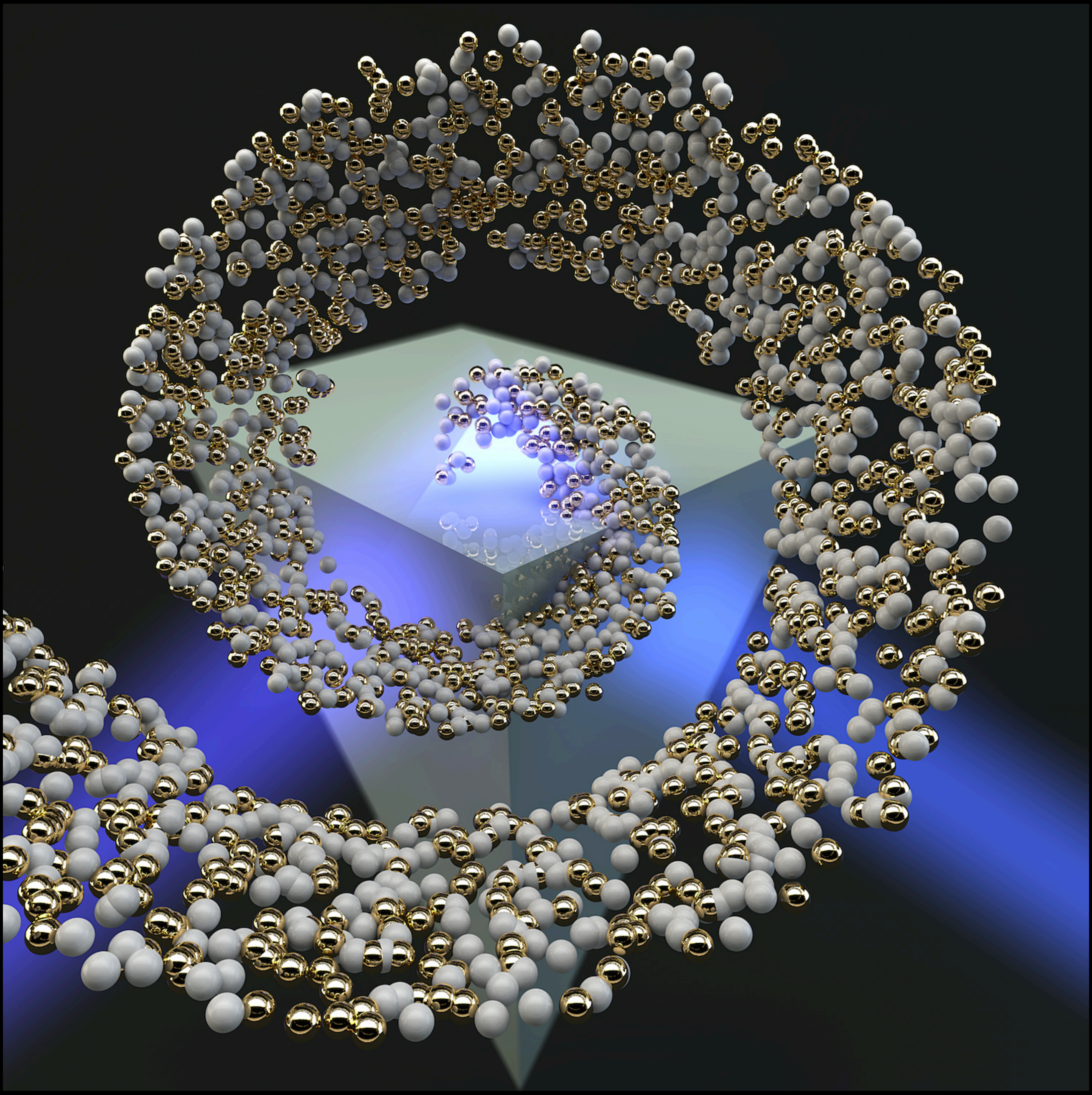
Electrodynamics.org
RESEARCH LABS

HIGHLIGHTS FROM 2010- 2020



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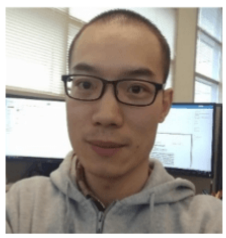
GROUP MEMBERS

OVER 10 YEARS

PROF. ZUBIN JACOB
Group Leader

Research Scientists and Post-Doctoral Fellows

DR. MOHAMMAD ALI JAVIDIAN

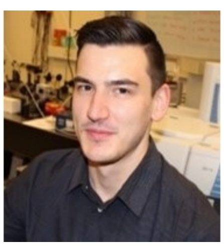


DR. LI-PING YANG

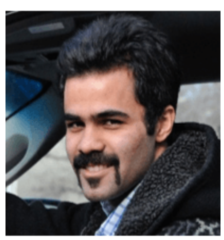
DR. CHINMAY KHANDEKAR

DR. FANGLIN BAO

PhDs



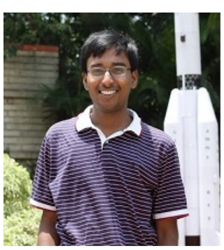
TODD VAN MECHELEN



FAHRAD KHOSRAVI

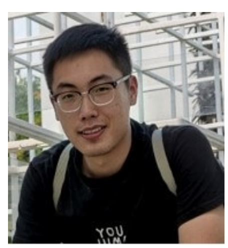
FARID KALHOR

ZOHREH POURSOTI

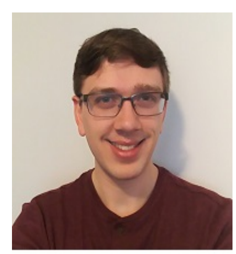


ASHWIN K. BODETTI

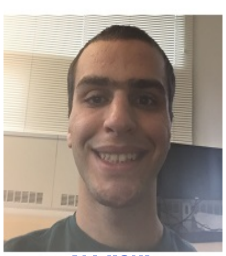
TYLER SENTZ



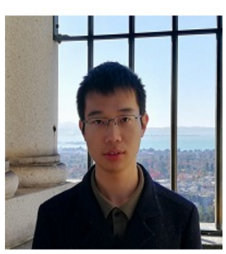
XUEJI WANG



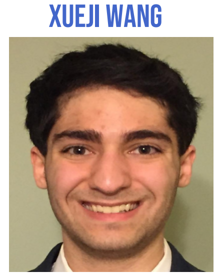
LEIF BAUER



ALI JISHI



WENBO SUN



MATT MANN

VISHAL CHOUDHURY

ALUMNI

PhD Alumni

Dr. Sean Molesky
Dr. Ward Newman
Dr. Saman Jahani
Dr. Cristian Cortes
Dr. Prashant Shekhar
Dr. Ryan Starko-Bowes

Post-doctoral Alumni

Dr. Sarang Pendharker
Dr. Parijat Sengupta
Dr. Zhou Li
Dr. Aman Satija

M.S. Alumni

Yu Guo
Huan Hu
Prashant Shekhar
Jonathan Atkinson

AWARDS & HONORS

DARPA Director's Fellowship 2019

Recognized among outstanding teachers at Purdue Engineering for Fall 2019

Instructor rating:4.9 with >90 % response rate for course evaluations, 25 student enrollment in ECE 695 Quantum Signal Processing

ECE Outstanding Graduate Mentor Award 2018

Purdue Seed for Success Award 2017

NSF CAREER 2017

DARPA Young Faculty Award 2017

Best PhD Dissertation Prize, Dmitri N. Chorafas Award, 2010

GRADUATE STUDENT AWARDS

Sean Molesky (Alberta)

Governor General's Gold Medal and George Walker Award for Best PhD Thesis at University of Alberta (Over the last 15 years less than 3ECE students at University of Alberta have won the award)

Ranked 1 among 43 applicants in Canada-wide electrical engineering post-doctoral scholarship competition (NSERC equivalent to NSF)

Ward Newman (Purdue)

Honored as DARPA D60 Riser in 2018- For DARPA'S 60th birthday, select top recent PhD graduates from various US universities were funded to travel to DC and present their research to DOD stakeholders

Cristian Cortes (Purdue)

Outstanding Graduate Student Award 2017

Prashant Shekhar (Alberta)

Finalist, Andrew Stewart Prize for Outstanding Graduate Research, 2018

Todd Van Mechelen (Purdue)

Finalist, Dmitri N. Chorafas Award, 2020

LEADING LARGE PROJECTS

Within 5 years at Purdue ECE, Dr. Jacob has served as principal investigator for grants totaling ~ $7M. This includes PI of 5 DARPA grants which are global competitions. Other performers in these DARPA programs include not only top industrial research labs and start-ups but also teams from UK, Germany, Switzerland etc.

PI Jacob has worked as the leader of many theory-driven experiments that comprise multi-university international partnerships.

PI DARPA Nascent Light-Matter Interactions

Co-PIs: Prof. Tongcang Li, Prof. Luna Lu, Prof. Yi Xuan, Prof. Rajib Rahman and industry partner United Technologies Research Center (UTRC)

The project led to theoretical proposal of new topological electromagnetic phases of matter as well as experimental demonstration of quantum vacuum effects with Prof. Tongcang Li's group.

PI DARPA DETECT

The project led to the proposal of a new quantum resource: giant susceptibility near a discontinuous quantum phase transition for designing next general single photon detectors.

PI DARPA QUEST

Co-PIs: Prof. Tongcang Li, Prof. Rajib Rahman

The project deals with new ways of controlling vacuum fluctuations inside matter.

PI DARPA Quantum Causality

Co-PIs: Prof. Vaneet Aggarwal

The project deals with bringing the field of causal inference to the quantum domain.

PI DARPA IAMBIC

Co-PIs: Prof. Dan Jiao, Prof. Vaneet Aggarwal

The project deals with quantum imaging and theory of super-resolution.

PI Institute of Oil Sands Alberta

Co-PIs: Prof. Neda Nazemifard

This project led to axial super-resolution evanescent wave tomography and nanoscale microscopy of oil sands particles for our industry partners.

PI Helmholtz Alberta Initiative

Co-PIs: Prof. Sandipan Pramanik, Prof. Robert Fedosejevs, Prof. Ying Tsui, Prof. Manfred Eich (TU Hamburg), Dr. Michael Stormer (Helmholtz center, Geesthacht)

This project led to the demonstration of the highest temperature thermal metamaterial that tailors thermal emission

PI Alberta Nanobridge

Co-PIs: Prof. Sandipan Pramanik, Prof. Robert Fedosejevs

This project led to successful large area fabrication of nanowires and hyperbolic metamaterials.

INDUSTRY PARTNERSHIPS

Guardian Industries

We partnered with Guardian Industries inc , the world's 2nd largest glass manufacturer to transition our technology on high temperature thermal metamaterials to commercial applications.

COMCAST

Our current project on quantum cybersecurity is with COMCAST, the largest internet service provided in the US.

Oil Sands Industry Consortium

Alberta's oil sands reserves has the third largest oil reserves in the world after Saudi Arabia and Venezuela. We developed a nano imaging technique specifically with axial super-resolution capabilities for our oil sands industry partners.

SUMMARY OF PUBLICATIONS

h-index: 35, total no. of citations > 9000

Journal Publications

At Purdue, 2016-2020, 45
At Alberta, 2011-2015, 29,
During PhD, 8,
Total: 82, > 65 with student or post-doctoral co-authors

Patent 1 granted, 2 provisional all at Purdue with students/PDFs

Conference publication (Total > 80)

Invited talks for Dr. Jacob > 100 [includes conferences and seminars at Universities]

High impact publications (original contributions):

Optica (4), Nano Letters (1), Science (1), Science Advances (1), Nature Communications (3) , NPJ Quantum Information (1) Other (perspectives and reviews): Science (1), Light: Science and Applications (1), Nature Materials (1), Nature Nanotechnology (1)

20 papers with >100 citations, 6 Original contributions by ZJ's students as first author cited > 100 times, 5 Other original contributions by ZJ's students as first author cited > 50 times, Total citations/no. of papers > 100

Papers with over 1000 citations (1 original contribution, 1 review paper)

QUANTUM MODEL UNLOCKS NEW APPROACH TO SINGLE-PHOTON DETECTION

To become more pervasive in daily life, quantum technology needs to better detect single particles of light, called photons, carrying quantum information.

The problem is that each photon is a very weak signal, making it difficult for measurement devices to efficiently detect them. Purdue University engineers have proposed a new quantum resource that could help design the next generation of single-photon detectors.

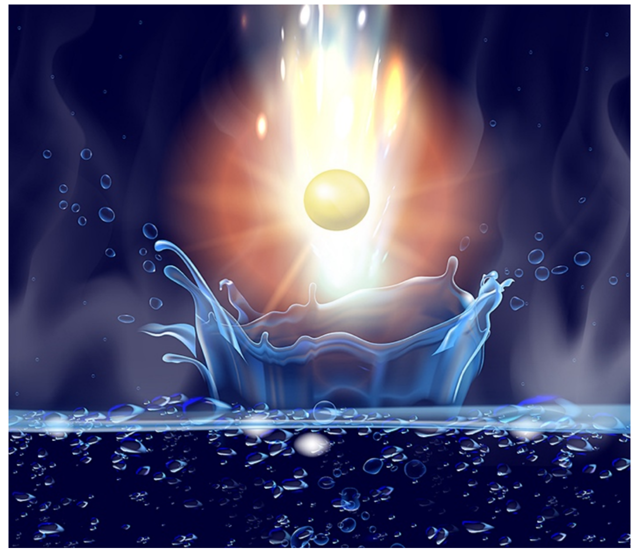
The type of quantum resource that the researchers discovered is called a "giant susceptibility," which is a violent response of a system to a tiny perturbation. This response is necessary for converting a weak signal in the quantum domain to an amplified strong signal like those used by cell phones and other classical technology.

In a paper published in **NPJ Quantum Information**, the researchers showed through a simulation that a system running on 100 computation units, called qubits, could exhibit a giant response when interacting with just one photon.

The research is part of the Defense Advanced Research Projects Agency's **DETECT program** to design new single-photon detectors. The researchers will be working with their collaborators to test this approach experimentally.

"Our search for better single photon detectors led us to an unorthodox concept of exploiting quantum phase transitions," said **Zubin Jacob**, a Purdue associate professor of **electrical and computer engineering**.

A quantum phase transition occurs at the point where the spin orientation of the qubit system undergoes a dramatic change while interacting with a single photon. According to the researchers' model, the giant response would only be unlocked



Engineering a qubit system close to the point of a quantum phase transition could make single photons easier to detect, just as a giant release of steam could be used to detect a tiny disturbance to superheated water, Purdue University researchers say. (Purdue University illustration/Xueji Wang)

when the multi-qubit system is engineered close to this quantum phase transition.

"The detector itself is analogous to water in a microwave," said Li-Ping Yang, a Purdue postdoctoral scholar who worked with Jacob on developing this model.

"A tiny disturbance to superheated water triggers an explosion releasing steam. Just as that giant release of steam could be used to detect the tiny disturbance, this multi-qubit system engineered near a quantum phase transition could help better detect a single photon."

*Patents related to this research have been filed through the **Purdue Research Foundation Office of Technology Commercialization**. DARPA DETECT funding for this work is associated with award number W911NF-18-1-0074*

Media contact: *Kayla Wiles,* ***wiles5@purdue.edu***

Source: *Zubin Jacob,* ***zjacob@purdue.edu***

LIGHTING A FIRE WITH VACUUM FRICTION

ONE OF THE SURPRISES OF QUANTUM MECHANICS IS ZERO POINT FLUCTUATIONS WHICH PERVADE BOTH VACUUM AND MATTER.

Far from just theoretical interest, practical consequences exist at the nanoscale when these fluctuations cause forces that attract or repel macroscopic bodies. They are also manifested at the molecular level where tiny fluctuating dipoles lead to molecular attractive or repulsive forces and energy transfer. However these forces are often small and difficult to enhance. In this issue, Guo et. al. have pointed out a giant fluctuational force between moving bodies caused by a singular Fabry-Perot mode.

Vacuum can interestingly exert a drag force between moving media if they are sufficiently close to each other. This is very much like the frictional force we all experience but with one key difference: no physical contact is needed, just a nanoscale vacuum gap! The force arises due to photons exchanged between the moving media which can be driven by a temperature difference. What is non-intuitive is that even when the temperatures of the two moving bodies are assumed to be same, an interesting effective temperature difference develops solely due to Doppler shifted frequencies. Think of it like a nanoscale circuit, where the energy carriers are photons instead of electrons and the potential difference of a battery is provided *by the Doppler shifted distribution* of photons inside the moving bodies.

Our article puts forth a giant enhancement in this vacuum frictional force arising due to a singular Fabry-Perot resonance. The canonical example of moving bodies is a pair of Fabry-Perot plates with a nanoscale gap between them. Light bouncing back and forth between Fabry-Perot plates is a textbook example every optical scientist studies. However, when the plates are set into motion the amplitude and phase of evanescent waves reflected from the plates develop fundamentally unique properties causing a giant increase in vacuum friction. This phenomenon requires energy from the mechanical motion of the plates and bears an uncanny similarity to lasing. The singular resonance causes a giant increase in the number of photons exchanged between the plates, enough to cause a fire due to vacuum friction! The effect is robust to loss and dispersion but the velocity of motion needs to be of the order of the Fermi velocity of electrons in the metal, a daunting task.

Strapline: Giant vacuum friction due to singular Fabry-Perot resonance

VACUUM CAN INTERESTINGLY EXERT A DRAG FORCE BETWEEN MOVING MEDIA IF THEY ARE SUFFICIENTLY CLOSE TO EACH OTHER

CONTROLLING FORCES BETWEEN ATOMS, PROMISING FOR '2-D HYPERBOLIC' MATERIALS

A new approach to control forces and interactions between atoms and molecules, such as those employed by geckos to climb vertical surfaces, could bring advances in new materials for developing quantum light sources.

"Closely spaced-atoms and molecules in our environment are constantly interacting, attracting and repelling each other," said **Zubin Jacob**, an assistant professor of electrical and computer engineering at Purdue University. "Such interactions ultimately enable a myriad of phenomena, such as the sticky pads on gecko feet, as well as photosynthesis."

Typically, these interactions occur when atoms and molecules are between 1 to 10 nanometers apart, or roughly 1/10,000th the width of a human hair.

"These include Van der Waals forces that take place between atoms and molecules only when they are very close together. The fact that they always require extremely short separation distances makes them difficult to control. This poses a major obstacle to exploit them for practical applications," he said.

For brief periods of time atoms are said to possess "fluctuating dipoles" because their positive and negative charges are momentarily separated. The dipoles from numerous atoms and molecules sometimes interact with each other, and these dipole-dipole interactions are the basis for Van der Waals and other forces between the closely-spaced atoms and molecules.

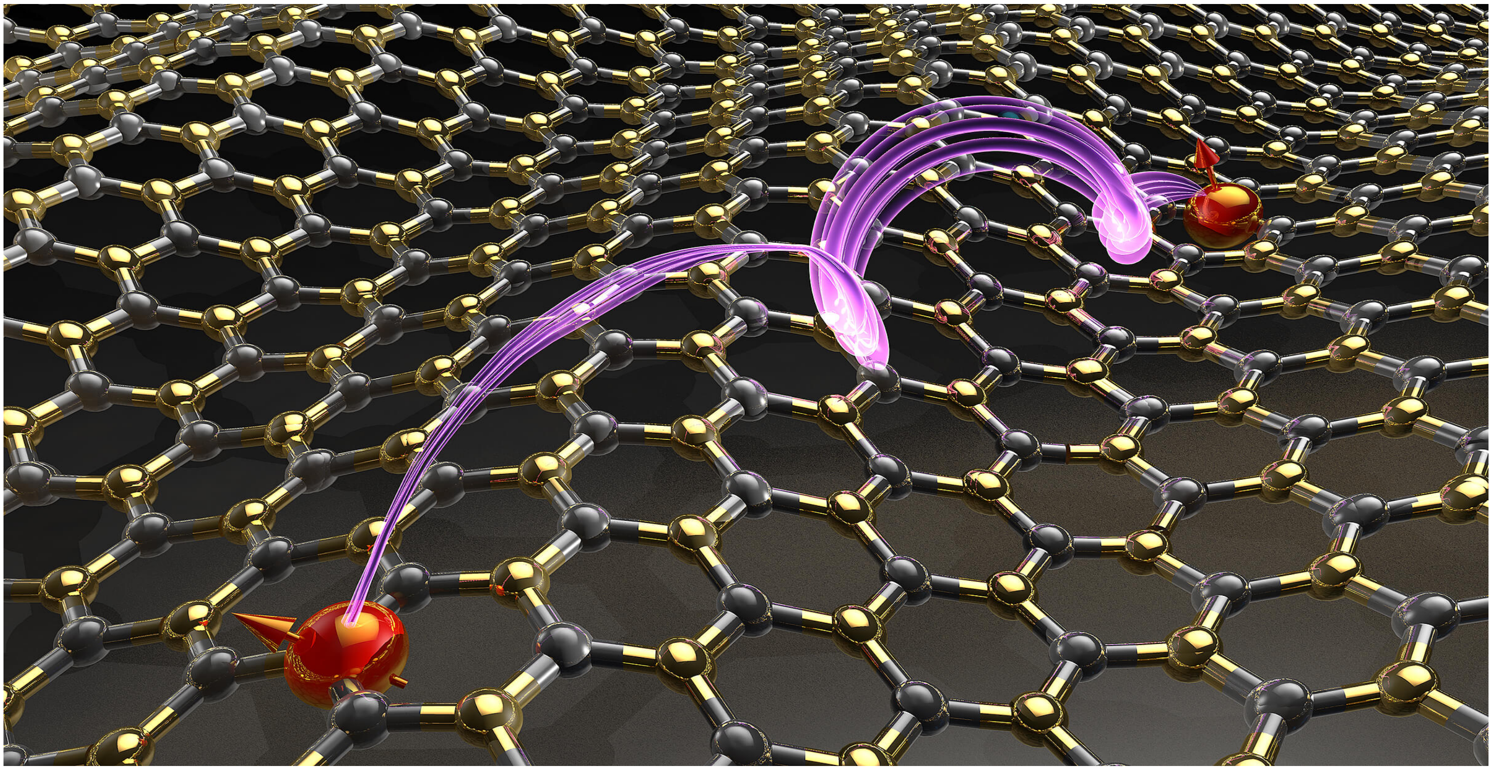
The researchers have demonstrated that these dipole-dipole interactions are fundamentally altered inside so-called two-dimensional materials, such as hexagonal boron nitride and black phosphorous, materials with a thickness consisting of only a few atomic layers. They also have shown that it's possible to achieve the dipole-dipole interactions even when the atoms and molecules are relatively distant, with a separation approaching one micron, or 100 times farther apart then would normally be required. This greater distance represents the potential for the practical application of the phenomenon for optical sources.

Findings are detailed in a paper published earlier this year in the journal Nature Communications. The paper was authored by doctoral student Cristian L. Cortes and Jacob.

"Our main goal was trying to understand whether it's possible to control and manipulate these sorts of interactions," Cortes said. "What we found was that by carefully engineering material properties, it is possible to significantly alter the strength and spatial range of these interactions. We found that so-called hyperbolic materials actually allow very long-range interactions unlike any other conventional material."

Dipole-dipole interactions also cause many fluorescent atoms and molecules to emit light in a synchronized manner. Ordinarily, fluorescent molecules emit light in random and spontaneous flashes. However, materials might be engineered to mediate interactions so that the emission becomes synchronized, flashing in unison, and increasing light output dramatically in a phenomenon called super-radiance.

The hyperbolic two-dimensional materials are engineered to induce this super-radiance between fluorescent quantum emitters placed far apart.



A new approach to control forces and interactions between atoms and molecules, such as those employed by geckos to climb vertical surfaces, could bring advances in new materials for developing quantum light sources. This graphic depicts "quantum emitters" in red. (Purdue University image/Zubin Jacob)

"When they are interacting through these materials they can get locked in with each other like two pendulums synchronized perfectly," Jacob said.

The materials are said to be "strongly interacting" due to the long-range dipole-dipole effect.

The "long-range" interactions could make possible new types of light sources that exploit super-radiance. Another challenging goal is to build quantum simulators using a network of interacting emitters to mimic "Coulomb interactions" or "spin interactions" between electrons in a material.

Although the Nature Communications paper focuses on theory, the researchers also suggested several experimental methods to validate the theory. They are performing an experiment using hyperbolic 2-D materials at the Birck Nanotechnology Center in Purdue's Discovery Park.

Jacob recently received a National Science Foundation Faculty Early Career Development '(CAREER) award to support the research. The award provides $461,877 for research over five years.

[1] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2V4. [2]Birck Nanotechnology Center and Purdue Quantum Center, School of Electrical and Computer Engineering, Purdue University, 1205 West State Street, West Lafayette, Indiana 47906, USA. Correspondence and requests for materials should be addressed to C.L.C. (email: cortes1@purdue.edu) or to Z.J. (email: zjacob@purdue.edu)

MOVING PLATES CREATE NEGATIVE-FREQUENCY PHOTONIC RESONANCE

When in relative motion, plates of a Fabry-Perot interferometer generate a unique resonance with negative frequency if separated by a gap of critical size.

We commonly encounter the idea of negative frequencies while analyzing electromagnetic waves and signals, which are often helpful as a mathematical concept to help us keep track of signals that vary over time. We can safely ignore negative frequencies in situations where incoming and outgoing electromagnetic radiation would be equivalent in the event that time was reversed; for example, in the case of a simple ray tracing problem of imaging with lenses. However, we cannot regard negative frequencies as simply a mathematical concept in cases where electromagnetic radiation behaves differently when time is reversed.

One such situation is a medium that is moving. In this case, electromagnetic waves that are propagated in the direction of motion of the medium and in the opposite direction undergo Doppler shifts of different sizes. This means the reflection co efficient of a light wave moving in the direction of the medium is red-shifted in frequency compared with when the medium is at rest. This Doppler effect has to be taken into account in scenarios such as laser measurements of the velocity of a moving fluid. If the medium is moving at a high enough velocity, this red shift in the frequency can be so large as to make the frequency zero or even negative. Such Doppler shift to negative frequencies only occurs if the velocity of motion is greater than the phase velocity of light in the medium, similar to the well-known Cherenkov radiation condition.

Incident evanescent electromagnetic waves in a moving medium seem to possess frequencies of different signs in the laboratory and in a moving frame of reference: see Figure 1. A regular decaying evanescent photonic mode in the laboratory can be Doppler-shifted to a negative frequency in a moving frame. The reflection coefficient, which describes the interaction of light with matter when bodies are at rest and in motion, has to be evaluated in the same frame of reference as a body in motion. For modes with negative frequency, carefully calculated reflection coefficients show the existence of instabilities and growing evanescent waves. This phenomenon has been studied in the case of moving plasmas, in which the presence of waves with negative energy implies that the moving plasma would enable a photonic mode to be generated from noise to decrease its net energy.

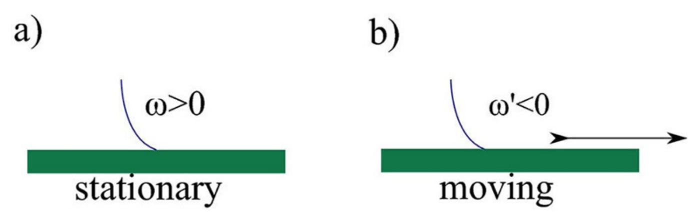


Figure 1. (a) An evanescent wave that is incident on a stationary plate is absorbed. (b) An evanescent wave that is incident on a moving plate can be amplified after reflection if the frequency of the wave is negative after Doppler shifting. ω: Angular frequency of incident wave. ω' : Angular frequency in co-moving frame.

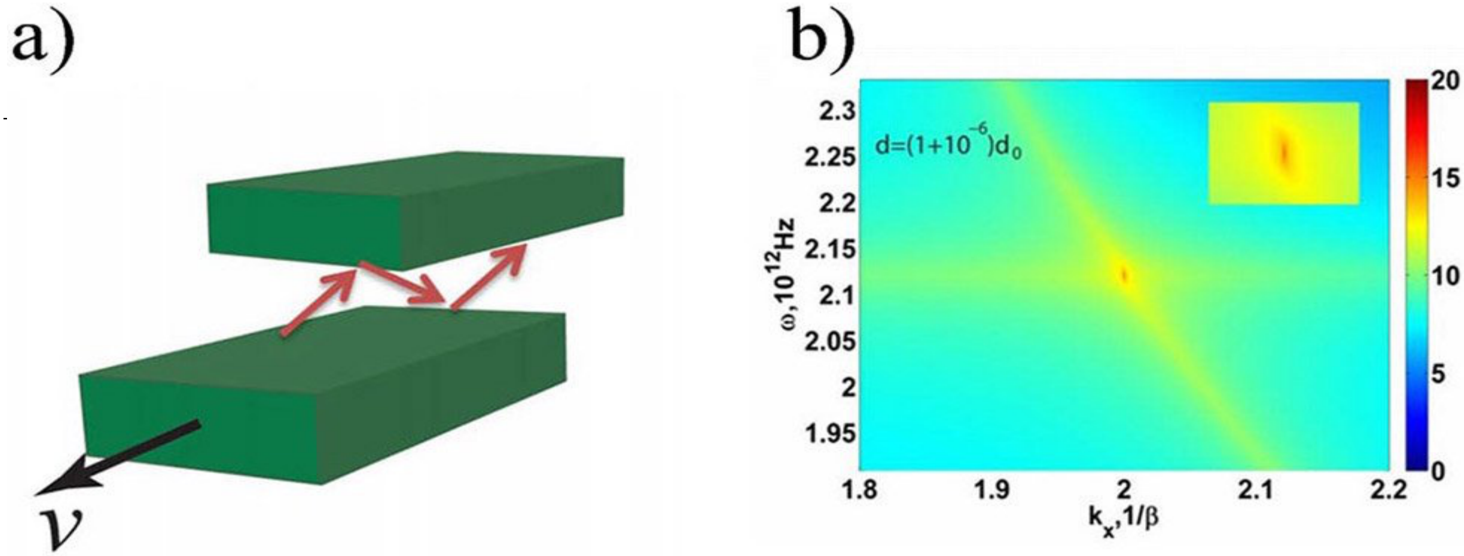


Figure 2. (a) Diagram shows the plates of a Fabry-Perot interferometer, which are in relative motion with a fixed gap and evanescent waves bouncing between them. Perfect coupling can occur between waves with positive and negative frequency modes, which leads to a unique resonance with infinite quality factor. (b) Between moving metallic plates a spectrum of thermal energy (right) is exchanged. The y-axis represents frequency and the x-axis the lateral momentum of the waves normalized according to the equation $\beta=v/c$. The gap d is close to the critical gap distance d_0. A large enhancement is seen (red region), which originates from the resonance with negative frequency. v: Velocity of motion. k_x: Momentum of wave. c: Speed of light.

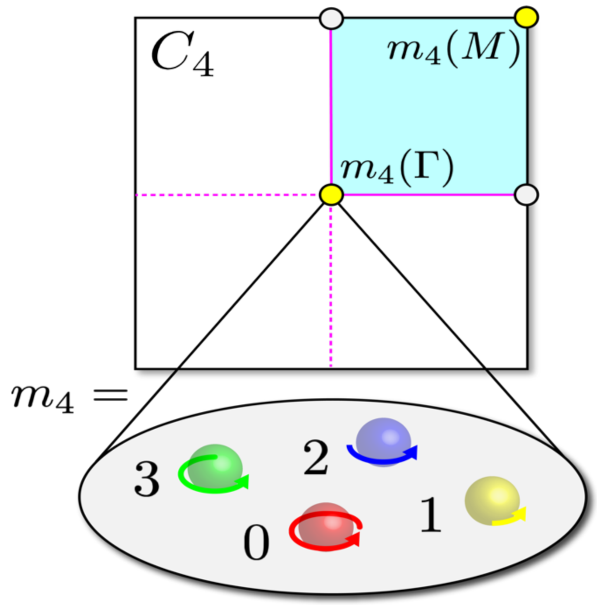
We have pointed out an extremely interesting case where coupling can occur between modes with positive and negative frequency,[1] which leads to a unique resonance in moving photonic media. A simple practical configuration where this can occur is if two plates separated by a small gap are in motion relative to each other: see Figure 2(a). A single wave can appear as a positive photonic mode on one plate and be Doppler-shifted to a mode of equal—but negative frequency—on the other plate if the velocity of the plates and the size of the gap between them both have critical values. This situation gives rise to perfect coupling of waves of positive and negative frequency in the near-field region and a resonance with an infinite quality factor, which is fundamentally different from any resonance in stationary systems.

One major implication of this resonance is with regard to the phenomenon of vacuum friction.[2, 3] Vacuum fluctuations exert a lateral force, referred to as the Casimir force, on the plates of a Fabry-Perot interferometer, which pushes them close together. Once the plates are set in motion relative to each other with a fixed gap, these fluctuations also exert a drag force, which acts to slow the plates down. This interaction takes place through all possible modes that exist in the moving plate system and we have shown that this force takes very high values, owing to this unique resonance with negative frequency: see Figure 2(b).[4]

The velocity of motion that is required to observe such a resonance with negative frequency is of the order of the Fermi velocity of electrons in the metallic plates. The gap needs to be maintained at roughly 10nm. This type of mechanical motion is very difficult to maintain and further research in nanoscale optomechanical systems will be necessary to achieve this. We could use techniques such as simulating a moving medium using pulses in a non-linear optical fiber. However, we may be able to demonstrate resonances with negative energy in an experiment using light-induced potentials or rapidly spinning nanoparticles.

NONLOCAL TOPOLOGICAL ELECTROMAGNETIC PHASES OF MATTER

Topological electromagnetic phases of matter are a unique class of quantum phases in atomic-scale media.



The ultimate origin of electromagnetic phases is nonlocal Hall conductivity. Unlike their electronic counterparts, topological electromagnetic materials are manifestly bosonic and boast protected spin-1 edge states. To uncover the signatures of these bosonic phases, the authors introduce the microscopic theory of photonic band structure and analyze the symmetries of the atomic lattice. Besides the Chern invariant, there are also symmetry-protected topological (SPT) invariants that are characterized by spin-1 eigenvalues of the electromagnetic field.

In (2+1)-dimensional materials, nonlocal topological electromagnetic phases are defined as atomic-scale media which host photonic monopoles in the bulk band structure and respect bosonic symmetries (e.g., time reversal T2=+1). Additionally, they support topologically protected spin-1 edge states, which are fundamentally different than spin-12 and pseudo-spin-12 edge states arising in fermionic and pseudofermionic systems. The striking feature of the edge state is that all electric and magnetic field components vanish at the boundary, in stark contrast to analogs of Jackiw-Rebbi domain wall states. This surprising open boundary solution of Maxwell's equations, dubbed the quantum gyroelectric effect [Phys. Rev. A **98**, 023842 (2018)], is the supersymmetric partner of the topological Dirac edge state where the spinor wave function completely vanishes at the boundary. The defining feature of such phases is the presence of temporal and spatial dispersion in conductivity (the linear response function). In this paper, we generalize these topological electromagnetic phases beyond the continuum approximation to the exact lattice field theory of a periodic atomic crystal. To accomplish this, we put forth the concept of microscopic photonic band structure of solids, analogous to the traditional theory of electronic band structure. Our definition of topological invariants utilizes optical Bloch modes and can be applied to naturally occurring crystalline materials. For the photon propagating within a periodic atomic crystal, our theory shows that besides the Chern invariant C∈Z, there are also symmetry-protected topological (SPT) invariants v∈ZN which are related to the cyclic point group CN of the crystal v=CmodN. Due to the rotational symmetries of light R(2π)=+1, these SPT phases are manifestly bosonic and behave very differently from their fermionic counterparts R(2π)=−1 encountered in conventional condensed-matter systems. Remarkably, the nontrivial bosonic phases v≠0 are determined entirely from rotational (spin-1) eigenvalues of the photon at high-symmetry points in the Brillouin zone. Our work accelerates progress toward the discovery of bosonic phases of matter where the electromagnetic field within an atomic crystal exhibits topological properties.

***Writers:** Todd Van Mechelen & Zubin Jacob*

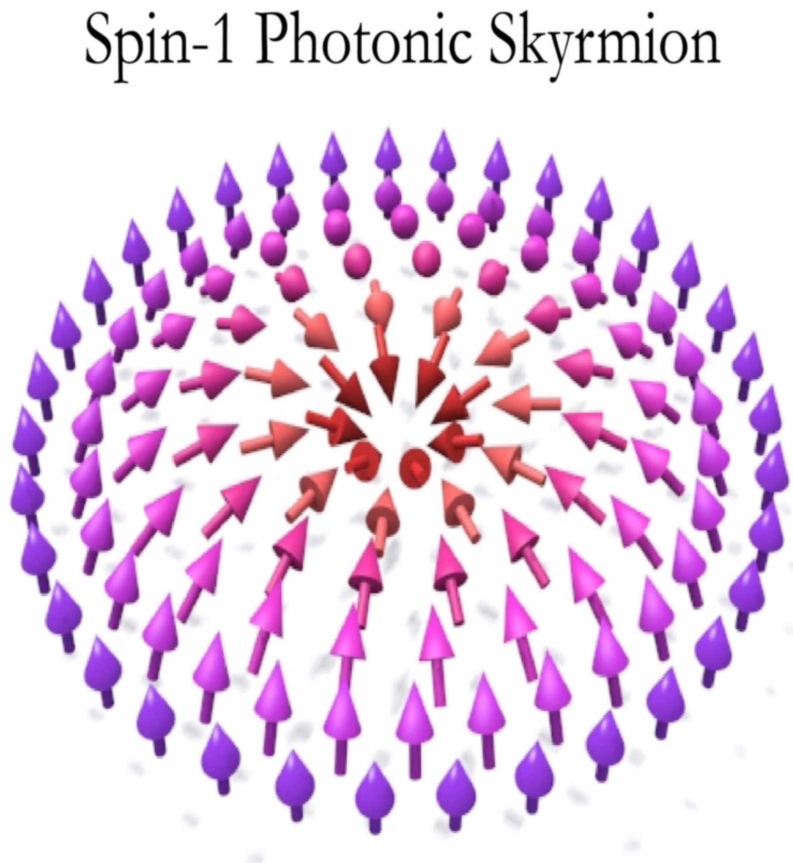
RESEARCHERS PROPOSE NEW TOPOLOGICAL PHASE OF ATOMIC MATTER HOSTING 'PHOTONIC SKYRMIONS'

The field of topology or the study of how surfaces behave in different dimensions has profoundly influenced the current understanding of matter.

The prime example is the topological insulator, which conducts electricity only on the surface while being completely insulating inside the bulk. Topological insulators behave like a metal, i.e., silver on the surface, but inside, it would behave like glass. These properties are defined using the conductivity or flow of electrons depicting whether there is a highway or a road-block for their motion. One major driver of future applications for topological insulators is in the field of spin-electronic devices since these electrons spin in unison, all aligned with each other while flowing on the surface.

"We showed there can exist a new topological phase of matter where light flows only on the edge of the atomic material but not inside it. There might exist some very special materials with this unique photonic property, and that's what we refer to as the quantum gyroelectric phase of matter," said Zubin Jacob, an associate professor of electrical and computer engineering at Purdue University.

Another key defining property of this phase of matter is a topological excitation known as the "photonic skyrmion." In conventional magnets, electron spins can be thought of as tiny arrows that either align or anti-align with each other. In stark contrast, skyrmions are spin excitations that show unique tumbling behavior of the spins (see image). They are extremely stable to stimuli and can be exploited for spintronic switches and memories. The quantum gyroelectric phase hosts skyrmions in energy-momentum space of photonic waves and can be used as a smoking gun signature of this phase of matter.



Depiction of spin-1 photonic skyrmion. Arrows are related to photon spin in energy-momentum space. (Purdue University image/ Todd van Mechelen)

Such a material might be synthesized by "doping," or altering the atomic structure, of existing materials. A good place to search for this phase is in two-dimensional materials such as graphene.

Jacob and doctoral student Todd Van Mechelen have authored a series of four papers published in research journals that puts forth the theory of this phase of matter.

The research was funded by the Defense Advanced Research Projects Agency's Nascent Light-Matter Interactions Program and the National Science Foundation.

Future research will explore doping 2D materials to achieve the quantum gyroelectric phase and investigate how light waves travel on the edge of a material.

[1] Birck Nanotechnology Center and Purdue Quantum Center, School of Electrical and Computer Engineering,PurdueUniversity,WestLafayette,Indiana47907,USA *zjacob@purdue.edu

"We showed there can exist a new topological phase of matter where light flows only on the edge of the atomic material but not inside it. There might exist some very special materials with this unique photonic property, and that's what we refer to as the quantum gyroelectric phase of matter," said Zubin Jacob, an associate professor of electrical and computer engineering at Purdue University.

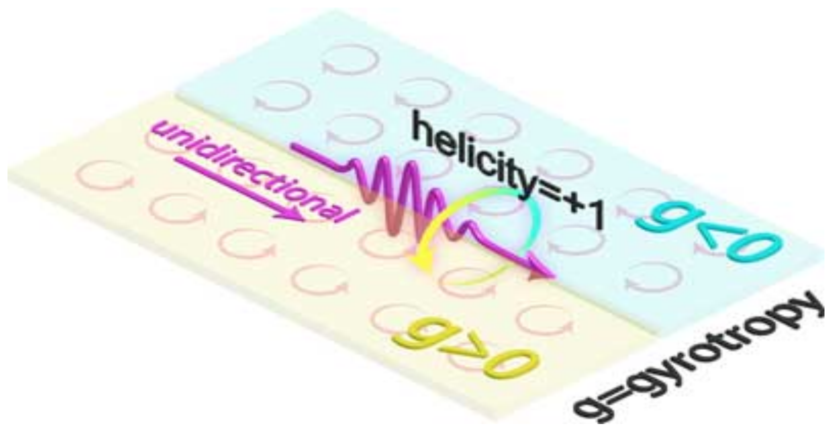
SPINNING LIGHTWAVES ON A ONE-WAY STREET: RESEARCHERS DOCUMENT A QUANTUM SPIN WAVE FOR LIGHT

*(*Nanowerk News*) Researchers at Purdue University have created a quantum spin wave for light. This can be a carrier of information for future nanotechnologies but with a unique twist: they only flow in one direction. The article by Todd Van Mechelen and Zubin Jacob has been published in the open access journal* Nanophotonics *("Unidirectional Maxwellian spin waves").*

Information technologies at the nanoscale rely on manipulating particles such as electrons and photons. The electron, which is the carrier of charge (electricity), is a fermion while the photon, which is the long-distance transmitter of information, is a boson.

The most important difference between a fermion and a boson is literally how they "spin". Even though electron spin is widely utilized in commercial nanotechnologies such as magnetic memories, optical spin has only recently become a fundamental degree of freedom in nanophotonics with possible applications in fiber optics, plasmonics, resonators and even quantum metrology. This explosion of research into optical spin is due to the remarkable features of strongly confined electromagnetic waves. At the nanoscale, spin and direction of motion of light are intrinsically locked to one another.

The researchers used many designs to achieve this behavior, in particular, an interface of mirror symmetric gyrotropic media, illustrated in the accompanying figure. Gyrotropy is a form of material response to light waves that transfer spinning behavior of electrons to photons (shown by circular arrows).



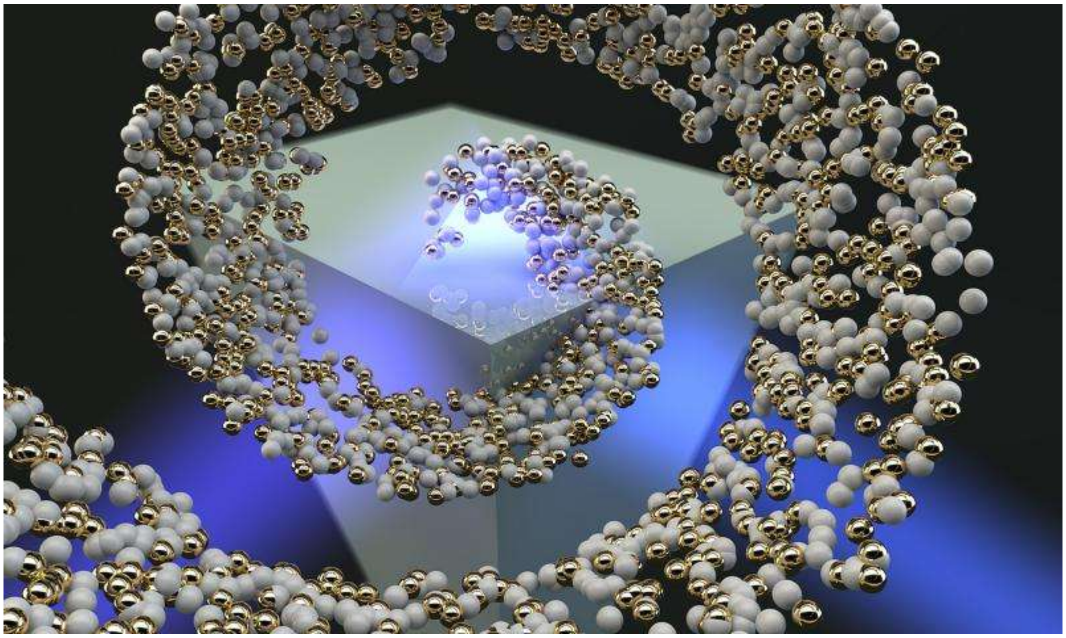
Unidirectional Maxwellian spin waves. (© De Gruyter)

in the reverse. This is important for the safe functioning of high power devices as well as for reducing interference between transmitted/received electromagnetic signals from cellphone antennas," said Zubin Jacob.

Source: De Gruyter

SPINNING LIGHT WAVES MIGHT BE 'LOCKED' FOR PHOTONICS TECHNOLOGIES

A newly described property related to the "spin" and momentum of light waves suggests potential practical applications in photonic communications and photonic circuits.



As shown in this artist's rendering, a light beam shining on a glass prism generates evanescent waves and spin-momentum locking, suggesting potential practical applications in photonic communications and photonic circuits. The effect could be probed using nanoparticles. Credit: Todd Van Mechelen, Zubin Jacob

Scientists already knew that light waves have an electric field that can rotate as they propagate, which is known as the polarization property of light, and that light waves carry momentum in their direction of motion. In new findings, researchers have discovered a "spin-momentum locking," meaning, for example, light waves that spin in a counterclockwise direction can only move forward, and vice versa.

"Researchers had noticed intriguing effects related to directional propagation of light coupled to its polarization," said Zubin Jacob, an assistant professor of electrical and computer engineering at Purdue University. "What we have shown is that this is a unique effect related to the spin and momentum of light analogous in many ways to the case of spin-momentum locking which occurs for electrons. We showed there is a very simple rule that governs this spin and momentum locking. And it's a universal property for all optical materials and nanostructures, which makes it potentially very useful for photonic devices. This universality is unique to light and does not occur for electrons."

Findings were detailed in a research paper that appeared in February in the journal Optica, published by the The Optical Society. The paper was authored by graduate student Todd Van Mechelen and Jacob, who demonstrated spin-momentum locking through analytical theory.

Spin-momentum locking might be applied to spin photonics, which could hypothetically harness the spin of photons in devices and circuits. Whereas microchips use electrons to perform computations and process information, photons are limited primarily to communications, transmitting data over optical fiber. However, using the spin of light waves could make possible devices that integrate electrons and photons to perform logic and memory operations.

"Lots of researchers in the field of electronics think future devices will utilize not only the charge of the electron but also the spin of the electron, a field called spintronics," Jacob said. "The question is how to interface photonics and spintronics. We would have to use some of these spin properties of light to interface with spintronics so that we might use both photons and electrons in devices."

The researchers learned that spin-momentum locking is inevitable when light waves decay.

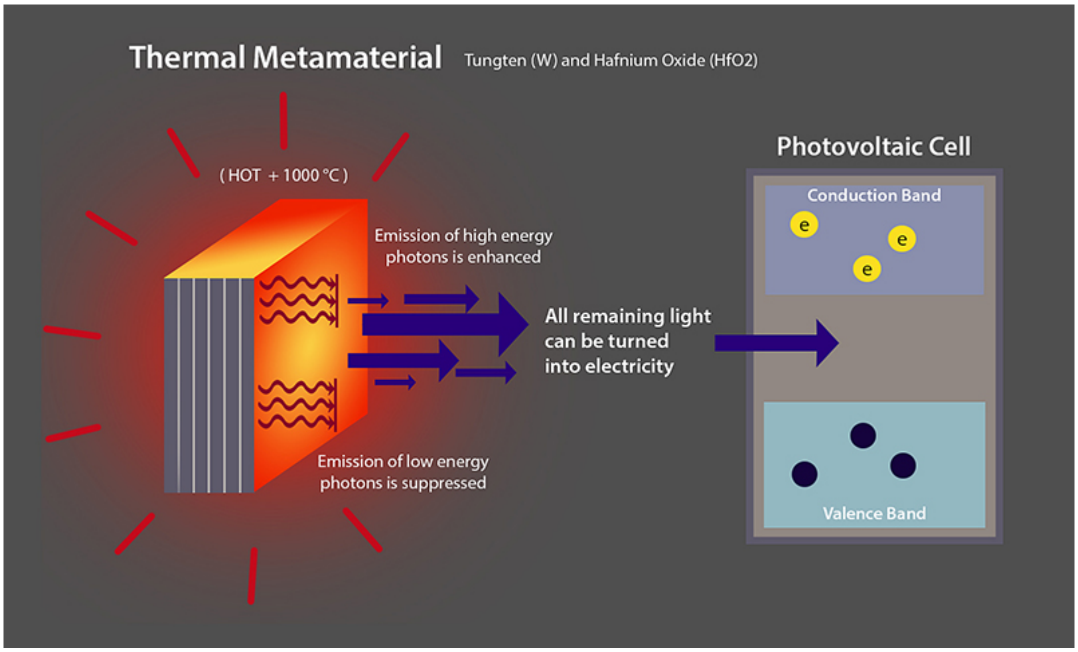
"If you transmit light along an optical fiber, most of the light is confined within the fiber but a small portion falls outside of the fiber, and this we refer to as the decaying evanescent light wave," Jacob said. "What we showed was that these evanescent waves are the fundamental reason spin-momentum locking is ubiquitous in practical scenarios."

The work is ongoing and may include experiments using a levitating nanoparticle to study the spin-momentum properties of light.

"The researchers learned that spin-momentum locking is inevitable when light waves decay."

'THERMAL METAMATERIAL' INNOVATION COULD HELP BRING WASTE-HEAT HARVESTING TECHNOLOGY TO POWER PLANTS, FACTORIES

An international research team has used a "thermal metamaterial" to control the emission of radiation at high temperatures, an advance that could bring devices able to efficiently harvest waste heat from power plants and factories.



The thermal metamaterial represented in this graphic could make possible more efficient thermophotovoltaic devices that generate electricity from thermal radiation. Such a technology might be adapted to industrial pipes in factories and power plants, as well as on car engines and automotive exhaust systems, to recapture a portion of the energy wasted as heat. (Purdue University image/ Gabriela Sincich and Matthew Bollinger)

Roughly 50 to 60 percent of the energy generated in coal and oil-based power plants is wasted as heat. However, thermophotovoltaic devices that generate electricity from thermal radiation might be adapted to industrial pipes in factories and power plants, as well as on car engines and automotive exhaust systems, to recapture much of the wasted energy.

In new findings, researchers demonstrated how to restrict emission of thermal radiation to a portion of the spectrum most needed for thermophotovoltaic technology.

"These devices require spectrally tailored thermal emission at high temperatures, and our research shows that intrinsic material properties can be controlled so that a very hot object glows only in certain colors," said Zubin Jacob, an assistant professor of electrical and computer engineering at Purdue University. "The main idea is to start controlling thermal emission at record high temperatures in ways that haven't been done before."

The thermal metamaterial – nanoscale layers of tungsten and hafnium oxide – was used to suppress the emission of one portion of the spectrum while enhancing emission in another. (An animation is available at https://youtu.be/mRhcNF1yyyU.)

Metamaterials are composite media that contain features, patterns or elements such as tiny nanoantennas that enable an unprecedented control of light. Under development for about 15 years, the metamaterials owe their unusual abilities to precision design and manufacture on the scale of nanometers.

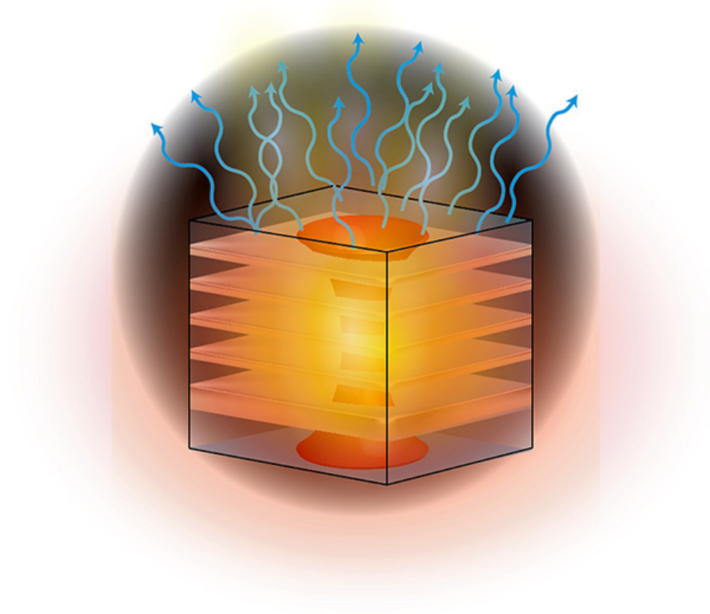
"They have been used mainly to manipulate coherent light, as in a laser, but the ability to manipulate infrared thermal radiation at 1,000 C opens up new areas of research," Jacob said. "The technique we used to achieve this thermal suppression and enhancement is fundamentally different from existing thermal engineering approaches and harnesses a phenomenon called topological transitions."

The research represents the first time the approach was used for thermal emission in high-temperature metamaterials, also called refractory metamaterials.

"My student, Sean Molesky, theoretically predicted it in 2012, and it has taken about four years and some exceptional materials engineering from our collaborators to perform the high-temperature experiments and demonstrate the thermal metamaterial," Jacob said.

Findings were detailed in a research paper published earlier this year in the journal Nature Communications. The work was performed by researchers at Purdue, the Hamburg University of Technology in Germany; University of Alberta in Canada; and Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research in Germany. The co-lead authors were Hamburg University of Technology postdoctoral researcher Pavel Dyachenko and University of Alberta doctoral student Sean Molesky.

The basic operating principle of a photovoltaic cell is that a semiconducting material is illuminated with light, causing electrons to move from one energy level to another. Electrons in the semiconductor occupy a region of energy called the valence band while the material is in the dark. But shining light on the material causes the electrons to



A new "thermal metamaterial" was developed in research aimed at efficiently harvesting waste heat from power plants and factories. The metamaterial – nanoscale layers of tungsten and hafnium oxide – was used to control thermal emission through its "photonic topology." (Purdue University image/ Sean Molesky)

absorb energy, elevating them into a region of higher energy called the conduction band. As the electrons move to the conduction band, they leave behind "holes" in the valance band. The region between both bands, where no electrons exist, is called the band gap.

"If you have energy below the band gap, that is generally wasted," Jacob said. "So what you want to do for high-efficiency thermal energy conversion is suppress the thermal emission below the band gap and enhance it above the band gap, and this is what we have done. We have used the topological transition in a way that was not done before for thermal enhancement and suppression, enhancing the high-energy part of the emission spectrum and suppressing the low-energy thermal photons. This allows us to emit light only within the energy spectrum above the band gap."

The paper's other authors were Jacob; Hamburg University of Technology researchers Alexander Yu

Petrov, Slawa Lang, Manfred Eich, T. Krekeler and M. Ritter; and senior research scientist Michael Störmer from the Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research.

Future research will include work to convert heat radiation from a thermal metamaterial to electron-hole pairs in a semiconducting material, a critical step in developing the technology. The thermophotovoltaic technology might be ready for commercialization within seven years, Jacob said.

A graphic depicting the high-temperature thermal metamaterial is available at https://www.purdue.edu/uns/images/2016/jacob-hyperboloidal.jpg

The graphic depicts how the thermal radiation is controlled using the shape of the surfaces: the metamaterial enhances thermal radiation in the "ellipsoidal regime" at left, but suppresses it in the "hyperboloidal regime" at right.

The research was funded by the German Research Foundation, National Science and Engineering Research Council of Canada, Alberta Innovates Technology Futures, and the Helmholtz-Alberta Initiative.

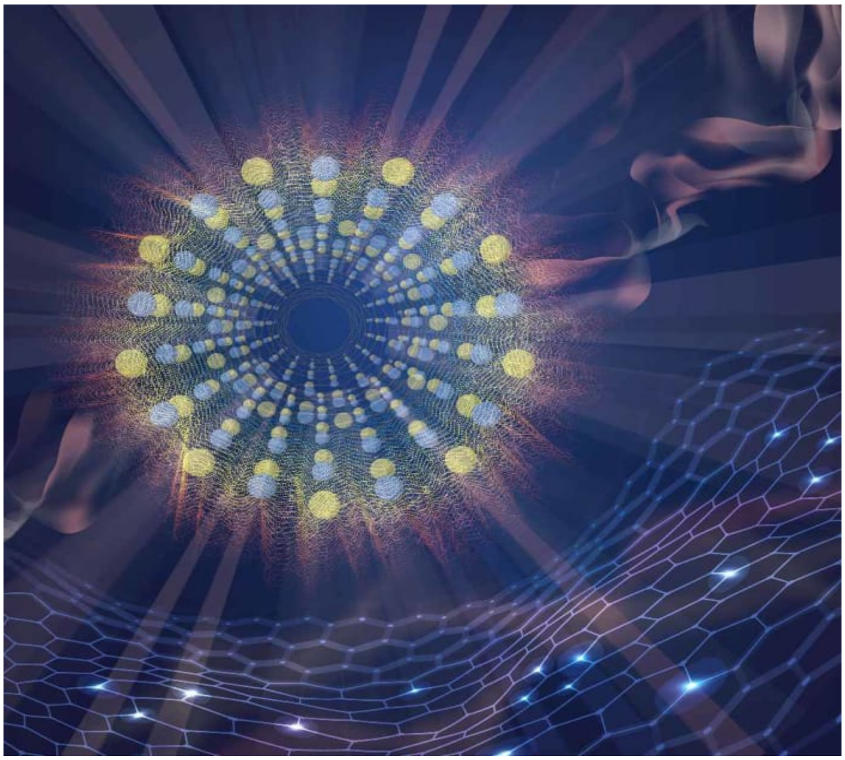
Writer: *Emil Venere, 765-494-4709, venere@purdue.edu*
Source: *Zubin Jacob, 765-494-3514, zjacob@purdue.edu*

Note to Journalists: *An electronic copy of the research paper is available by contacting press@nature.com or Emil Venere, 765-494-4709, venere@purdue.edu.*

An animation, available at https://youtu.be/dbePERsPh-g, was prepared by College of Engineering digital producer Erin Easterling, 765-496-3388, Easterling@purdue.edu

IN HIGH TEMPERATURES, A NEW CLASS OF CERAMICS CONTROLS HEAT RADIATION

Manufacturers frequently use coatings to protect the structural stability of engines or power generators operating at high temperatures. Ceramic shields, however, have not been able to adequately address a critical, performance-limiting factor: heat radiation.



Researchers have engineered ceramic nanotubes (shown in yellow). The nanotubes act as antennas, which use light-matter oscillations to control heat radiation. The design is a step toward a new class of ceramics that work more efficiently at high temperatures. (Purdue University illustration/Xueji Wang

A new ceramic coating from Purdue University acts as a kind of thermal antenna, using light-matter oscillations, or polaritrons, to control the direction and electromagnetic spectrum of thermal radiation.

According to the researchers, including Purdue professor Zubin Jacob, the design is a step toward a new class of ceramics that work more efficiently at high temperatures.

“These nanotubes work as a system of high-temperature ceramic antenna emitters, creating strong mid-infrared thermal emission and distinct spectral and spatial thermal emission patterns,” Zubin Jacob told Tech Briefs.

The team built the nanotubes built nanotubes from an emerging ceramic material known for its high thermal stability: hexagonal boron nitride.

The ability to control radiation occurs when the boron nitride becomes a cylinder. In cylindrical form, boron nitride nanotubes (BNNTs) possess subwavelength oscillations capable of coupling to heat radiation.

The coating’s hexagonal boron nitride, or hBN, contains part-light, part-matter quasiparticles known as polaritrons. When excited by high

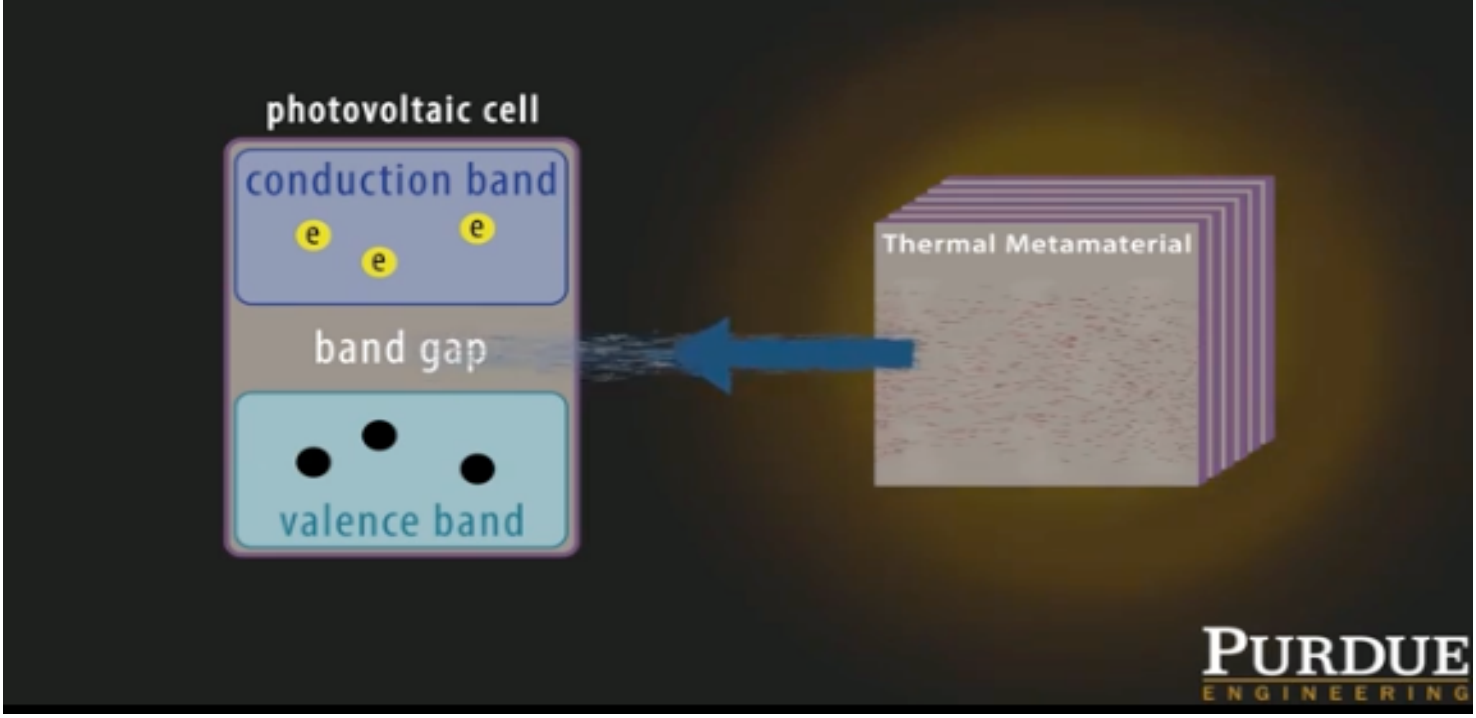


Photo taken from YouTube Animation Video, "Thermal Metamaterial Innovation"
Available at: https://youtu.be/01L57fVoGps

temperatures, the nanotubes, acting as antennas, bind the polaritrons to the outgoing energy.

The 1 x 1 cm mid-IR thermal antenna emitters, made from the high-frequency optical phonons present in the boron nanotubes, operate at temperatures as high as 938 K. The multi-walled BNNTs are of an average diameter of 50 nm and lengths of 5–20 µm.

With further design efforts, the radiative engineering effect of the BNNT thin film presents a pair of engine-performance benefits, according to the Purdue professor of electrical and computer engineering.

"By controlling radiation at these high temperatures, we can increase the lifetime of the coating," said Jacob. "The performance of the engine would also increase because it could be kept hotter with more isolation for longer periods of time."

In an interview with Tech Briefs below, Jacob reveals what other applications are possible when you can take control of thermal radiation.

Tech Briefs: What did you create exactly?

Zubin Jacob: We have developed a polaritonic ceramic. This is a fundamentally new class of materials that combines high-temperature properties of ceramics and adds the functionality of "polaritons." Polaritons are collective light-matter oscillations which are thermally excited at high temperatures.

We developed a disordered multi-walled boron nitride nanotube (BNNT) system by drop-coating BNNT powders on tungsten thin films. These nanotubes work as a system of high-temperature ceramic antenna emitters, creating strong mid-infrared thermal emission and distinct spectral and spatial thermal emission patterns.

Tech Briefs: How does the BNNT system work?

Zubin Jacob: Hexagonal boron nitride (hBN) is a 2D material with a unique set of optical properties. The phonon polariton resonances and hyperbolic anisotropy of hBN create strong near-field radiation at elevated temperatures. By rolling sheets of hBN into a tubular geometry, we can form subwavelength particles (BNNTs), which can couple these near-field dark modes to the thermal radiation in the far-field.

***Tech Briefs*: Why is this achievement an important one?**

Zubin Jacob: First of all, hBN and BNNTs produce the highest optical phonon frequency among all known materials, which extend the scope of the material database for mid-infrared thermal engineering.

Secondly, these boron nitride ceramic nanotube coatings show high thermal stability, which enables their application in extreme environments including high-temperature power generators and aircraft engines.

Finally, the BNNTs are natural ceramic antennas. Compared with other methods for thermal radiation control, such as artificial thermal metasurfaces or photonic crystals, this BNNT coating doesn't require any complicated fabrication techniques and is extremely easy for large-scale production. This simple disordered BNNT system can also withstand higher temperatures than other nano-structured thermal emitters.

***Tech Briefs*: How do the nanotubes control radiation?**

Zubin Jacob: Generally, thermal radiation is considered to be omnidirectional and spectrally broad. However, the thermal radiation from our ceramic nanotube emitters has three narrow emission bands at different wavelengths. These three emission bands also show specific angular dependence. This is very different from the thermal radiation of usual objects/materials but is very similar to the emission pattern of antennas. This is achieved by the novel light-matter interactions (phonon polaritons) in the unique 1D structure of BNNTs.

***Tech Briefs:* Have you tried to create similar metamaterials?**

Zubin Jacob: We have some other works in which we use different materials to engineer thermal emission.

In 2016, we developed a thermal metamaterial that is made of a multi-layer stack of tungsten and hafnium oxide. This thermal metamaterial was designed to enhance a specific spectral range of the thermal radiation that can be absorbed by photovoltaic cells and suppress the thermal radiation at other wavelengths. This metamaterial shows high-thermal stability up to 1000 °C. It can be used in thermophotovoltaic cells to utilize waste heat harvested from power plants and factories. (Nature Communications volume 7, 11809, 2016)

In 2018, we also created a bi-periodic grating emitter using silicon carbide and achieved a dual-band thermal radiation control. This silicon carbide emitter is stable at temperatures up to 1000 K. (Journal of Quantitative Spectroscopy and Radiative Transfer, 216, 99-104, 2018)

***Tech Briefs:* What needs to happen to commercialize the material that you most recently developed?**

Zubin Jacob: We need to find the proper approach to large-scale production and integration.

Additionally, we are studying other interesting properties of hBN and BNNTs and trying to create some other novel systems to control thermal radiation. We are also trying to find more polaritonic ceramics that are suitable for thermal radiation control.

Writer: *Billy Hurley*

NEW ANTENNA TECH TO EQUIP CERAMIC COATINGS WITH HEAT RADIATION CONTROL

The gas turbines powering aircraft engines rely on ceramic coatings that ensure structural stability at high temperatures. But these coatings don't control heat radiation, limiting the performance of the engine.

Researchers at Purdue University have engineered ceramic "nanotubes" that behave as thermal antennas, offering control over the spectrum and direction of high-temperature heat radiation.

The work is published in Nano Letters, a journal by the American Chemical Society. An illustration of the ceramic nanotubes will be featured as the journal's supplementary cover in a forthcoming issue.

"By controlling radiation at these high temperatures, we can increase the lifetime of the coating. The performance of the engine would also increase because it could be kept hotter with more isolation for longer periods of time," said Zubin Jacob, an associate professor of electrical and computer engineering at Purdue.

The work is part of a larger search in the field for a wide range of materials that can withstand higher temperatures. In 2016, Jacob's team developed a thermal "metamaterial" – made of tungsten and hafnium oxide – that controls heat radiation with the intention of improving how waste heat is harvested from power plants and factories.

A new class of ceramics would expand on ways to more efficiently use heat radiation.

Jacob's team, in collaboration with Purdue professors Luna Lu and Tongcang Li, built nanotubes out of an emerging ceramic material called boron nitride, known for its high thermal stability.

These boron nitride nanotubes control radiation through oscillations of light and matter, called polaritons, inside the ceramic material. High temperatures excite the polaritons, which the nanotubes – as antennas – then couple efficiently to outgoing heat radiation.

The antennas could bring the ability to accelerate the radiation, perform enhanced cooling of a system or send information in very specific directions or wavelengths, Jacob said.

The researchers plan to engineer more ceramic materials with polaritonic features for a host of different applications.

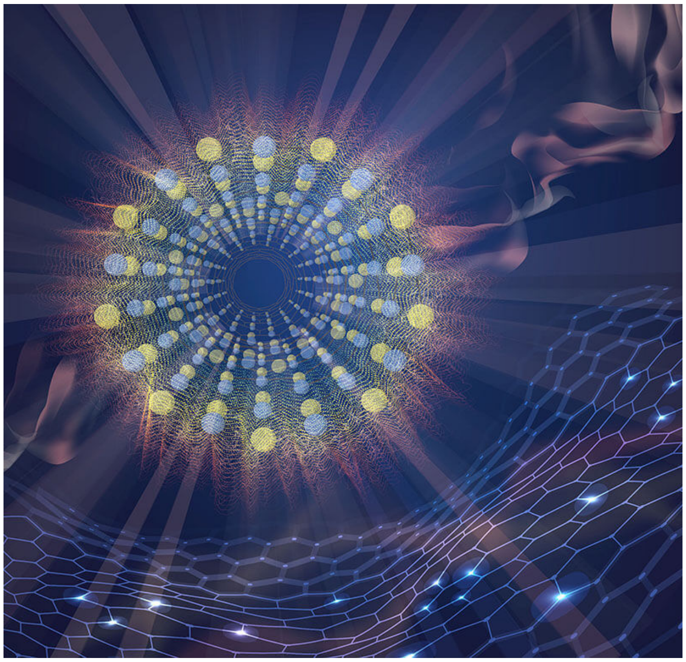
"Polaritonic ceramics can be game changing and we want them to be used widely," Jacob said.

This research was performed in the Purdue Discovery Park Birck Nanotechnology Center and is supported through Nascent Light-Matter Interactions, a program by the Defense Advanced Research Projects Agency. The program is led by Purdue University's School of Electrical and Computer Engineering.

About Discovery Park

Discovery Park is a place where Purdue researchers move beyond traditional boundaries, collaborating across disciplines and with policymakers and business leaders to create solutions for a better world. Grand challenges of global health, global conflict and security, and those that lie at the nexus of sustainable energy, world food supply, water and the environment are the focus of researchers in Discovery Park. The translation of discovery to impact is integrated into the fabric of Discovery Park through entrepreneurship programs and partnerships.

THERMAL ELECTRODYNAMICS



Researchers have engineered ceramic nanotubes (shown in yellow). The nanotubes act as antennas, which use light-matter oscillations to control heat radiation. The design is a step toward a new class of ceramics that work more efficiently at high temperatures. (Purdue University illustration/Xueji Wang

Writer: *Kayla Wiles, 765-494-2432 wiles5@purdue.edu*
Source: *Zubin Jacob, 765-494-3514, zjacob@purdue.edu*
Note to Journalists: For a copy of the paper, please contact Kayla Wiles, Purdue News Service, at wiles5@purdue.edu

CONTROLLING HEAT WITH CERAMIC NANOTUBES

New ceramic nanotubes could prolong aircraft engine coatings by controlling high-temperature heat radiation. Idha Valeur reports.

In an attempt to increase the lifetime of ceramic coatings used for gas turbines in aircrafts, researchers have developed a new material that can control the engine's heat radiation.

The material, a polaritonic ceramic, combines high-temperature properties of ceramics with the functionality of polaritons. To do this, the team developed a polaritonic ceramic coating to make high-temperature thermal antennae and claimed this offered control over the spectrum and direction of high-temperature heat radiation. Purdue University PhD student, Xueji Wang, explained that their theoretical work suggested that hexagonal boron nitride (hBN), a polaritonic ceramic material that is stable at high temperatures, has unique thermal emission characteristics. 'But the unique thermal emission of bulk hBN material is confined to the near field, up to 1um away from the material surface,' Wang told Materials World.

'We found multi-walled boron nitride nanotubes (BNNT), which share the similar polaritonic properties and high-temperature stability of hBN and also show antenna effects to couple the near-field dark modes into far-field thermal radiation. We designed the device structure, developed the drop coating method and finally got this BNNT thermal emitter.'

When using the drop coating method, commercial BNNT powders are dispersed into an ethanol solvent, Wang said. 'Then the BNNT-containing ethanol is dropped on to a 300nm tungsten thin film on a polished silicon wafer with pipettes. After ethanol volatilised, the BNNTs form a disordered film and coat on the tungsten surface.

'All these steps can be done in less than one hour regardless of the size of the substrate.'

Expressing the importance of this progression, Purdue University, USA, Associate Professor of electrical and computer engineering and team leader, Zubin Jacob, told Materials World that hBN and BNNTs produce the highest optical phonon frequency of all known materials, hence extending the scope of the material database for mid-infrared thermal engineering. He added that the boron nitride ceramic nanotube coating shows high thermal stability at temperatures up to 938K, which makes them suitable for applications in extreme environments such as power generators and aircraft engines.

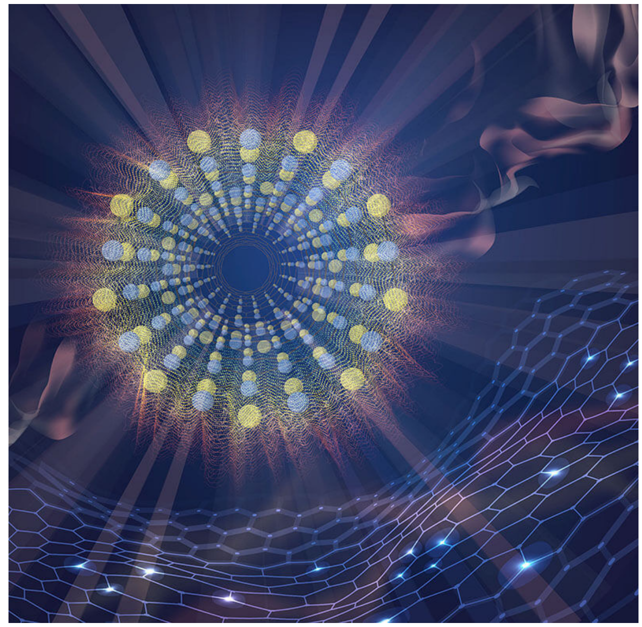
According to Wang, the team demonstrated its stability by heating it and measuring the thermal emission signal. They did this using a self-made thermal emission spectroscopy set up, which showed no significant degradation. This indicated that the BNNT coatings are thermally stable. 'Finally, the BNNTs are natural ceramic antennas. Compared with other methods for thermal radiation control, such as artificial thermal metasurfaces or photonic crystals, this BNNT coating doesn't require any complicated fabrication techniques and is extremely easy for large-scale production,' Jacob said.

Wang added that the reason the BNNT coating is easy to scale up is because it does not require nano-lithography processes, which often require vast amounts of cleanroom work and expensive tools. 'Thus, compared with other nano-structured thermal emitters, this BNNT coating is more suitable for large-scale production,' he said.

According to Jacob, thermal radiation is generally considered to be omnidirectional with a broad spectre, but that the radiation from their nanotube emitters has three narrow bands – all at different wavelengths. 'These three emission bands also show some angular dependence. This is very different from the thermal radiation of usual object and materials but is very similar to the emission pattern of antennas,' he said. 'This is achieved by the novel light-matter interactions – phonon polaritons – in the unique 1D structure of BNNTs.'

Moving forward

Currently, the team is looking at other properties of hBN and BNNTs that could be of interest and attempting to create other novel systems to control thermal radiation. 'We are also trying to find more polaritonic ceramics that are suitable for thermal radiation control', Jacob said.



An illustration of the BNNT and thermal radiation. Credit: Purdue University Illustration/Xueji Wang

Writer: Idha Valeur
Materials World magazine, 6 Jan 2020

EXPLOITING LOSS

Metamaterials operating at frequency ranges in which the dielectric permittivity is close to zero have been discussed for use across a wide range of optical applications.

Sean Molesky and colleagues from the University of Alberta in Canada, have now proposed methods for engineering thermally excited far-field electromagnetic radiation using epsilon-near-zero metamaterials. In the same paper, the researchers also introduce epsilon-near-pole metamaterials, where there selected wavelength is that corresponding to the resonance pole, rather than the wavelength that gives zero permittivity. The researchers showed that these concepts may be useful for high-temperature applications such as capturing lost thermal energy in photovoltaic and other energy-conversion devices. In particular, they claim that photovoltaic devices with metamaterial emitters near temperatures of 1,500 K may surpass the Shockley–Queisser efficiency limit of 41%. They propose two metamaterial structures that should be able to be fabricated using current technology. One structure consists of simple layers of metal and dielectric films, and the other is a two-dimensional array of metallic nanowires in a dielectric matrix. The main advantages of thermal emitters based on these metamaterials include omnidirectional thermal emission, narrowband emissivity and polarization insensitivity. Importantly, the epsilon-near-zero and epsilon-near-pole emitters also function in reverse as highly effective thin absorbers.

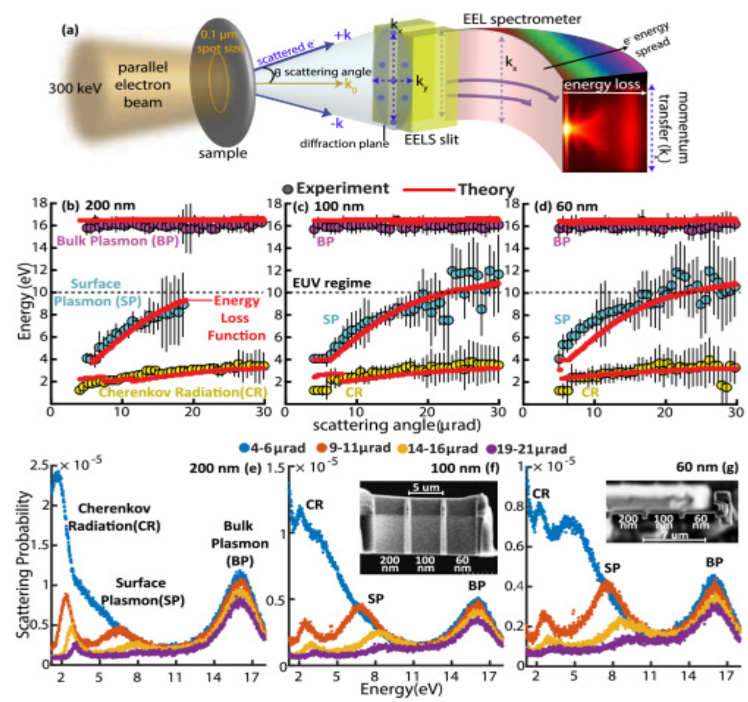
"The main advantages of thermal emitters based on these metamaterials include omnidirectional thermal emission, narrowband emissivity and polarization insensitivity."

Writer: *David Pile*

EXTREME ULTRAVIOLET PLASMONICS AND CHERENKOV RADIATION IN SILICON

Silicon is widely used as the material of choice for semiconductor and insulator applications in nanoelectronics, micro-electro-mechanical systems, solar cells, and on-chip photonics.

In stark contrast, in this paper, we explore silicon's metallic properties and show that it can support propagating surface plasmons, collective charge oscillations, in the extreme ultraviolet (EUV) energy regime not possible with other plasmonic materials such as aluminum, silver, or gold. This is fundamentally different from conventional approaches, where doping semiconductors is considered necessary to observe plasmonic behavior. We experimentally map the photonic band structure of EUV surface and bulk plasmons in silicon using momentum-resolved electron energy loss spectroscopy. Our experimental observations are validated by macroscopic electrodynamic electron energy loss theory simulations as well as quantum density functional theory calculations. As an example of exploiting these EUV plasmons for applications, we propose a tunable and broadband thresholdless Cherenkov radiation source in the EUV using silicon plasmonic metamaterials. Our work can pave the way for the field of EUV plasmonics.



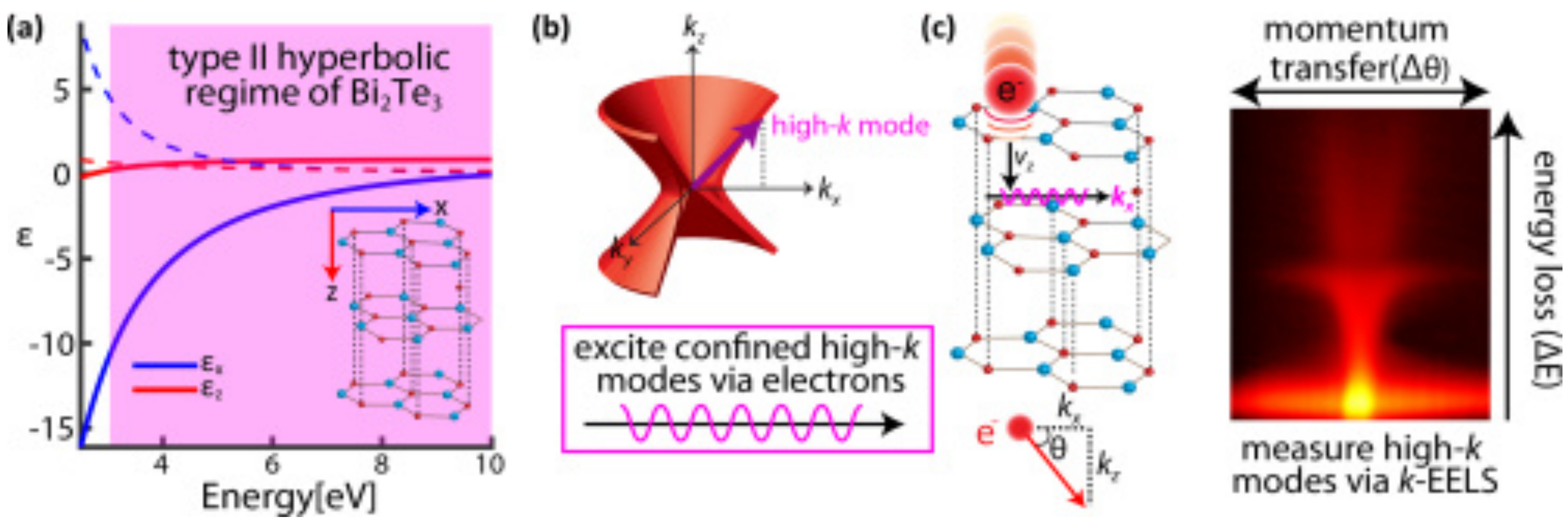
*EUV plasmons and CR in silicon measured with ℏk-EELS. (a) Schematic showing the key components of the ℏk-EELS technique for measuring the momentum-resolved photonic band structure of silicon. The ℏk-EELS experiment was performed with a Hitachi HF-3300 TEM with a GIF Tridiem in ℏk-EELS mode at 300 keV incident energy with parallel illumination resulting in a quantitative energy-momentum dispersion map of the excitations in the sample (details in Supplement 1). The photonic band structure of (b) 200 nm; (c) 100 nm; and (d) 60 nm thick silicon films measured with ℏk-EELS (error bars show 95% confidence interval). All three films show evidence of the BP at (≈16eV≈16eV) and the SP at (≈4–11.5eV≈4–11.5eV) in the EUV as well as CR in the visible in the (≈2–4eV≈2–4eV) region mapped to large scattering angles (large momentum with ℏk>5*ℏk0k>5*k0). A good agreement to the macroscopic electrodynamic energy loss function (red line) is seen for all three thicknesses. (e), (f), and (g) show the electron scattering probability for the three excitations as measured by ℏk-EELS integrated over the indicated scattering angles for the 200, 100, and 60 nm silicon films, respectively. Insets in (f) and (g) show scanning electron microscope images of the free-standing silicon films prepared via FIB milling and mounted to the TEM grid.*

Writers: *Prashant Shekhar, Sarang Pendharker, Harshad Sahasrabudhe, Douglas Vick, Marek Malac, Rajib Rahman, and Zubin Jacob*

FAST ELECTRONS INTERACTING WITH A NATURAL HYPERBOLIC MEDIUM: BISMUTH TELLURIDE

Fast electrons interacting with matter have been instrumental for probing bulk and surface photonic excitations including Cherenkov radiation and plasmons.

Additionally, fast electrons are ideal to investigate unique bulk and longitudinal photonic modes in hyperbolic materials at large wavevectors difficult to probe optically. Here, we use momentum-resolved electron energy loss spectroscopy (k-EELS) to perform the first experimental demonstration of high-k modes and hyperbolic Cherenkov radiation in the natural hyperbolic material Bi_2Te_3. This work establishes Bi_2Te_3 as one of the few viable natural hyperbolic materials in the visible and paves the way for k-EELS as a fundamental tool to probe hyperbolic media.



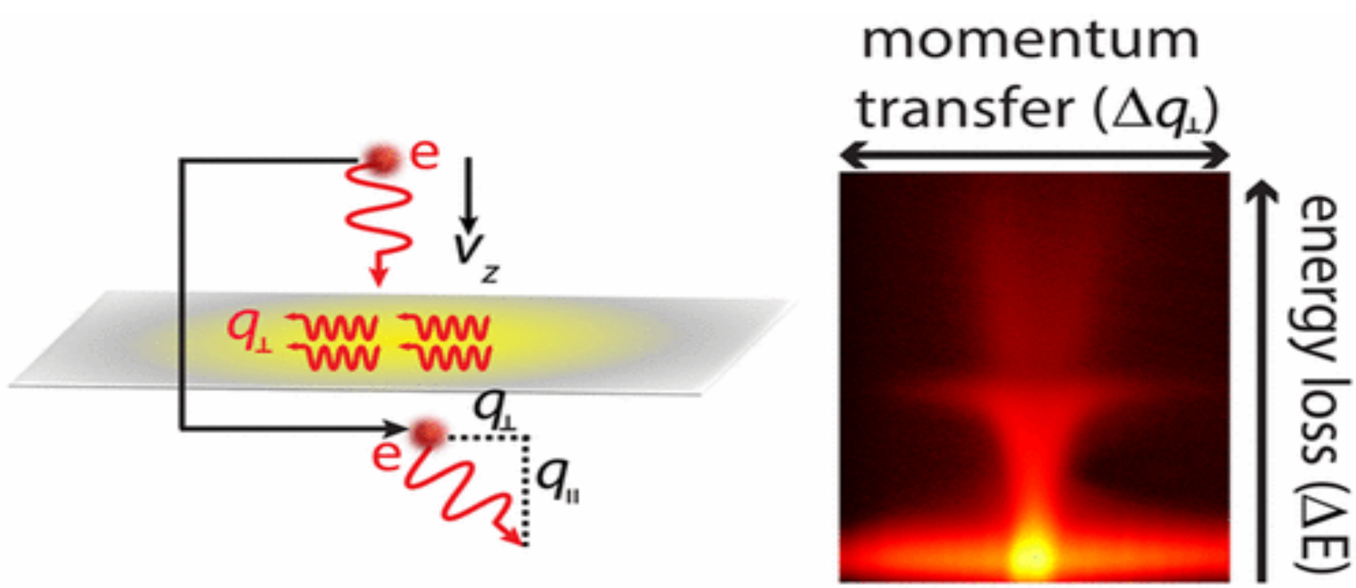
(a) Uniaxial dielectric permittivity of Bi_2Te_3 parallel (ϵ_z) and perpendicular (ϵ_x) to the c-axis showing type II hyperbolic behaviour ($\epsilon_x < 0$, $\epsilon_z > 0$) in the visible to the UV. Note the estimated plasma frequency of the ϵ_z component is blue shifted by 1.5 eV compared to [18] as a parameter fit to our experimental data. (b) The type II hyperbolic isofrequency surface of Bi_2Te_3 that can support photonic excitations with large momentum (high-k modes) that would normally decay in conventional media. (c) Schematic showing the excitation of high-k modes in Bi_2Te_3 via fast electrons. The subsequent energy loss (ΔE) and scattering angle (ϑ) of the electron as it passes through the sample is measured and corresponds directly to the energy and momentum (k) of the excited modes in the structure.

Writers: *Prashant Shekhar, Sarang Pendharker, Douglas Vick, Marek Malac, and Zubin Jacob*

Momentum-Resolved Electron Energy Loss Spectroscopy for Mapping the Photonic Density of States

Strong nanoscale light-matter interaction is often accompanied by ultraconfined photonic modes and large momentum polaritons existing far beyond the light cone.

A direct probe of such phenomena is difficult due to the momentum mismatch of these modes with free space light, however, fast electron probes can reveal the fundamental quantum and spatially dispersive behavior of these excitations. Here, we use momentum-resolved electron energy loss spectroscopy (q-EELS) in a transmission electron microscope to explore the optical response of plasmonic thin films including momentum transfer up to wavevectors (q) significantly exceeding the light line wave vector. We show close agreement between experimental q-EELS maps, theoretical simulations of fast electrons passing through thin films and the momentum-resolved photonic density of states (q-PDOS) dispersion. Although a direct link between q-EELS and the q-PDOS exists for an infinite medium, here we show fundamental differences between q-EELS measurements and the q-PDOS that must be taken into consideration for realistic finite structures with no translational invariance along the direction of electron motion. Our work paves the way for using q-EELS as the preeminent tool for mapping the q-PDOS of exotic phenomena with large momenta (high-q) such as hyperbolic polaritons and spatially dispersive plasmons.



Writers: *Prashant Shekar, Marek Malac, Vaibhav Gaind, Neda Dalili, Al Meldrum and Zubin Jacob*

TRAPPING LIGHT THAT DOESN'T BOUNCE OFF TRACK FOR FASTER ELECTRONICS

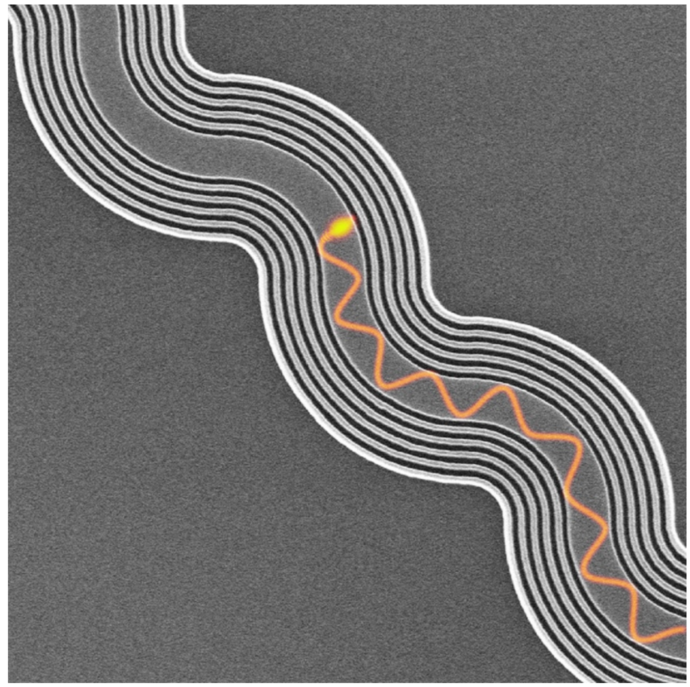
WEST LAFAYETTE, Ind. — Replacing traditional computer chip components with light-based counterparts will eventually make electronic devices faster due to the wide bandwidth of light.

A new protective metamaterial "cladding" prevents light from leaking out of the very curvy pathways it would travel in a computer chip.

Because processing information with light can be more efficient than with electrons used in current devices, there is good reason to confine light onto a chip. But light and the bits of information it carries tend to leak and scatter out of the tiny components that must fit on a chip.

A Purdue University-led effort has built a novel cladding along the highways for light travel, called waveguides, to prevent information leaks – particularly around sharp bends where light bounces off track and scatters. Information then gets lost or jumbled rather than communicated throughout a device. Preventing this could facilitate the integration of photonic with electric circuitry, increasing communication speed and reducing power consumption.

"We want the bits of information that we are sending in the waveguide to travel along tight bends and simultaneously not be lost as heat. This is a challenge," said **Zubin Jacob**, Purdue assistant professor of **electrical and computer engineering**. What makes the waveguide cladding so unique is anisotropy, meaning that the cladding design enables light to travel at different velocities in different directions. By controlling the anisotropy of the cladding, the researchers prevented light from leaking off track into other waveguides where "crosstalk," or mixing, of information would occur. Instead, bits of information carried by light bounce off by "total internal reflection" and stay strongly confined within a waveguide.



An anisotropic metamaterial waveguide cladding keeps light travel on track throughout a computer chip, preventing leaked and jumbled bits of information. (Purdue University image/Saman Jahani)

"The waveguide we made is an extreme skin-depth structure, which means that any leakage that does happen will be really small," said Saman Jahani, Purdue graduate research assistant in electrical and computer engineering. "This approach can pave the way for dense photonic integration on a computer chip without worrying about light leakage."

This work was performed by an international team of researchers at Purdue University, University of Alberta, Texas Tech University, the University of British Columbia and the Shanghai

Institute of Microsystem and Information Technology. The team's findings appear in the journal **Nature Communications**.

Various sources of funding supported the research, including the National Science Foundation, the Chinese Academy of Sciences, the Shanghai Municipal Government, the Natural Sciences and Engineering Research Council of Canada and the Silicon Electronic-Photonic Integrated Circuits Program.

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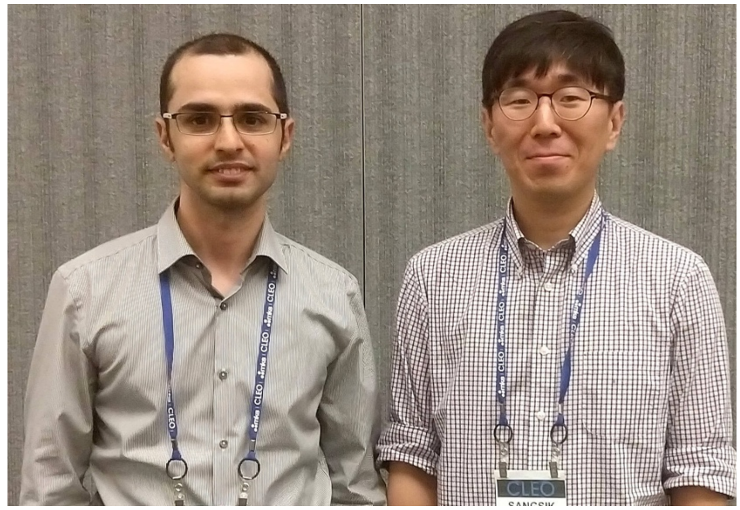
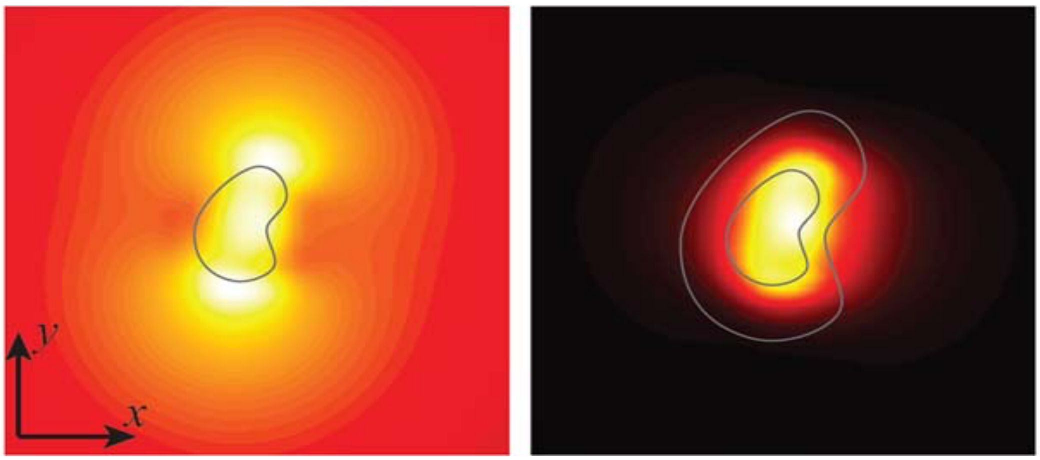


Researchers Saman Jahani (left) of Purdue and Sangsik Kim of Texas Tech University conducted work on a way to reinforce light travel for smaller chip components. (Purdue University image provided by Saman Jahani)

BREAKTHROUGHS IN PHOTONICS 2014: RELAXED TOTAL INTERNAL REFLECTION

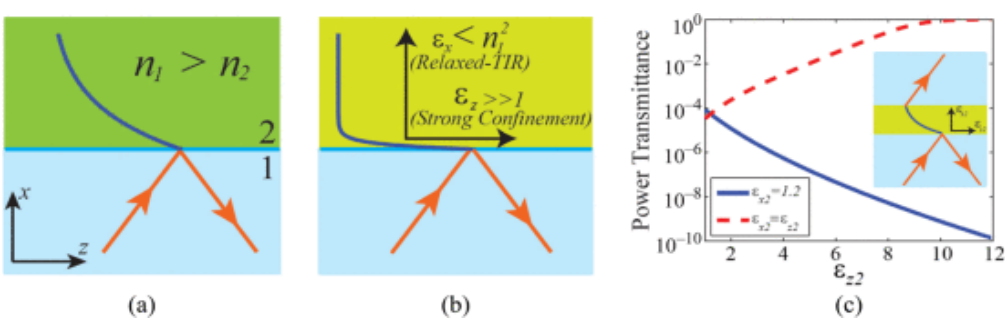
Total internal reflection (TIR) is a ubiquitous phenomenon used in photonic devices ranging from waveguides and resonators to lasers and optical sensors.



Relaxed Total Internal Reflection

Total internal reflection (TIR) is a ubiquitous phenomenon used in photonic devices ranging from waveguides and resonators to lasers and optical sensors. Controlling this phenomenon and light confinement are keys to the future integration of nanoelectronics and nanophotonics on the same silicon platform. We introduced the concept of relaxed TIR, in 2014, to control evanescent waves generated during TIR. These unchecked evanescent waves are the fundamental reason photonic devices are inevitably diffraction limited and cannot be miniaturized.

Our key design concept is the engineered anisotropy of the medium into which the evanescent wave extends, thus allowing for skin depth engineering without any metallic components. In this paper, we give an overview of our approach and compare it to key classes of photonic devices such as plasmonic waveguides, photonic crystal waveguides, and slot waveguides. We show how our work can overcome a long-standing issue in photonics, namely, nanoscale light confinement with fully transparent dielectric media.



Relaxed total internal reflection. (a) Conventional total internal reflection [14]. (b) Relaxed total internal reflection [14]. (c) Controlling the evanescent wave tunneling of a p-polarized light using transparent anisotropic metamaterials. In all cases, εy=εz. Fundamentally different scaling of tunneled energy is observed for the two cases.

Writers: *Saman Jahani, Zubin Jacob*
Published in: *IEEE Photonics Journal (Volume: 7 , Issue: 3 , June 2015)*

AXIAL SUPER-RESOLUTION EVANESCENT WAVE TOMOGRAPHY

Optical tomographic reconstruction of a three-dimensional (3D) nanoscale specimen is hindered by the axial diffraction limit, which is 2–3 times worse than the focal plane resolution.

We propose and experimentally demonstrate an axial super-resolution evanescent wave tomography method that enables the use of regular evanescent wave microscopes like the total internal reflection fluorescence microscope beyond surface imaging and achieve a tomographic reconstruction with axial super-resolution. Our proposed method based on Fourier reconstruction achieves axial super-resolution by extracting information from multiple sets of 3D fluorescence images when the sample is illuminated by an evanescent wave. We propose a procedure to extract super-resolution features from the incremental penetration of an evanescent wave and support our theory by one-dimensional (along the optical axis) and 3D simulations. We validate our claims by experimentally demonstrating tomographic reconstruction of microtubules in HeLa cells with an axial resolution of ∼130 nm∼130 nm. Our method does not require any additional optical components or sample preparation. The proposed method can be combined with focal plane super-resolution techniques like stochastic optical reconstruction microscopy and can also be adapted for THz and microwave near-field tomography.

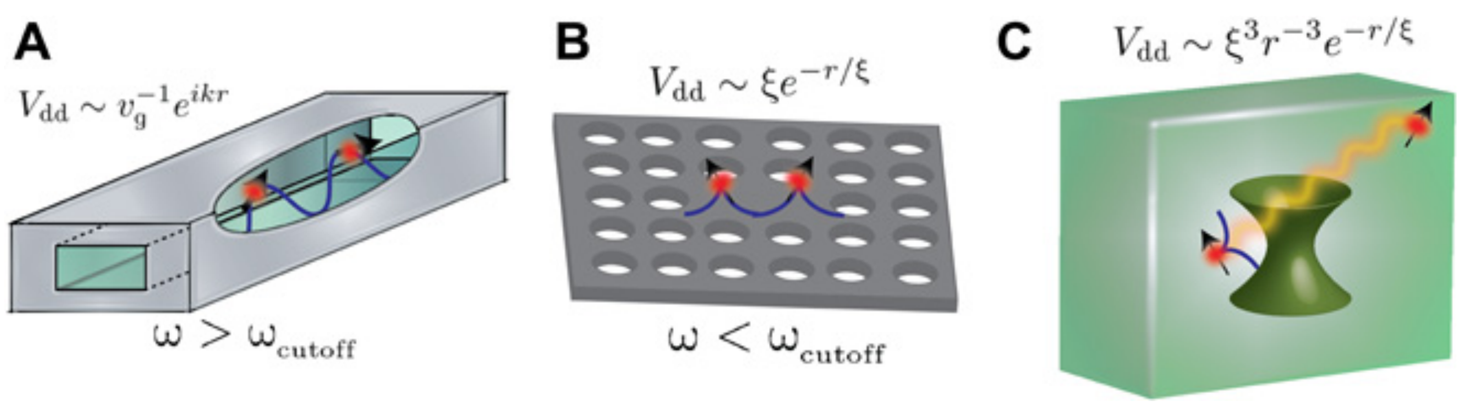
"We validate our claims by experimentally demonstrating tomographic reconstruction of microtubules in HeLa cells with an axial resolution of ∼130 nm∼130 nm."

Writers: *Sarang Pendharker, Swapnali Shende, Ward Newman, Stephen Ogg, Neda Nazemifard, and Zubin Jacob*

OBSERVATION OF LONG-RANGE DIPOLE-DIPOLE INTERACTIONS IN HYPERBOLIC METAMATERIALS

Dipole-dipole interactions (V_{dd}) between closely spaced atoms and molecules are related to real photon and virtual photon exchange between them and decrease in the near field connected with the characteristic Coulombic dipole field law.

The control and modification of this marked scaling with distance have become a long-standing theme in quantum engineering since dipole-dipole interactions govern Van der Waals forces, collective Lamb shifts, atom blockade effects, and Förster resonance energy transfer. We show that metamaterials can fundamentally modify these interactions despite large physical separation between interacting quantum emitters. We demonstrate a two orders of magnitude increase in the near-field resonant dipole-dipole interactions at intermediate field distances (10 times the near field) and observe the distance scaling law consistent with a super-Coulombic interaction theory curtailed only by absorption and finite size effects of the metamaterial constituents. We develop a first-principles numerical approach of many-body dipole-dipole interactions in metamaterials to confirm our theoretical predictions and experimental observations. In marked distinction to existing approaches of engineering radiative interactions, our work paves the way for controlling long-range dipole-dipole interactions using hyperbolic metamaterials and natural hyperbolic two-dimensional materials.



Comparison of dipole-dipole interactions (V_{dd}) in metallic waveguides, photonic crystal band-edge structures, and hyperbolic metamaterials.

*Here, r is the distance between interacting emitters, v_g is the group velocity of the waveguide mode with wave vector k, ω_{cutoff} is the cutoff frequency of the metallic waveguide mode or photonic crystal, and ξ is an interaction range. (**A**) When the transition frequencies of interacting atoms lie above the cutoff, they will have a sinusoidal-type interaction. (**B**) On the other hand, at the band edge of a photonic crystal, there occur interactions with a divergent strength and range. (**C**) Hyperbolic media exhibit fundamentally different Coulombic long-range interactions, which diverge for specific angular directions in the low-loss effective medium limit.*

Writers: *Ward D. Newman, Cristian L. Cortes, Amir Afshar, Ken Cadien, Al Meldrum, Robert Fedosejevs and Zubin Jacob*

NANO-OPTICAL CABLES FOR WIRING UP PHOTONIC CIRCUITS

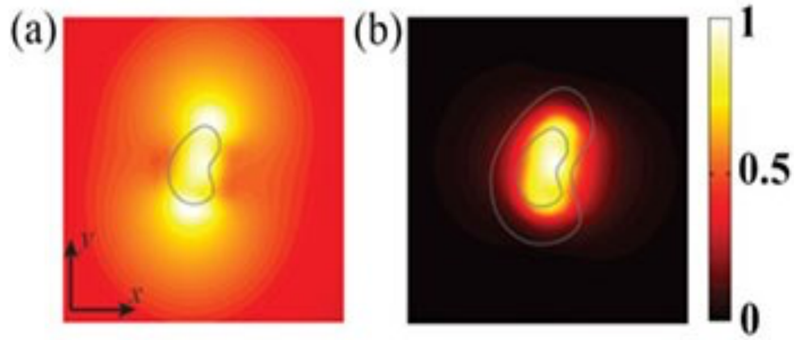
Researchers at the University of Alberta, Canada, have proposed a new approach to confining light at subdiffraction wavelengths, using transparent metamaterials—without creating heat or losing data, and with dramatically reduced crosstalk (Optica, doi:10.1364/OPTICA.1.000096).

The team believes that the approach could ultimately spur development of fiber-optic-like "nano-cables" used for interconnects on computer chips, which one of the paper's authors, Zubin Jacob, calls "the Holy Grail" in nanophotonics.

The continual drive toward miniaturization, power scalability and energy efficiency in computer chips has pushed integration of electronics and photonics at ever-smaller scales. But as the length scales dip below the wavelength of light, problems arise in existing approaches to light confinement. One approach, plasmonics, uses metals to achieve nanoscale waveguiding, but because of the metal's absorption properties, the light energy is quickly lost and dissipated as heat. All-dielectric approaches to subdiffraction waveguiding, meanwhile, fall prey to crosstalk between waveguides crowded onto a single chip—the bane of nanophotonic integration.

In what they refer to as a "paradigm shift in light-confinement strategy," Jacob and coauthor Saman Jahani propose focusing not on manipulation of propagating waves within the waveguide, but on the evanescent waves outside of the waveguide core that give rise to crosstalk.

Their approach involves surrounding a conventional dielectric waveguide core with a multilayer metamaterial cladding, consisting of alternating subwavelength layers of germanium (26 nm) and silica (14 nm). The transparent cladding forms an extremely anisotropic medium between separate waveguides.



Simulated electric-energy distribution in 2-D dielectric waveguide without metamaterial cladding (a) and with cladding (b). The addition of the cladding dramatically increases the fraction of total power confined within the waveguide core. [Source: Jahani and Jacob, Optica 1, 96 (2014)]

That medium transforms the optical momentum of the evanescent waves entering it, preserving propagation in the direction of the waveguide while causing the component perpendicular to the waveguide to quickly decay.

The result, the authors say, is the potential for all-dielectric waveguides that provide lossless propagation—with crosstalk an order of magnitude lower than seen in alternative approaches. They believe that the work will lead to a new class of devices based on controlling momentum of the evanescent field. "What we've done," asserts Jacob, "is come up with a fundamentally new way of confining light to the nano scale."

Writer: *Stewart Wills*