by developing a nanopatterned electrolyte gating concept that allowed for the creation of excess charges at the nanometer scale. By combining electrolyte gating with an ion-impenetrable e-beam-defined resist mask, we were able to overcome the limitations of traditional gating techniques based on capacitive coupling through a gate dielectric. Our electrostatic simulations indicated high carrier density variations of $\Delta n \sim 10^{14}$ cm^{-2} across a length of only 15 nm at the mask boundaries on the surface of a 2D conductor.

To implement this technique, we used cross-linked poly(methyl methacrylate) and experimentally proved its ion-impenetrability. We also demonstrated e-beam patterning of the resist mask down to 30 nm half-pitch resolution. The spatial versatility of our technique allowed us to demonstrate a compact mid-infrared graphene thermopile with a geometry optimized for Gaussian incident radiation. The thermopile had a small footprint despite the number of thermocouples in the device, paving the way for more compact high-speed thermal detectors and cameras.

Overall, our results demonstrated the potential of nanopatterned electrolyte gating for the fabrication of faster, smaller, and more efficient 2D material-based devices with high carrier density variations at the nanometer scale. By overcoming the limitations of traditional gating techniques, our approach could enable the development of new device concepts such as plasmonics and metamaterials based on spatial charge density variation.

Publication: Cheng Peng, Dmitri K. Efetov, Sebastien Nanot, Ren-Jye Shiue, Gabriele Grosso, Yafang Yang, Marek Hempel, Pablo Jarillo-Herrero, Jing Kong, Frank H. L. Koppens, Dirk Englund, ``Compact mid-infrared graphene thermopile enabled by a nanopatterning technique of electrolyte gates," New Journal of Physics 20 (2018)

Abstract: A central challenge in making two-dimensional (2D) material-based devices faster, smaller, more efficient is to control their charge carrier density at the nanometer scale. Traditional gating techniques based on capacitive coupling through a gate dielectric cannot generate strong and uniform electric fields at this scale due to divergence of the fields in dielectrics. This field divergence limits the gating strength, boundary sharpness, minimum feature size of local gates, precluding certain device concepts (such as plasmonics and metamaterials based on spatial charge density variation) and resulting in large device footprints. Here we present a nanopatterned electrolyte gating concept that allows locally creating excess charges by combining electrolyte gating with an ion-impenetrable e-beam-defined resist mask.

Electrostatic simulations indicate high carrier density variations of Δn ~ 1014 cm−2 across a length of only 15 nm at the mask boundaries on the surface of a 2D conductor. We implement this technique using cross-linked poly(methyl methacrylate), experimentally prove its ion-impenetrability and demonstrate e-beam patterning of the resist mask down to 30 nm half-pitch resolution. The spatial versatility enables us to demonstrate a compact mid-infrared graphene thermopile with a geometry optimized for Gaussian incident radiation. The thermopile has a small footprint despite the number of thermocouples in the device, paving the way for more compact high-speed thermal detectors and cameras.

High-Speed Phase-Only Spatial Light Modulators with Two-Dimensional Tunable Microcavity Arrays

Spatial light modulators (SLMs) have been used in numerous applications ranging from high-speed displays to adaptive optics, structured illumination microscopy, and holography. Despite decades of advances, SLM arrays based on liquid crystals had slow modulation speeds that presented limitations for many applications. In support of this program, we proposed a new SLM architecture that could achieve two-dimensional phase-only modulation at high speed in excess of GHz. We proposed this architecture in dielectrics instead of graphene since our graphene didn't reach sufficient quality during this program and we wanted to move the applications forward.

The architecture consisted of a tunable two-dimensional array of vertically oriented, one-sided microcavities that were tuned through an electro-optic material such as barium titanate (BTO). The optimized microcavity design achieved a π phase shift under an applied bias voltage below 10 V while maintaining nearly constant reflection amplitude.

As two model applications, high-speed 2D beam steering, and beam forming were considered. The outlined design methodology could also benefit the future design of spatial light modulators with other specifications, for example, amplitude modulators.

This high-speed SLM architecture promised a wide range of new applications ranging from fully tunable metasurfaces to optical computing accelerators, high-speed interconnects, true 2D phased array beam steering, and quantum computing with cold atom arrays.

Publication: Cheng Peng, Ryan Hamerly, Mohammad Soltani, Dirk Englund, ``High-Speed Phase-Only Spatial Light Modulators with Two-Dimensional Tunable Microcavity Arrays," Optics Express Vol. 27, Issue 21, pp. 30669-30680 (2019)
Acknowledgement: The research leading to these results has received funding from the US Army

Research Office (Award W911NF-17-1-0435)

Abstract: Spatial light modulators (SLMs) are central to numerous applications ranging from high-speed displays to adaptive optics, structured illumination microscopy, holography. After decades of advances, SLM arrays based on liquid crystals can now reach large pixel counts exceeding 106 with phase-only modulation with a pixel pitch of less than 10 μm and reflectance around 75%. However, the rather slow modulation speed in such SLMs (below hundreds of Hz) presents limitations for many applications. Here we propose an SLM architecture that can achieve two-dimensional phase-only modulation at high speed in excess of GHz. The architecture consists of a tunable two-dimensional array of vertically oriented, one-sided microcavities that are tuned through an electro-optic material such as barium titanate (BTO). We calculate that the optimized microcavity design achieves a π phase shift under an applied bias voltage below 10 V, while maintaining nearly constant reflection amplitude. As two model applications, we consider high-speed 2D beam steering as well as beam forming. The outlined design methodology could also benefit future design of spatial light modulators with other specifications (for example amplitude modulators). This high-speed SLM architecture promises a wide range of new applications ranging from fully tunable metasurfaces to optical computing accelerators, high-speed interconnects, true 2D phased array beam steering, quantum computing with cold atom arrays.

Graphene-based Josephson junction microwave bolometer

As part of our development of graphene plasmon modulators, we unlocked unforeseen new possibilities. In particular, in a collaboration with colleagues at Harvard and BBN Raytheon (especially Dr KC Fong), we advanced the concept of using monolayer graphene as an ultimately thin bolometric sensor for sensitive microwave detection in radioastronomy, dark matter axion searches, and superconducting quantum information science. The conventional strategy of nanofabricating smaller devices to augment thermal response is becoming increasingly difficult. To overcome this challenge, we developed a superconductor-graphene-superconductor (SGS) Josephson junction bolometer embedded in a microwave resonator of resonant frequency 7.9 GHz with over 99% coupling efficiency.

By utilizing the minute electronic specific heat and thermal conductivity of graphene, we were able to achieve a noise equivalent power (NEP) of 7 ×10−19 W/Hz1/2, corresponding to an energy resolution of one single photon at 32 GHz. The dependence of the Josephson switching current on the operating temperature, charge density, input power, and frequency was also analyzed. Our results demonstrate that we reached the fundamental limit imposed by intrinsic thermal fluctuation at 0.19 K. This represents a significant achievement in the field of microwave detection, and our findings provide a promising avenue for future advances in this area of *research.*

Sensitive microwave detectors are critical instruments in radioastronomy, dark matter axion searches, superconducting quantum information science. The conventional strategy towards higher-sensitivity bolometry is to nanofabricate an ever-smaller device to augment the thermal response. However, this direction is increasingly more difficult to obtain efficient photon coupling and maintain the material properties in a device with a large surface-to-volume ratio. Here we advance this concept to an ultimately thin bolometric sensor based on monolayer graphene. To utilize its minute electronic specific heat and thermal conductivity, we develop a superconductor-graphene-superconductor (SGS) Josephson junction bolometer embedded in a microwave resonator of resonant frequency 7.9 GHz with over 99\% coupling efficiency. From the dependence of the Josephson switching current on the operating temperature, charge density, input power, frequency, we demonstrate a noise equivalent power (NEP) of 7 ×10−19 W/Hz1/2, corresponding to an energy resolution of one single photon at 32 GHz and reaching the fundamental limit imposed by intrinsic thermal fluctuation at 0.19 K.

Publication: Gil-Ho Lee, Dmitri K. Efetov, Leonardo Ranzani, Evan D. Walsh, Thomas A. Ohki, Takashi Taniguchi, Kenji Watanabe, Philip Kim, Dirk Englund, Kin Chung Fong, ``Graphene-based Josephson junction microwave bolometer,'' Nature 586, 42–46 (2020)

Acknowledgement: We acknowledge discussions with L. Levitov, M.-H. Nguyen and W. Kalfus. We thank H.-J. Lee for fabrication facility support for some of the devices. W.J. and G.-H.L. acknowledge support from the Samsung Science and Technology Foundation under Project Number SSTFBA1702-05. D.K.E. acknowledges support from the Ministry of Economy and Competitiveness of Spain through the "Severo Ochoa" programme for Centres of Excellence in R&D (SE5-0522), Fundació Privada Cellex, Fundació Privada Mir-Puig, Generalitat de Catalunya through the CERCA programme, the H2020 Programme under grant agreement 820378 (project 2D·SIPC) and the La Caixa Foundation. The work of E.D.W. and D.E. was supported in part by the Army Research Laboratory Institute for Soldier Nanotechnologies programme W911NF-18-2-0048 and the US Army Research Laboratory (award W911NF-17-1-0435). K.W. and T.T. acknowledge support from the Elemental Strategy Initiative conducted by MEXT, Japan, grant number JPMXP0112101001, JSPS KAKENHI grant number JP20H00354 and CREST(JPMJCR15F3), JST. The work of P.K. and K.C.F. was supported by the US Army Research Office under Cooperative Agreement number W911NF-17-1-0574.)"

Progress on mid-IR beam steering

We also worked on the investigation of the optical conductivity spatial modulation device concept, and fabricated devices on CVD graphene transferred on a SiO2 substrate. Nanoribbon-shaped spatial modulation of optical conductivity was enabled by the nanopatterned electrolyte gates with various dimensions. Such devices were designed to have plasmonic resonances in the 4-10 µm range, according to finite difference time domain (FDTD) simulations. We were in the process of characterizing the voltage-tunable optical transmission of these devices in the mid-IR with FTIR measurements. The results were compared to those for etched graphene nanostructures on the same substrate with the same CVD-grown graphene sample, fabricated and characterized previously as a reference. This allowed us to evaluate the role played by edge scattering loss in etched graphene plasmonic nanostructures.

(a) Graphene synthesis and transfer:

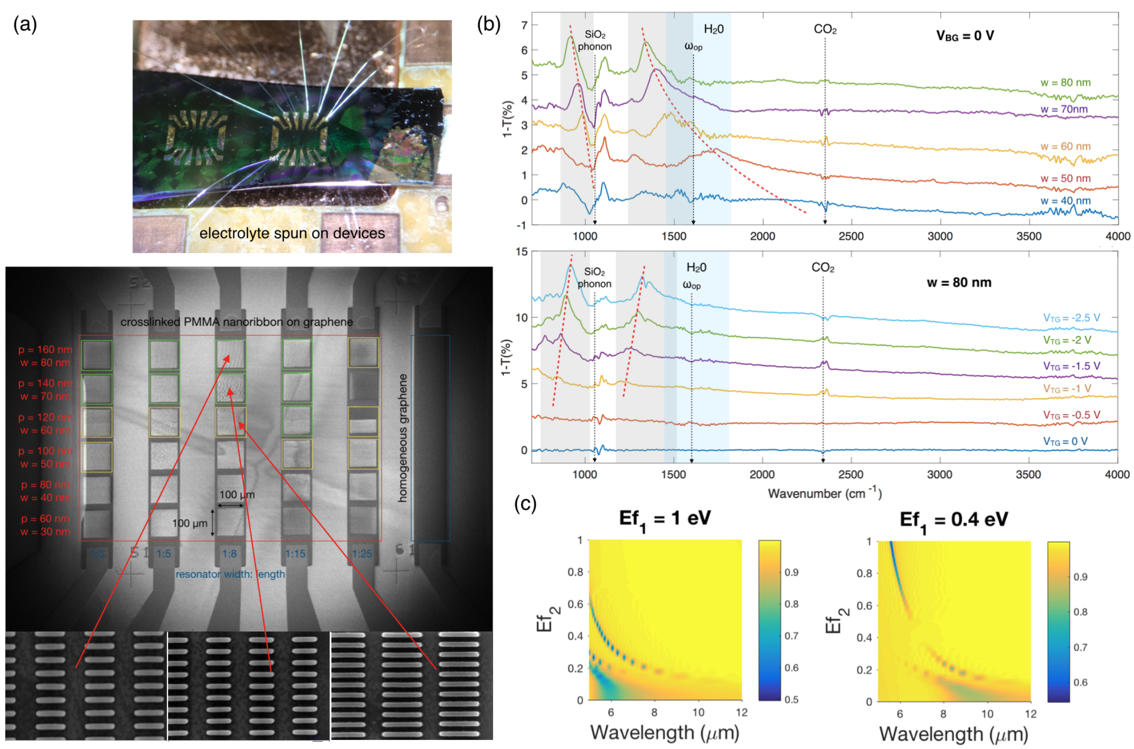

Figure 1 *Preliminary test results on graphene transfer and spectroscopy,*

In our research on graphene nanostructures, we identified the importance of selecting the *appropriate substrate for CVD graphene samples. We found that nanometer-scale strain variations in the graphene sample, caused by random pseudo-magnetic field fluctuations from the substrate, were the main source of disorder. This strain variation limited both carrier mobility in microscopic transport characterization of the devices and carrier scattering rate and lifetime, which were essential to the quality factor of plasmons. Therefore, finding the right substrate for graphene and optimizing the material transfer method in the fabrication process became key tasks for achieving our goal.*

Working with Prof Jing Kong and her group, we synthesized monolayer single-crystalline hBN flakes with sizes up to 50 μm and continuous polycrystalline hBN films centimeter in size, making them ideal substrate choices for graphene due to their atomically flat surface that allowed minimal strain in graphene. We also developed a vacuum-based dry transfer setup for wafer-scale thin film transfer of CVD 2D materials to realize low-strain and high-mobility CVD graphene on CVD hBN. This was necessary because in the wet transfer process, strain caused by trapped water bubbles between graphene and hBN surface was hard to avoid.

(b) Fabrication of graphene nanoscale carrier density modulation devices and preliminary FTIR characterization

*We investigated the concept of the optical conductivity spatial modulation device. We made devices on a SiO2 substrate with CVD graphene transferred onto it. Nanopatterned electrolyte gates with various dimensions (width = 30 nm to 80 nm) enabled nanoribbon-shaped spatial modulation of optical conductivity (*Fig. 1*(a)). We designed these devices to have plasmonic resonances in the 4-10 μm range, according to finite difference time domain (FDTD) simulations (*Fig. 1 *(c)).*

We characterized the voltage-tunable optical transmission of these devices in the mid-IR with FTIR measurements. We compared the results to those for etched graphene nanostructures on the same substrate with the same CVD-grown graphene sample, fabricated and characterized previously as a reference (Figure 2(b)). This allowed us to evaluate the role played by edge scattering loss in etched graphene plasmonic nanostructures.

The FTIR transmission spectra of the reference devices with etched graphene nanostructures with different dimensions and different graphene Fermi levels (gate voltages) are shown in Figure 2(b). The optical microscope and scanning electron microscope (SEM) images of optical conductivity modulation devices enabled by nanopatterning electrolyte gates are also shown in Figure 2(a). The SEM images show devices with cross-linked PMMA masks prior to electrolyte deposition.

We are pleased to report that our investigations have yielded promising results. We have successfully demonstrated the voltage-tunable optical transmission of these devices in the mid-IR range. Our findings will contribute to the development of more efficient and versatile plasmonic devices.

4. Training

This program has trained three PhD students -- Cheng Peng, Jordan Goldstein, and Christopher Panuski -- and postdoc Dr Bevin Huang.

5. Dissemination

5.1. Publications:

1. *Cheng Peng, Dmitri K. Efetov, Sebastien Nanot, Ren-Jye Shiue, Gabriele Grosso, Yafang Yang, Marek Hempel, Pablo Jarillo-Herrero, Jing Kong, Frank H. L. Koppens, Dirk Englund, ``Compact mid-infrared graphene thermopile enabled by a nanopatterning technique of electrolyte gates,'' New Journal of Physics 20 (2018)*
2. *David Alcaraz Iranzo, Sebastien Nanot, Eduardo J. C. Dias, Itai Epstein, Cheng Peng, Dmitri K. Efetov, Mark B. Lundeberg, Romain Parret, Johann Osmond, Jin-Yong Hong, Jing Kong, Dirk Englund, Nuno M. R. Peres, Frank H.L. Koppens, ``Probing the Ultimate Plasmon Confinement Limits with a Van der Waals heterostructure,'' Science Vol. 360, Issue 6386 (2018)*
3. *Cheng Peng, Ryan Hamerly, Mohammad Soltani, Dirk Englund, ``High-Speed Phase-Only Spatial Light Modulators with Two-Dimensional Tunable Microcavity Arrays,'' Optics Express Vol. 27, Issue 21, pp. 30669-30680 (2019)*
4. *Gil-Ho Lee, Dmitri K. Efetov, Leonardo Ranzani, Evan D. Walsh, Thomas A. Ohki, Takashi Taniguchi, Kenji Watanabe, Philip Kim, Dirk Englund, Kin Chung Fong, ``Graphene-based Josephson junction microwave bolometer,'' Nature 586, 42–46 (2020)*
5. *Irati Alonso Calafell, Lee A. Rozema, David Alcaraz Iranzo, Alessandro Trenti, Philipp K. Jenke, Joel D. Cox, Avinash Kumar, Hlib Bieliaiev, Sébastien Nanot, Cheng Peng, Dmitri K. Efetov, Jin-Yong Hong, Jing Kong, Dirk R. Englund, F. Javier García de Abajo, Frank H. L. Koppens, Philip Walther , ``Giant enhancement of third-harmonic generation in graphene-metal heterostructures,'' Nature Nanotechnology (2020)*

6. *Evan D. Walsh, Woochan Jung, Gil-Ho Lee, Dmitri K. Efetov, Bae-Ian Wu, K.-F. Huang, Thomas A. Ohki, Takashi Taniguchi, Kenji Watanabe, Philip Kim, Dirk Englund, Kin Chung Fong, ``Josephson-junction infrared single-photon detector,'' Science 372, Issue 6540, pp. 409-412 (2021)*

5.2. Research Presentations

- *Kevin Chen, Eric Bersin, Sara L. Mouradian, Dirk Englund, ''Alligator Photonic Crystal Cavities in Bulk Diamond,'' MRS Fall 2019 (12/2/2019)*
- *Hyeongrak Choi, Dirk Englund, ''Noise Resilient Entanglement Creation of Remote Quantum Memories,'' MRS Fall 2019 (12/3/2019)*
- *Cheng Peng, Ryan Hamerly, Mohammad Soltani, Dirk Englund, ''High-Speed Phase-Only Spatial Light Modulators with Two-Dimensional Tunable Microcavity Arrays,'' MRS Fall 2019 (12/2/2019)*
- *Liane Bernstein, Alexander Sludds, Ryan Hamerly, Vivienne Sze, Joel Emer, Dirk Englund, ''Digital Optical Neural Networks for Large-Scale Machine Learning,'' CLEO 2020 (5/11/2020)*
- *Dirk Englund, ''Large-Scale Photonic Circuits for Quantum Information Processing,'' Photonic quantum information processing: DARPA Information Meeting (2/19/2020)*
- *Dirk Englund, ''Large-Scale Quantum Photonics for Computing and Communications ,'' Colloquium at the Max Planck Institute for Quantum Optics, Garching (5/5/2020)*
- *Dirk Englund, ''Programmable Photonic Circuits for Quantum Information Processing & Machine Learning,'' CLEO 2020: Session on Integrated Quantum Photonics: Circuits (FF2D)a (5/15/2020)*
- *Dirk Englund, ''Large-Scale Quantum Photonics for Computing and Communications ,'' Photonics for Quantum Conference #2, Rochester Institute of Technology | Rochester, NY (7/17/2020)*
- *Dirk Englund, ''Ab-Initio Solid-State Quantum Materials Design, Production, and Characterization at the Atomic Scale,'' Office of Secretary of Defense MURI Review Conference (July 7-8, 2020.)*
- *Dirk Englund, ''Photonic Accelerators for Machine Intelligence,'' DARPA Photonics for Computing ERI Workshop (8/19/2020)*

- *Dirk Englund, ''System-Level Quantum Photonics Applications and Blueprints,'' NSF Workshop on Mid-Scale Infrastructure for Quantum Photonic Science, Engineering, and Technology (8/14/2020)*
- *Dirk Englund, ''Center for Quantum Networks Briefing ,'' (8/27/2020)*
- *Dirk Englund, ''Large-Scale Quantum Photonics for Computing and Communications ,'' FIO (9/17/2020)*
- *Dirk Englund, ''Photonic Accelerators for Machine Intelligence,'' IEEE Photonics - Boston (10/21/2020)*
- *Dirk Englund, ''Photonic Accelerators for Machine Intelligence,'' Army Science Planning and Strategy Meeting (11/4/2020)*
- *Dirk Englund, ''Photonic Accelerators for Machine Intelligence,'' NTT Upgrade (9/22/2020)*
- *Dirk Englund, ''Programmable Photonics for Optical Accelerators ,'' NTT PHI (11/12/2020)*
- *Dirk Englund, ''Programming Complexity: Large-Scale Photonics for Quantum Information & Machine Learning,'' Max Planck Institute for Light Distinguished Lecture Series (12/17/2020)*
- *Dirk Englund, ''Scalable Quantum Networks with Artificial Atoms ,'' MRS Fall Meeting (12/4/2020)*
- *Dirk Englund, ''Large-Scale Photonics for Quantum Information & Machine Learning,'' Berkeley Nanosciences and Nanoengineering Institute (4/23/2021)*
- *Dirk Englund, ''2D materials for quantum information processing and sensing,'' Heraeus Symposium on 2D materials (5/28/2021)*
- *Dirk Englund, ''Scalable Quantum Technologies with Artificial Atoms in Diamond,'' NSF Workshop on Quantum Engineering Infrastructure (4/14/2021)*
- *Dirk Englund, ''SC455: Integrated Photonics for Quantum Information Science and Technology,'' CLEO 2021 (5/11/2021)*
- *Dirk Englund, ''Programming Complexity: Large-Scale Photonics for Quantum Information & Machine Learning,'' Stanford SystemX/EE310 Class (2/11/2021)*
- *Dirk Englund, ''Large-Scale Photonics for Quantum Information and Machine Learning,'' Calgary Optics and Photonics Student Society (5/6/2021)*
- *Dirk Englund, ''Programmable Photonics for Quantum Information and Machine Learning ,'' University of Toronto ECE Seminar (10/6/2021)*
- *Dirk Englund, ''Quantum Networks using Spins and Photons ,'' Brookhaven National Laboratory (1/5/2022)*
- *Dirk Englund, ''Quantum Networks using Spins and Photons ,'' International Symposium on Novel maTerials and quantum Technologies (ISNTT 21) (12/15/2022)*

- *Dirk Englund, ''Scalable Quantum Networks with Artificial Atoms,'' 2021 IEEE Research and Applications of Photonics in Defense Conference (RAPID) (7/27/2021)*
- *Dirk Englund, ''Programmable Photonics for Quantum Information and Machine Learning,'' International Max Planck Research Schools (10/26/2021)*
- *Dirk Englund, ''2D materials for quantum information processing and sensing,'' International Conference on Advanced Materials and Devices (ICAMD) - Soul, South Korea (12/6/2021)*
- *Dirk Englund, ''Optical Accelerators for Machine Learning: How to Control Errors in Analog Inference Machines?,'' OFC 2021 (6/9/2021)*
- *Dirk Englund, ''Scalable Quantum Networks with Artificial Atoms,'' U. Cambdrige Quantum Information Workshop (10/8/2021)*
- *Uday Saha, James Siverns, John Hannegan, Univ. of Maryland, College Park (United States); Mihika Prabhu, Eric Bersin, Saumil Bandyopadhyay, Massachusetts Institute of Technology (United States); Jacques Carolan, Univ. College London (United Kingdom); Qudsia Quraishi, DEVCOM Army Research Lab. (United States); Dirk R. Englund, Massachusetts Institute of Technology (United States); Edo Waks, Univ. of Maryland, College Park (United States), ''Scalable routing of single photons from a trapped ion on a photonic chip,'' SPIE Photonics West (7/14/1905)*
- *Dirk Englund and Saikat Guha, ''The Center for Quantum Networks, Part I: Building a quantum network using spins and photons,'' SPIE Photonics West (7/14/1905)*
- *Liane Bernstein, Alexander Sludds, Christopher Panuski, Sivan Trajtenberg-Mills, Ryan Hamerly, Dirk Englund, ''Scalable Ultralow Latency Photonic Tensor Processor,'' CLEO 2022 (5/19/2022)*
- *Ryan Hamerly, Alex Sludds, Liane Bernstein, Lamia Ateshian, Marin Soljacic, Dirk Englund, ''Towards Large-Scale Photonic Accelerators for Deep Learning,'' The 50th Winter Colloquium on the Physics of Quantum Electronics (PQE-2020) (1/5-10/2020)*
- *Ryan Hamerly, Takahiro Inagaki, Peter McMahon, Davide Venturelli, Alireza Marandi, Dirk Englund, Yoshihisa Yamamoto, ''Synchronously-pumped OPO coherent Ising machine: benchmarking and prospects,'' Photonics West OPTO (2/5/2020)*
- *Ryan Hamerly, Alex Sludds, Liane Bernstein, Lamia Ateshian, Marin Soljacic, Dirk Englund, ''Towards Optical Neural Networks and Annealing Machines at the Quantum Limit,'' SIAM PP20 (2/15/2020)*
- *Ryan Hamerly, Alex Sludds, Liane Bernstein, Lamia Ateshian, Marin Soljacic, Dirk Englund, ''Scalable Optical Neural Networks based on Coherent Detection,'' ECOC 2020 (12/6/2020)*

- *Ryan Hamerly, Alexander Sludds, Liane Bernstein, Vivienne Sze, Joel Emer, Marin Soljacic, Dirk Englund, ''Progress on photonic tensor processors based on time multiplexing and photoelectric multiplication,'' Photonics West OPTO (3/6/2021)*
- *Ryan Hamerly, Saumil Bandyopadhyay, Dirk Englund, ''Robust zero-change self-configuration of the rectangular mesh,'' OFC 2021 (6/8/2021)*
- *Ryan Hamerly, Alex Sludds, Liane Bernstein, Marin Soljacic, Dirk Englund, ''Progress on optical neural networks based on time multiplexing and coherent detection,'' ISC HPC 2021 (6/28/2021)*
- *Ryan Hamerly, Alexander Sludds, Saumil Bandyopadhyay, Liane Bernstein, Zaijun Chen, Manya Ghobadi, and Dirk Englund, ''Low-Power Edge Computing with WDM-defined Optical Neural Networks,'' SPIE Optics+Photonics 2021 (8/3/2021)*
- *Ryan Hamerly, Saumil Bandyopadhyay, Alex Sludds, Dirk Englund, ''Design of Asymptotically Perfect Linear Photonic Circuits,'' Photonics West OPTO (1/25/2022)*
- *Ryan Hamerly, Saumil Bandyopadhyay, Alex Sludds, Dirk Englund, ''Design of Asymptotically Perfect Linear Feedforward Photonic Circuits,'' OFC 2022 (3/9/2022)*
- *Ryan Hamerly, Ryotatsu Yanagimoto, Edwin Ng, Hideo Mabuchi, Dirk Englund, ''Enabling Single-Photon Nonlinear Optics with XPM Temporal Trapping,'' APS March Meeting 2022 (3/15/2022)*
- *Artur Hermans, Ian R. Christen, Christopher Panuski, Matthew Zimmermann, Andrew J. Leenheer, Mark Dong, Gerald Gilbert, Matt Eichenfield, and Dirk Englund, ''Piezoelectric High-Speed Spatial Light Modulator Based on Guided-Mode Resonances,'' CLEO 2022 (5/20/2022)*
- *D Englund, ''Short Course: Integrated Photonics for Quantum Information Science and Technology,'' CLEO San Jose, CA (5/16/2022)*
- *Dirk Englund, ''Plenary talk: Programming Complex Systems for Quantum Information & Machine Learning,'' 2022 Optics, Photonics, and Lasers (OPL) conference (11/11/2022)*
- *Dirk Englund, ''"Programmable Photonics" for Quantum Information & Machine Learning,'' DARPA "Where the future may lie seminar series" (2022.10.21)*
- *Dirk Englund, ''Machine Learning with In-Physics Computing,'' JQI Seminar @ University of Maryland (11/7/2022)*
- *Dirk Englund, ''Programming Complex Systems for Quantum Information & Machine Learning,'' CSEM - MIT Workshop (11/30/2022)*
- *Dirk Englund, ''Programming Complex Systems for Quantum Information & Machine Learning,'' MIT Physics - Lunch talk (12/3/2022)*

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7. Honors

- *Dirk Englund: 2017 ACS Photonics Young Investigator Award*
- *Dirk Englund: The OSA's 2017 Adolph Lomb Medal*
- *Dirk Englund: Bose Research Fellowship in 2018*
- *Dirk Englund: Humboldt Research Fellowship (2020)*
- *Dirk Englund: OSA Fellow*
- *Dirk Englund: Humboldt Professorship (awarded)*

8. Tech Transfer

- *Working with BBN Raytheon as partner for technology transition*

9. References

[1] *C. Peng, S. Nanot, R.-J. Shiue, G. Grosso, Y. Yang, M. Hempel, P. Jarillo-Herrero, J. Kong, F. H. L. Koppens, D. K. Efetov, and Others, Compact Mid-Infrared Graphene Thermopile Enabled by a Nanopatterning Technique of Electrolyte Gates, New J. Phys. 20, 083050 (2018).*

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