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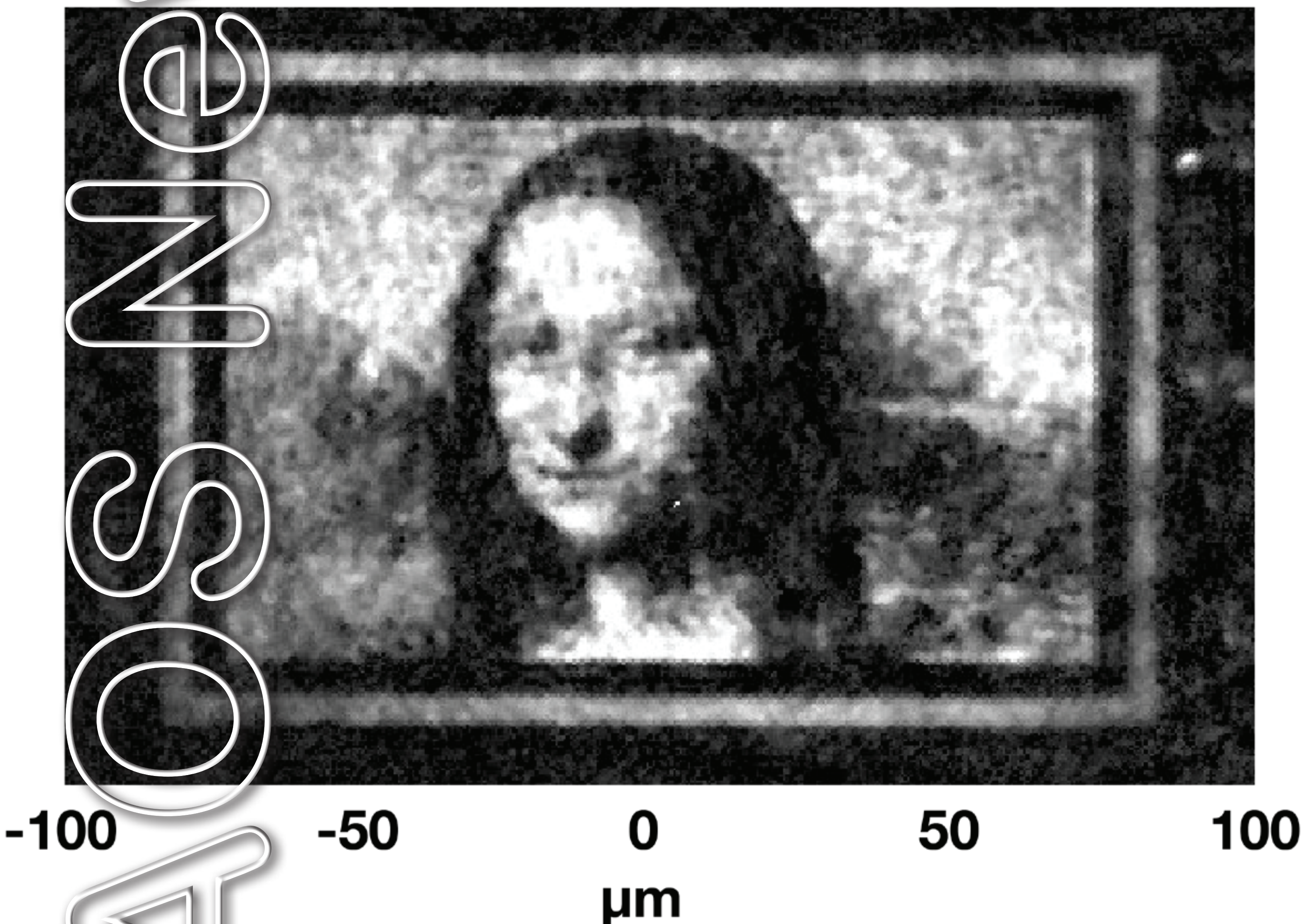
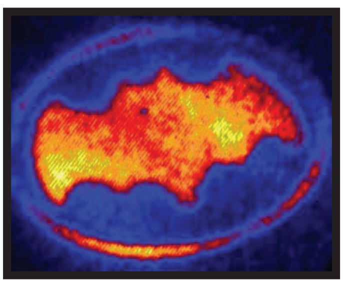
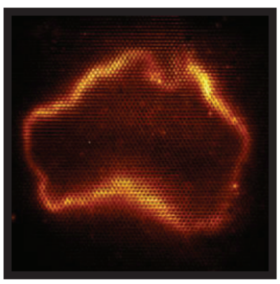
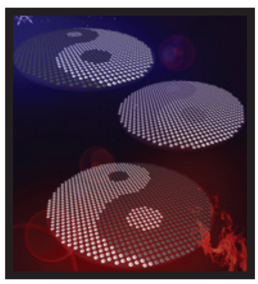


AUSTRALIAN OPTICAL SOCIETY







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AOS News is the official news magazine of the Australian Optical Society. Formed in 1983, the Society is a non-profit organisation for the advancement of optics in Australia. Membership is open to all persons contributing to, or interested in, optics in the widest sense. See the back page (or the AOS website) for details on joining the Society.

Submission guidelines

The AOS News is always looking for contributions, especially from AOS members. Here is a short summary of how to make a submission.

Call for submissions!

Please consider writing something for the next issue.
We are looking for:

Scientific articles on any aspect of optics

Review articles on work in your lab

Conference reports from meetings you attend

Articles for the Optics in Everday Life section

General interest articles

How can you submit?

► The easiest way is by email. We accept nearly all file formats. (Famous last words!).

► Submitted articles will be imported into an Adobe InDesign file. It is best if the diagrams and other graphics are submitted as separate files. All common graphics formats are acceptable, but the resolution must be in excess of 300d.p.i.. Be aware that all colour diagrams will be rendered in grayscale, so if you do use colours, choose colours that show up well in grayscale.

► When using Greek letters and mathematical symbols, use font sets such as Symbol or MT Extra. Please avoid using symbols that are in Roman fonts, where the Option or Alt key is used; e.g. Opt-m in Times font on the Mac for the Greek letter mu.

► If using TeX, use a style file similar to that for Phys Rev. Letters (one column for the title, author and by-line, and two for the main body). The top and bottom margins must be at least 20mm and the side margins 25mm. Submit a pdf file with the diagrams included (no page numbers), as well as copies of the diagrams in their original format in separate files.

► If using a word processor, use a single column. If you do include the graphics in the main document, they should be placed in-line rather than with anchors, but must be submitted separately as well.

What can you submit?

- Scientific Article: A scientific paper in any area of optics.
- Review Article: Simply give a run down of the work conducted at your laboratory, or some aspect of this work.
- Conference Report
- General Interest Article: Any item of interest to members such as reports on community engagement, science in society, etc.
- Article for Optics in Everyday Life section: An explanation of the optics behind any interesting effect, phenomenon, or device.
- News Item
- Obituary
- Book Review
- Cartoon or drawing
- Crossword or puzzle

Reviewing of papers

On submission of a scientific or review article you may request that the paper be refereed, and if subsequently accepted it will be identified as a refereed paper in the contents page. The refereeing process will be the same as for any of the regular peer reviewed scientific journals. Please bear in mind that refereeing takes time and the article should therefore be submitted well in advance of the publication date.

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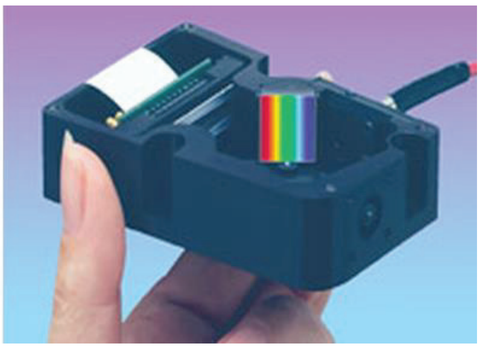

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December 2019 Volume 33 Number 3

Articles

Departments

Cover Pictures:

- The next winner of the AOS photo competition is Tyler Neely. Below a certain temperature, typically on the order of 100 nK, ultracold Rubidium atoms can condense into the ground state of the confining potential, forming a superfluid Bose-Einstein condensate. Since the BEC follows the form of the trapping potential, sculpted light produced by optical tweezers can precisely control the density distribution of the condensate. Here we have used optical tweezers to configure a BEC, which upon imaging the atoms reproduces the famous Mona Lisa painting – in effect "painting" with ultracold matter waves.
- Insets (left to right)
  - Laser-cooled atoms have seen advances in recent years. Here is a false colour image of a shaped electron bunch from a cold atomic gas that has kept its shape after propagating 24cm. From Nature Physics 7 785 (2011), see page 15.
  - Experimental image of third-harmonic generation from nanoscale topological edge states to give an Australia-shaped contour, see page 29.
  - Image of a nanostructured Yin-Yang pattern, designed to give different transmission at different temperatures, allowing reversible image contrast manipulation, see page 24.

SUBMISSION OF COPY:
Contributions on any topic of interest to the Australian optics community are solicited, and should be sent to the editor, or a member of the AOS council. Use of electronic mail is strongly encouraged, although submission of hard copy together with a text file on CD will be considered.

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COPY DEADLINE
Articles for the next issue (Apr 2020) should be with the editor no later than 13 Mar 2020, advertising deadline 6 Mar 2020.

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AOS News is the official news magazine of the Australian Optical Society. The views expressed in AOS News do not necessarily represent the policies of the Australian Optical Society.

Australian Optical Society website:
http://www.optics.org.au

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President's Report

As 2019 ends it is an appropriate time to look back on what the Australian Optical Society has achieved and to look forward to new developments over the next decade.

December 2019 was the month when we held the biennial ANZCOP conference. This year's meeting was the fourth such conference since the first time that we combined all of the previous optics related conferences into a single meeting with the ANZCOP label. The meeting in Melbourne which was ably organised by our Treasurer, was co-located with another major international optics meeting, as we joined forces with SPIE to run a combined meeting. At previous ANZCOP meetings, the SPIE meeting in Melbourne has run in an adjacent week, and this has meant that local participants have generally had to choose which meeting they could attend, which has a big impact on the economics of running both meetings.

From my personal experience in Melbourne, the meeting at RMIT was a great success, with a combined attendance of over three hundred and fifty participants. The addition of the SPIE meeting on Astronomy to our traditional discussion areas, provided a great opportunity for the Optics and Photonics community in our region to hear about the latest advances in this area, and was for me a highlight of the combined meeting. The experience of combining the meetings was not without its problems, not least amongst which was the time shift between the SPIE organising team in Bellingham and the local organising team. Recent developments in video conferencing technology have greatly facilitated such organisation, but I must pay tribute to Arnan and his team, in coordinating what turned out to be quite a complex set of requirements from the two Societies.

It is still too early to say whether we will be combining with SPIE again in 2021, but the meeting in Melbourne provided valuable experience on colocation which we can apply in the future. Several members of the AOS Council will be meeting with SPIE at Photonics West in February to discuss the December meeting further, and we will have another Council meeting in January to discuss future plans.

In November, I was also able to attend the "Science meets Parliament" (SmP) meeting in Canberra organised by Science and Technology Australia (STA) which I found fascinating, since we do not have an equivalent of STA in New Zealand. This was the 20th anniversary of the founding of STA, and Ken Baldwin (one of our Councillors) was presented with a special award by AIP at this meeting to recognise his efforts twenty years ago in founding the organisation. AOS members have played a significant role in the development of STA over the years, not limited to its establishment however, notably Jim Piper who served as STA president and Judith Dawes who is the current STA Treasurer. Whilst STA's most high profile event is SmP, there are a number of other ways in which STA contributes to raising the profile of Scientists in the political arena, and it is now established as a valuable and respected organisation fulfilling the needs of the community.

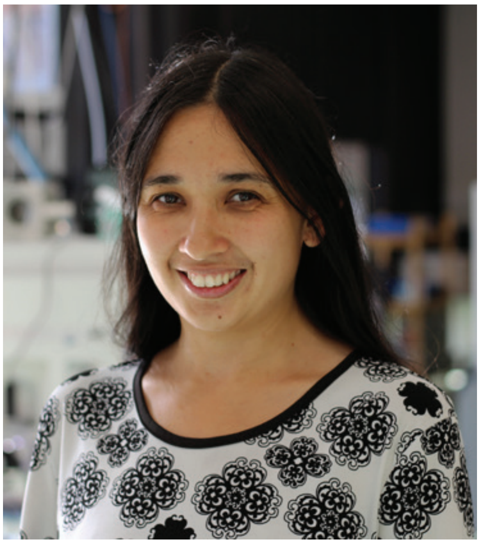
As mentioned in a previous report, the Global Environmental Measuring and Monitoring network is of particular relevance to many AOS members working in the area of optical sensing technologies. This network was formed initially with the support of the Optical Society of America (OSA), but OSA has now joined forces with the American Geophysical Union (AGU) to promote the network, and during November I organised the founding workshop of the New Zealand node of the GEMM network. Whilst optical sensors are very important in environmental monitoring, this was very different from organising a meeting in the area of Photonics, since it involved so many different organisations concerned with monitoring the effects of climate change, but was all the more rewarding for that reason. We look forward to a continuing series of GEMM network meetings in New Zealand and potentially to the formation of a GEMM node in Australia, where the problems posed by climate change are very different from those in New Zealand.

I would like to close with an update on the survey of the Photonics industry in our region, which was released at the industry session of the ANZCOP meeting this month. Several people when first seeing the headline numbers find them surprising, but the proportion of Photonics enabled production in manufacturing are very similar to those of many countries at similar stages of economic development. The headline numbers need repeating however, as they will form a basis for new initiatives of our Society in the next decade. Photonics in the Australian and New Zealand economies generates value from over 500 companies, employing more than 12000 people, with an annual economic output of greater than 4 Billion AUD. The results expressed as a proportion of population are very similar between Australia and New Zealand.

Whilst the results of the survey were presented at ANZCOP as a series of slides in two talks, the next step is to convert those talks into a report which can be referenced and used in different ways, where the methodology is explained and validated. I am confident that the results are robust, and we will need to revisit the survey every two years to monitor the growth rate of the industry, which is clearly a key to the future prosperity of both countries.

John Harvey
AOS president

Editor's Intro



Welcome to another issue of AOS News. We have a great selection of articles for you this time including items from two of the winners of the 2018 AOS Awards. Rob Scholten, 2018 recipient of the John Love award for technical optics gives us an overview of the work in his group using laser-cooled atoms for nanoscale imaging and fabrication. Mohsen Rahmani, winner of the Geoff Opat early career researcher prize in 2018 provides details about tunable metasurfaces. There is also a look at topology in nonlinear photonics, and our 'Optics in Everyday Life' section explores tidal disruption. Please send in articles or conference reports if you can as we haven't had many new contributors and would love to hear from you. I would like to thank everyone who has provided articles throughout the year, especially Tony Klein for continually finding interesting topics for our optics in everyday life section.

The Conversation ran a series of articles about the future of education in the middle of the year, asking some interesting questions. Whilst this is not necessarily of direct relevance to everyone, many of our members are involved in the higher education sector and may need to be prepared for future changes and the impact this may have even for those not involved in teaching. One article considered the reason for education, which has been an age-old issue, but is increasingly relevant when you consider the large number of students who attend universities, leaving with considerable amounts of debt. Currently it is generally seen that education exists to provide knowledge about the world and the skills to work in it. Schools and universities are there to enable people to get a job, offering benefit to both individuals and society. There are opposing ideas on the purpose of education, with suggestions that learning is a goal in itself and that it helps people become fully developed. This means it can still be worthwhile studying areas of interest even if there is no obvious economic outcome.

Another article in the series looked at how universities can survive in the changing landscape. It contemplates the impact of massive open online courses (MOOCs) and their effect on learning. If amazing courses are offered online why would people continue to attend universities? The article investigates what needs to change and suggests that generic degrees with impersonal teaching need to transform into something different. It proposes that programs should offer the chance to do real work and that students should learn by doing, with the learning connecting theory and practice. Tests should be for learning purposes rather than assessment. The authors also think that universities should prepare students for an interconnected world, help them cross disciplines and prepare them for life and the many changes of careers that students are likely to encounter. They should also promote well-being and embrace personalised learning and smart tools as well as sharing expertise across the globe.

A recent report on the same theme, the future of higher education, by Ernst and Young suggested there are five issues that are affecting the sector. The first is the changing world of work, particularly with technology disruption affecting employment and employability. Having digital technologies integrated into courses is seen as something that is important to help with this. Blurring industry boundaries as new providers offer education is the second issue, meaning that it is important that universities have industry links. Evolving digital behaviour is another issue, with a need for digital learning and online courses that offer the possibility of interaction with both fellow students and teachers. The fourth item, increasing international competition can be addressed via forming collaborations around the globe. The final item is the rise of continuous learning, which means that people need content they can control that is affordable. The report recommends that universities should decide where to position themselves and work towards this. It points out that the products and services offered and how they are provided may well change, with the emergence of digital platforms seen as a necessity. Highlighted are the different types of university that may well emerge and the fact that these will also depend on government funding and decisions. The authors see commercial and disruptor universities as the most likely forms of universities of the future, which may well be very different from what we have today.

An article in Scientific American on the future of education with a focus on the STEM area pointed out that in recent times, many science courses have changed. They now provide an understanding of the area and the scientific method as these are vital for everyone, but know that only a small percentage of students will go on to work in that specific area. Young scientists often move between academia and industry, so providing a more integrated curriculum with a mix of critical thinking and science skills alongside those that are considered more professional or vocational will help prepare students for a dynamic future. The author suggests that challenge-driven education is needed with team-based learning as this reflects more of what happens in real-life.

There is much in common about the ideas from the different articles and reports. They all suggest that there are significant changes and challenges ahead, but that this can offer benefit to students and universities as long as suitable consideration and preparation are taken.

Jessica Kvansakul
Editor

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ANZCOP, ACOFT, ACOLS and AOS Conferences

by Simon Fleming

Our domestic conference is of great importance in bringing our community together. Since 2013 this has been under the ANZCOP name, as the conference for optics and photonics in Australia and New Zealand. It has, rather informally, incorporated ACOFT, ACOLS and the AOS Conference. The decision has now been made to formalise this successful and effective arrangement from 2021. The intention is to continue to run this as an annual domestic conference, and to continue the arrangement to collocate with the AIP Congress on even numbered years.

The proliferation of conferences exists largely for historical reasons and it has become clear over the last decade that it will serve our community better in the future to remove this complexity and confusion and hold just one conference.

We will just use the ANZCOP name in future, incorporating into this ACOFT, ACOLS and the AOS Conference. The ANZCOP name better covers the technical scope across all optics and photonics, and makes explicit the geographical scope across Australia and New Zealand.

Whilst there remain communities which identify with these historic "brands" we will seek to preserve their existence in the conference description and, of course, in the conference scope. This amalgamation will resolve the issue with the technical scopes of the constituent conferences overlapping and will provide more flexibility for including new fields of research. We will bring the various arrangements associated with the constituent events, such as the Wanda Henry Prize and the Frew Fellow, into the amalgamated event.

There will be one steering committee, led by the AOS Council, modelled on the ACOFT steering committee, with members including past, current and future ANZCOP chairs, industry and student members, and with representation offered to Engineers Australia and AIP. We will continue actively to seek to attract major international and regional events to Australia to collocate with ANZCOP.

Simon Fleming is the Past President of the Australian Optical Society and is with the School of Physics, University of Sydney.

Conferences

2-6 August 2020, CLEO-PR 2020

The 14th Pacific Rim Conference on Lasers and Electro-Optics (CLEO Pacific Rim, CLEO-PR 2020) will be held at the International Convention Centre, Sydney, Australia from 2 to 6 August 2020. The Conference will cover all major areas in lasers and optoelectronics along with tutorial sessions, invited sessions and workshops in areas of current interest. The organising committee invites you to join us in Sydney in 2020. We look forward to seeing you there. www.cleopr2020.org

6-10 December 2020, AIP Congress

The Australian Institute of Physics runs biennial Congresses to bring the Australian Physics community together. A new host is chosen each time, and the program committee draws heavily on input from the topical groups. AOS expects to participate again in the AIP Congress in 2020.

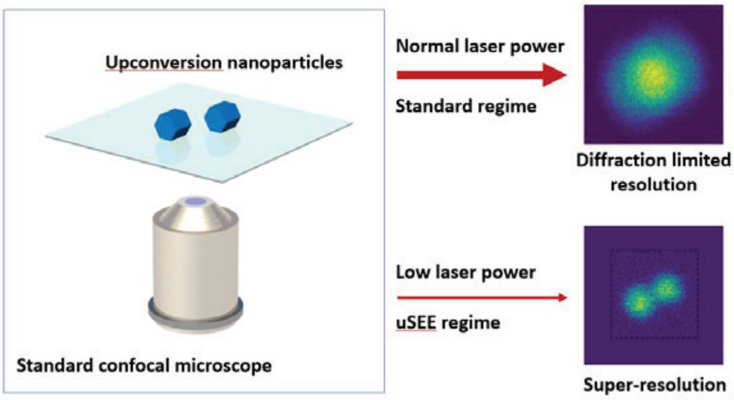
The 2020 Congress will be held in Adelaide from 6-10th December 2020.
https://aip.org.au/congress/

AUSTRALIAN OPTICAL SOCIETY

Australasian Research in the News

3D super-resolution helping scientists take a closer look

Nanoscale microscopy, a tool relied on by scientists tackling tough health challenges, will be more accessible and affordable, thanks to a team of Australian researchers. A team from the ARC Centre of Excellence for Nanoscale BioPhotonics (CNBP) report in Nature Communications a simple way to bypass diffraction limitations using standard optical imaging tools. The University of Queensland's Dr Martin Ploschner, one of the lead authors, said super-resolution microscopy allowed users to observe breathtaking details of nanoscale structures, but for many labs, it was a costly addition to their usual microscopes. "Standard optical microscopes can image cells and bacteria but not their nanoscale features which are blurred by diffraction," Dr Ploschner said. "Optical microscopes have evolved over the last two decades in order to bypass this diffraction limit; however, these so-called super-resolution techniques typically require expensive and elaborate instrumentation or imaging procedures."



Super-resolution imaging is possible using a standard microscope and super-linear fluorescent markers, upconversion nanoparticles. Image credit: University of Queensland.

Dr Ploschner and his team discovered a way to bypass the usual complexities and costs of super-resolution nanoscale microscopy by using a 'super-linear' fluorescent marker. Normally, the brightness of light emitted by fluorescent markers is proportional to the absorbed light, but the brightness grows at a much faster rate for 'super-linear' markers. As a result, when a laser beam scans a super-linear marker, it is only the brightest, central part of the beam that causes significant glow from the fluorescent marker. This results in sharper resolution, as the size of the emitting region is smaller than the beam itself.

"Our key discovery is that if this effect is exploited under the right imaging conditions, any standard scanning optical microscope can spontaneously image with super-resolution, at practically no extra cost," Dr Ploschner said. "Interestingly, our technique offers better resolution at relatively low laser power. This, coupled with the use of near-infrared laser, makes the technique appealing for imaging of biological samples," he said.

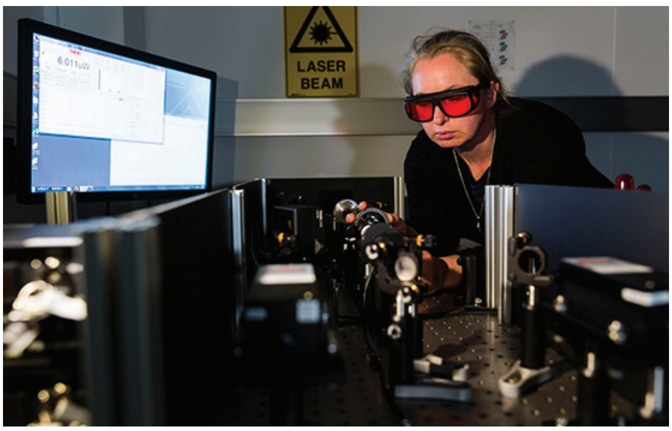
The team believes the approach has the potential to open new avenues in the research of super-liner emitters, combining them with other imaging processes to improve their performance. CNBP node leader at Macquarie University, Professor James Piper AM, who is also an author on the paper, says the concept has been around for a while, but its practical realisation was elusive due to the need to combine the distinct research fields of biology, material science, optical engineering and physics. "CNBP offered an ideal meeting platform for scientists with diverse expertise to join forces and take the idea from the drawing board to a practical imaging tool," Professor Piper says. CNBP scientists affiliated with Macquarie University, RMIT University, and Griffith University worked on the project.

Source material: https://www.uq.edu.au/news/article/2019/09/3d-super-resolution-helping-scientists-take-closer-look
https://www.sciencedaily.com/releases/2019/08/190816075545.htm

Original article: Denitza Denkova, Martin Ploschner, Minakshi Das, Lindsay M Parker, Xianlin Zheng, Yiqing Lu, Antony Orth, Nicolle H Packer, James A Piper. *3D sub-diffraction imaging in a conventional confocal configuration by exploiting super-linear emitters*. Nature Communications **10**, 3695 (2019). https://doi.org/10.1038/s41467-019-11603-0.

Saving lives faster: Monash develops world-first laser incubator for blood

Researchers from BioPRIA, based at Australia's Monash University, together with industry partner Haemokinesis, have developed the world's first blood incubator using laser technology. This could prevent fatal blood transfusions in critically ill patients, and can detect antibodies in pregnant women that can kill a foetus. According to results published in Nature's Scientific Reports, these findings could bring pre-transfusion testing out of the pathology lab to point-of-care, with blood incubation time slashed to just 40 seconds, compared with the industry gold standard of five minutes.



Dr Clare Manderson and research colleagues from BioPRIA, based at Monash University, have developed the world's first blood incubator using laser technology. Image credit: Monash University.

This breakthrough has the potential to improve the pre-transfusion testing of millions of patients undergoing blood transfusions across the world, especially those having major surgery, going into labour, or causalities of mass and individual trauma. The detection of immunoglobulin G (IgG) antibodies requires incubation at 37°C, often for up to 15 minutes. But current incubation technology relies on slow thermal procedures, such as heating blocks and hot-water baths. This delay adds to pathology costs and turnaround time, which substantially affects a patient's chance of survival.

To address this problem, BioPRIA's blood diagnostics team developed a laser incubation model where a targeted illumination of a blood-antibody sample in a diagnostic gel card is converted into heat, via photothermal absorption. The laser-incubator heats the 75 μL blood-antibody sample to 37°C in under 30 seconds. Most importantly, no significant damage is detected to the cells or antibodies for laser incubations of up to 15 minutes.

The study was led by Dr Clare Manderson from the Bioresource Processing Institute of Australia (BioPRIA), Monash University, in conjunction with blood diagnostics manufacturer Haemokinesis. "Laser incubation can be extremely valuable when time and accuracy is vital, especially in critical and emergency settings - like mass trauma - where pre-transfusion testing needs to be performed quickly in order to save lives," Dr Manderson said. "We show that red blood cells act as photothermal agents under near-infrared laser incubation, triggering rapid antigen-antibody binding with no significant damage to the cells or antibodies for up to 15 minutes. This study demonstrates laser-incubated immunohaematological testing to be both faster and more sensitive than current best practice, with clearly positive results seen from incubations of just 40 seconds."

Researchers explored the roles of incubation time and temperature of the IgG anti-D antibody and the Rh blood group system's D antigen, which indicates the positive or negative attributed to a person's ABO blood type group. Anti-D is the most common antibody, and is present in a person's plasma. Blood group type is based on the presence of antigens on the surface of the red blood cell membranes, forming roughly 346 known blood groups. "Giving blood transfusions to people isn't as simple as giving O-negative to anybody. The 'universal donor' of O-negative blood can seriously harm a lot of people, even kill them. The world of pre-transfusion of blood group typing is huge, and it's really important that it's done quickly and accurately to help save lives," Dr Manderson said. "For the patient, it can mean that if there's a critical blood-loss scenario and they're in desperate need of a transfusion, they need to have their blood group typed and antibody screened as quickly as possible. We're aiming to bring that down to seconds instead of tens of minutes."

Blood transfusion is a critical treatment for a variety of conditions, and transfusion reactions are common if the recipient and donor aren't correctly matched. More than 1.2 million blood components are transfused each year in Australia, and 21 million in the US. While the technology isn't yet commercially available, Haemokinesis holds a patent for this innovation.

Source material: https://www.monash.edu/news/articles/saving-lives-faster-monash-develops-world-first-laser-incubator-for-blood

Original article: Clare Manderson, Heather McLiesh, Rodrigo Curvello, Gil Garnier, Rico Tabor, and Jim Manolios. *Photothermal incubation of red blood cells by laser for rapid pre-transfusion blood group typing*. Sci Rep **9**, 11221 (2019). https://doi.org/10.1038/s41598-019-47646-y

AOS Image Competition

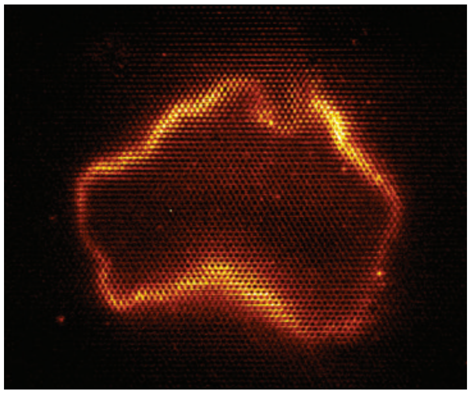
Help us demonstrate the beauty of optics and photonics

Please submit photographs or images that capture some aspects of optics and photonics, and are aesthetically pleasing. They can, for instance, be of your research, of optical phenomena, of optical devices.

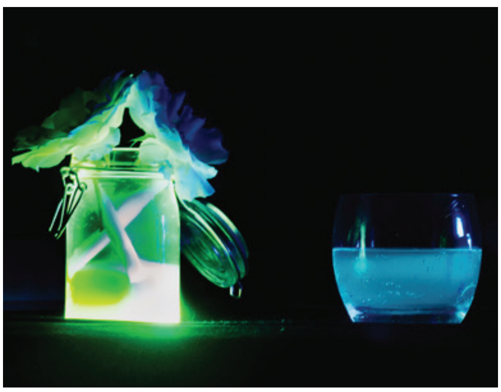
We want your assistance in generating photographs that we can use to promote Australian and New Zealand optics and photonics in print and online. We will publish the best photograph on the front cover of AOS News, and whoever submits this will get a year's membership free.

The photos will be judged by a panel including three AOS Councillors, the Editor of the AOS News and the AOS Webmaster. The competition will continue on an approximately quarterly basis with judging for each issue of AOS News. AOS will carry forward high scoring entries from one round to the next. The AOS reserves the right in any particular round to award multiple winners or to award no winner. A person may only win once in each calendar year. The competition will run until end of 2022. AOS may extend this date or terminate earlier, advising by email, through AOS News, or other reasonable communication.

Queries to ausoptsoc@gmail.com



Our past winners are pictured here. Right: Topological Australia, by Sergey Kruk, Australian National University. Lower right: Sunrise above Rangitoto Island, New Zealand, by Krzysztof Maliszewski. Lower middle: Phosphorescence, by Krzysztof Maliszewski. Lower left: Ice bow, by Stephane Coen, University of Auckland.



Hyperspectral Imaging

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Nanoscale Imaging and Fabrication Using Laser-Cooled Atoms

by Robert Scholten

Theodor Maiman famously said, "A laser is a solution looking for a problem", and the same is even more true for laser cooling of atoms. First proposed in 1975 by Hänsch and Schawlow and simultaneously by Wineland and Dehmelt, laser cooling of neutral atoms was demonstrated experimentally by Bill Phillips and Hal Metcalf in 1982. Cold atom research has exploded, enabling new tests of fundamental physics, the most precise clocks, advances in magnetometers, gravimeters, and quantum computing, and underpinned physics Nobel prizes in 1997 and 2001. After more than forty years, we still cannot buy products using laser-cooled atoms – but that may be about to change, with the advent of cold-atom electron and ion sources for microscopy and nanofabrication.

Introduction

Nanoscale imaging and fabrication underpin advances in materials science, semiconductor devices, magnetic storage, solid-state quantum computers, biomolecular structure determination, and unravelling biological function at the molecular level. Both electron-based and ion-based microscopy and nanofabrication are of critical importance, and many microscopy and nanotech labs feature many tools using both electrons and ions. However it is clear that the quest to improve the spatial and temporal resolution of electron and ion systems is encountering fundamental limitations in the electron or ion sources.

How can laser cooling of atoms play a role? A key parameter of an electron or ion source is the transverse coherence length, or equivalently, the transverse momentum spread. In the same way that the light from an incandescent bulb cannot be focused to a small spot, the imaging resolution that can be achieved with an electron or ion source is constrained by the initial spread of transverse momenta. If the particles are emitted in many random directions, optics cannot correct those trajectories into a tight focus.

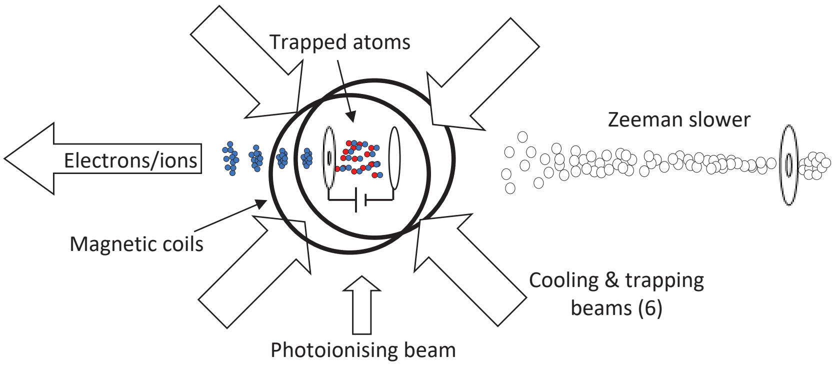

Figure 1: High coherence electron/ion source. Atoms are laser-cooled and trapped, and then photoionised to produce very cold electron or ion bunches.

A cold atom source can produce electrons and ions with extraordinarily low temperature and thus momentum spread: below one millikelvin in the case of ions, and a few kelvin for electrons, many orders of magnitude below the effective temperature of conventional sources such as electron field emission tips or liquid metal ion sources.

The key components of a cold atom electron/ion source are shown in figure 1. Atoms evaporated from an effusive oven are slowed by counterpropagating laser beams in a magnetic field gradient (a Zeeman slower), and further cooled and trapped by six counterpropagating lasers in a magnetic quadrupole (a magneto-

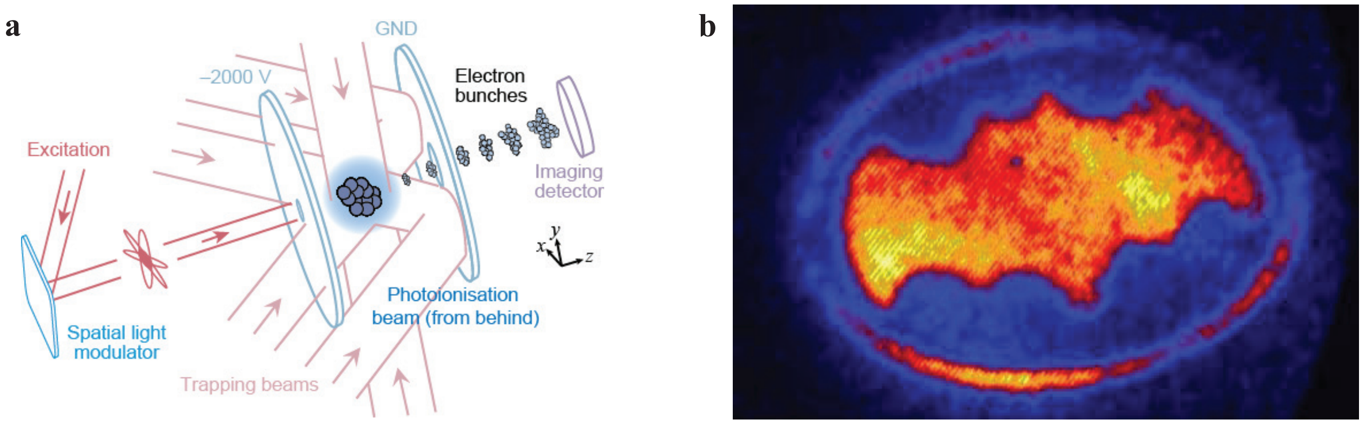

Figure 2: Arbitrarily shaped electron bunches from a cold atomic gas a) Selectively photoionising and accelerating the electrons from a laser-cooled rubidium cloud produces an electron bunch with a well-controlled distribution. b) False colour image of the electrons after propagating 24cm. The extremely low temperature of the resulting electrons and the absence of space-charge effects enable it to retain its shape as it travels away from the gas. From Nature Physics **7** 785 (2011).

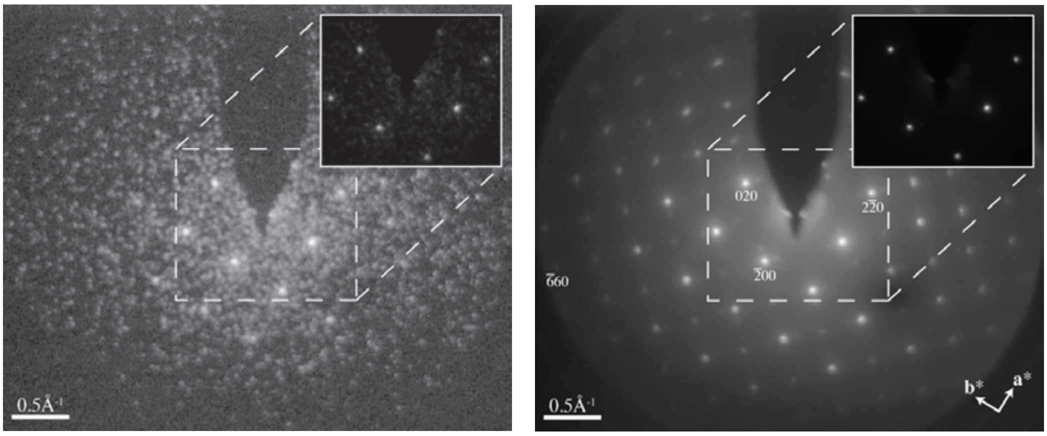

Figure 3: Single-shot (left) and 2000-shot average (right) transmission electron diffraction from gold, using cold atom electron source; logarithmic scaling (insets: linear scaling). From J. Phys. B: At. Mol. Opt. Phys. **48** 214002 (2015).

optic trap, MOT). The cold atoms are then photoionised. Because the atoms are so cold, the Doppler effect is negligible, and the photoionisation laser wavelengths can be tuned precisely to the ionisation threshold, releasing the electron-ion pairs with very little excess energy. Ions or electrons can then be extracted with conventional charged-particle optics.

Low temperature and thus low transverse momentum uncertainty translate into high transverse coherence length. The transverse coherence length defines the maximum size of an object that can be reconstructed using coherent diffractive imaging. For example, working with the ultramicroscopy team at the Monash Centre for Electron Microscopy, we were able to configure a $10M 300 keV aberration-corrected electron microscope to achieve a high transverse coherence length L_c=0.15 nm, large enough to enable coherent diffractive imaging of boron nitride structures with atomic resolution[1]. With a cold atom electron source we have measured transverse coherence length of 8 nm[2]: 50 times higher, large enough for diffractive imaging of large biomolecules or even a small virus.

Cold electrons

Cold atom sources offer a unique ability to create charged particle bunches with arbitrary shapes in three dimensions, using spatial structure in the photoionising laser beams. We have demonstrated patterning in two and three dimensions, for example to create a bunch in the shape shown in figure 2(b). The shape can be changed in a few milliseconds, and the spatial light modulator and imaging optics give an optical resolution at the source of about 10μm. Using the bunch-shaping capability, we have been able to demonstrate reversal of electron-electron repulsion to reverse the so-called Coulomb explosion[3].

The low momentum spread of the electrons and precise spatial control allow detailed investigation of the photonionisation process; for example, the electron trajectories and temporal bunch shape can be dramatically altered by variation of the precise wavelengths of the two lasers, by the external electrostatic field and Stark shift, and by tunnelling[4]. The ultimate goal of our electron work was to achieve atomic resolution, ultrafast, single-shot coherent diffractive imaging. Figure 3 shows single-shot transmission electron diffraction from gold, and the average of 2000 such images. The result allows Bragg spots to be identified out to the $(\bar{6}60)$ reflection, with an effective resolution of 2.08 Å, limited by the size of the detector.

In little more than a decade, cold electron sources have progressed from concept to single-shot diffractive imaging of crystalline structures. The future may include coherent diffractive imaging of complex structures such as biomolecules, and seeding of x-ray free-electron lasers and synchrotrons. A full review of these new sources can be found in reference[5].

Cold ions

Even at temperatures of a few Kelvin, electrons move very quickly: in the experiments of figure 1, the electron bunch was expanding at speeds of 17,000 m/s. But the associated ions are both much colder and much more massive. Their thermal speeds are then just cm/s, such that the charge interactions can occur over much longer time scales as a bunch drifts from source to detector. Cold ion bunches created with ionisation pulse durations of a few nanoseconds demonstrate space–charge effects equivalent to those in picosecond electron bunches. For example, we observed[6] the formation of startling patterns for closely-spaced ion bunches (figure 4).

Ions play an important role in nanofabrication and imaging, and cold atom ion sources are likely to be the first major commercial application of laser cooling of atoms. Focused ion beams (FIBs) are a key enabler in many areas of nanotechnology, able to both image and fabricate with resolution of a few nanometres (see figure 5). FIBs are used to create ultrathin sections of biological samples for transmission electron microscopy, to machine prototype semiconductor devices, and to dissect next-generation integrated circuits to diagnose faults. But the resolution of conventional ion beam technology is limiting progress in these areas. Most FIBs use a gallium liquid metal ion source (LMIS) for fabrication of structures of 10 to 15nm in size. With computer chips now

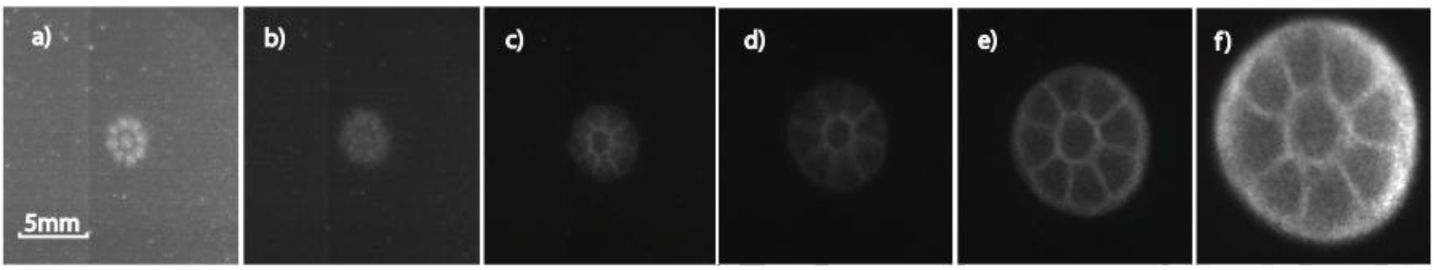

Figure 4: Expansion of nine closely spaced cold ion bunches. Measured distribution of charge after free expansion for 8 μs, with increasing initial charge from just a few ions for 20 fC total. From Nature Comms **5** 4489 (2014).

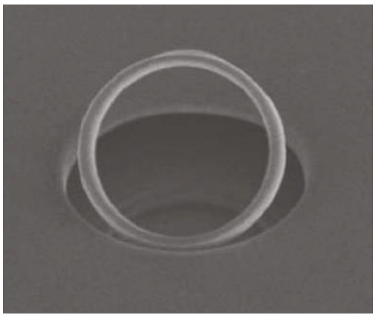

Figure 5: Diamond ring 5µm x 300nm, machined with a focused ion beam. From SD Prawer, U. Melbourne.

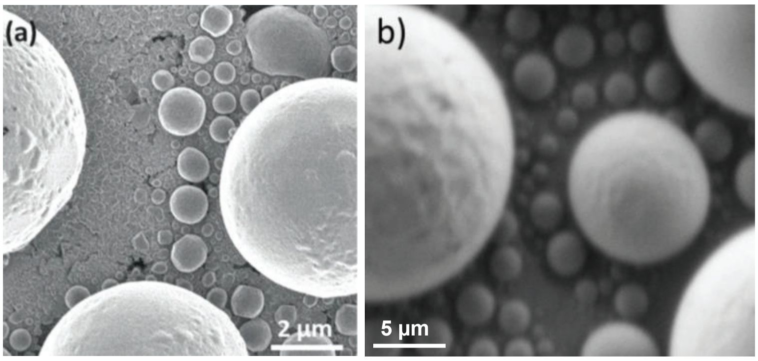

Figure 6: Images of tin balls acquired with a) prototype commercial caesium cold atom ion beam microscope and b) standard gallium liquid metal ion microscope. Note change of scale.

relying on features at 7nm, and 5nm on the horizon, there is huge demand from major semiconductor manufacturers such as IBM and Intel calling for new FIBs with an order of magnitude improvement in resolution, to characterise and repair current and next generation integrated circuits. At even smaller scales, there is demand for the ability to create and implant single atoms and ions with atomic scale resolution for realisation of quantum-based devices.

In 2005, a detailed concept for a cold atom ion source was introduced[7], with a number of advantages identified. Firstly, any element that can be laser cooled (currently 27 atomic species) can produce a bright beam of ions. Second, the very low emittance (low temperature and high transverse coherence) allows for tightly focused spots at high current. Even in the early development stage, the cold atom ion source has already demonstrated ion beams with over 20 times the brightness and 5 times smaller spot size (2.1nm) relative to a liquid metal ion source (figure 6)[8]. Using cold atoms, it is also possible to extract single ions on demand, and when combined with the nanometre resolution of modern ion beam columns, the cold ion source will enable true atomic scale ion implantation and imaging.

At the University of Melbourne, we have been involved in studying the physics of cold atom electron and ion sources. Although the advantages of cold FIBs are already clear, we are investigating several physical processes for further improvements, including using electron-ion correlations to counteract aberrations and enhance resolution, and using Rydberg blockade to create a high-current deterministic source of single ions at atomic resolution.

Electron-ion correlations

Photoionisation of a cold atom produces an electron-ion pair that are highly correlated in their momenta. If the momentum of one is measured, we can infer something of the momentum of the other. For example, in an ion microscope, we can in principle detect the unwanted electrons and measure their transverse momenta and use that information to correct the trajectories of the correlated ions (figure 7).

The idea is similar to ghost imaging which typically uses entanglement between two photons produced by parametric down-conversion. We have demonstrated electron-ion correlations and gating in proof-of-principle experiments[9].

We are working towards implementing correlated feedback at the nanoscale and combine with exceptional-state ionisation to reduce chromatic aberration and achieve nanometre resolution.

Single-ion source

The ability to precisely implant a single ion on demand has great potential for doping in ever-shrinking semiconductor devices, for proposed solid-state quantum computing qubits, and for single photon sources for quantum communication and sensing. In the cold atom ion source, the electron-ion pairs are generated stochastically, and although the electrons can be used to herald the ions[9], there are limits on the speed: the ions must be temporally and hence spatially separated. We have developed two approaches for separating the ions: first, using Coulomb repulsion between closely spaced ions as they pass through a small aperture. Closely-spaced ions deflect each other and reduce transmission; only single ions will propagate through[9].

Another approach is based on Rydberg blockade[10]. Atoms in Rydberg states are highly susceptible to long-range dipole interactions. If we attempt to excite two closely-spaced atoms to the same Rydberg state, the dipole of one shifts the Rydberg energy of the other, inhibiting excitation at the same laser frequency. Widely separated Rydberg atoms will then be ionised as they propagate through an external electric field, and detection of the liberated electron used to gate the field before the next Rydberg atom arrives[11,12]. The combination of single ion generation, electron momentum detection and real-time feedback aberration correction will create a powerful tool for single ion implantation at nanometre resolution. Although rubidium ion implantation is not expected to have direct applications, the concept can then be translated to other ions such as nitrogen, aluminium or even

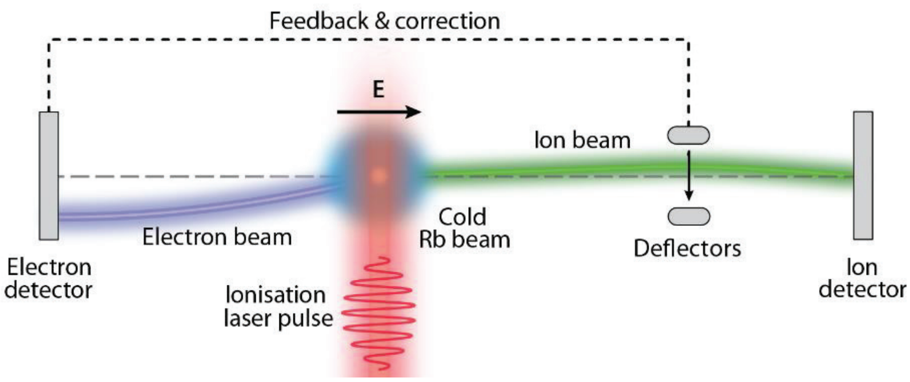

Figure 7: A schematic of the correlated electron-ion ghost imaging concept. The electron is detected and used to infer the momentum of the ion, and deflectors used to compensate the ion trajectory.

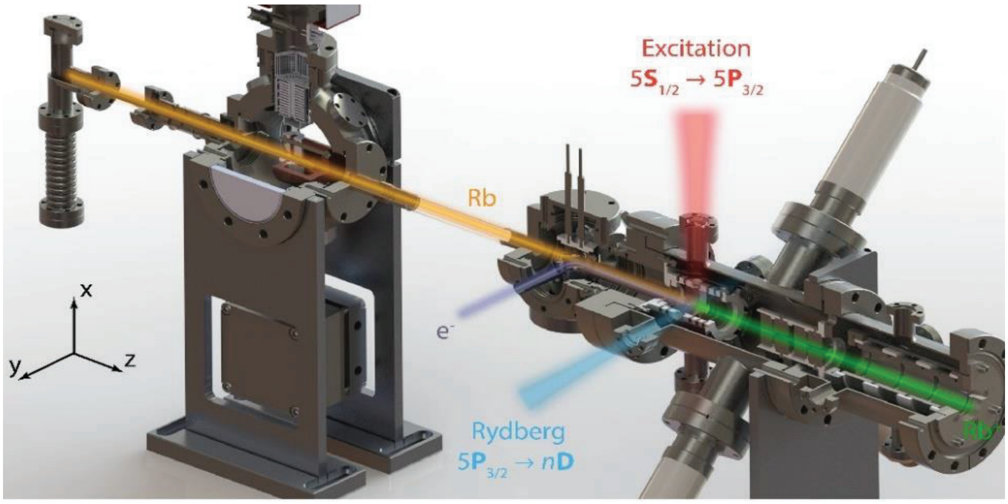

Figure 8: Continuous cold ion source with electrostatic optics for coupling to a commercial FIB column, with coincident electron-ion detection capability. Atom beam (top left to centre, orange) is collimated at the first vacuum chamber, then transversely cooled and focused in a magneto-optic compressor (not shown). Atoms are excited and ionised at the intersection of red and blue laser beams. Electrons (purple) and ions (green) are ejected in opposite directions; as shown, ions propagate to the right where they enter a commercial microscope column from Tescan Orsay (not shown). From AJ McCulloch, U. Melbourne.

phosphorus (via radioactive decay of ^{15}Si).

Realisation

To demonstrate these ideas on a practical focused ion beam imaging and nanofab system, we are combining a novel cold atom electron/ion source with a commercial FIB column. We are using a continuous atomic beam rather than a three-dimensional magneto-optic trap (see figure 8). For imaging and nanofabrication, only the transverse temperature of the atoms is important, and hence to reduce complexity and increase flux and effective brightness the new system uses transverse laser cooling and focusing of the atom beam in a continuous magneto-optic compressor (MOC). The high-density beam will propagate into a system of electrostatic optics where the atoms are excited to a specific Rydberg level via a two-step process with 780nm and 480nm laser beams. From the Rydberg state, the atoms self-ionise due to Stark lowering of the Coulomb binding barrier in an external electric field. The source shown in figure 8 is now being connected to a Tescan Orsay FIB40 focused ion beam column, following the approach demonstrated by Tescan Orsay themselves with caesium[13], the group at NIST with lithium[14] and most recently by Eindhoven with rubidium[15]. We expect to have a working cold-ion microscope mid-2020.

Technology transfer

Technical innovation is a critical underpinning of our research, particularly in relation to lasers. Remaining competitive has relied on creative ideas and insights in the physics (for which I thank the many outstanding collaborators identified below), but also development of enabling technology. Necessity drives invention, and in that sense Australia's limited research funding can be seen in a positive light, leading to many peer-review journal articles on technology and instrumentation[16-27] and the establishment of MOG Laboratories Pty Ltd in 2007. MOGLabs began with the electronics for powering and controlling tunable narrow-linewidth lasers for cooling, trapping, and imaging atoms. MOGLabs now employs 17 staff involved in research, development and manufacture of lasers and related instruments, predominantly for export to scientific and industrial customers around the globe.

Acknowledgements

The work presented here predominantly reflects the ideas, inspiration, insight and plain hard work of many collaborators. Particular thanks to Keith Nugent (ANU) for extensive collaboration and support over 25 years; postdocs Andrew McCulloch, Benjamin Sparkes, David Sheludko and Corey Putkunz; and to many students including Dene Murphy, Sebastian Saliba, Simon Bell, and Rory Speirs.

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Professor Robert Scholten is with the School of Physics, University of Melbourne. He was the 2018 recipient of the AOS John Love Award for innovations and technical advances in optics.

News

Congratulations to the 2019 AOS Award winners

WH (Beattie) Steel Medal: Professor Chennupati Jagadish, Australian National University
This Medal is the most prestigious award of the Australian Optical Society. It would normally be presented only to a nominee at an advanced stage of their professional career and with a strong and sustained record of authority, enterprise and innovation in the field of optics in Australia or New Zealand.

Geoff Opat Early Career Researcher Prize: Dr Jiawen Li, University of Adelaide and Dr Ke Wang, RMIT University
This Prize recognises an outstanding early career researcher for their contribution to the field of optics. The prize is $1500, awarded annually, and includes an invitation to give an extended presentation at the annual AOS conference. The winner of this prize will also write an article for AOS News.

Postgraduate Student Prize: Gayathri Bharathan, Macquarie University and Kai Wang, Australian National University
The Australian Optical Society wishes to encourage participation in national and international conferences by high-quality postgraduate students, and thus the Society has instituted the Australian Optical Society Postgraduate Student Prize, which is a grant for conference travel valued up to $1500. Up to one award will be made in each year.

John Love Award: Dr Sergio Leon-Saval, University of Sydney
This award recognises innovations and technical advances in the field of Optics. In particular, the award seeks to recognise strong efforts in translational optical research towards industrial applications and commercialisation by an individual or small team. The winner will receive a prize consisting of $300 cash, one year's free membership of AOS, and an invitation to attend the AOS conference and make an oral presentation of their work.

Warsash Science Communication Prize in Optics: Kai Wang, Australian National University
This Prize is open to AOS student members whose Honours, Masters or PhD research work has been accepted for publication in a refereed journal in the past year. A submission consists of a 300-word summary of the published research, written in the style of a New Scientist article or similar, explaining the significance of the applicant's research project to a casual reader outside the field. The $500 Prize is sponsored by Warsash Scientific Pty Ltd.

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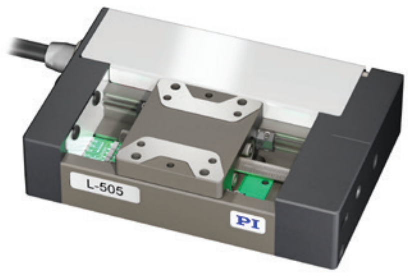
Product News

L-505 compact linear stage

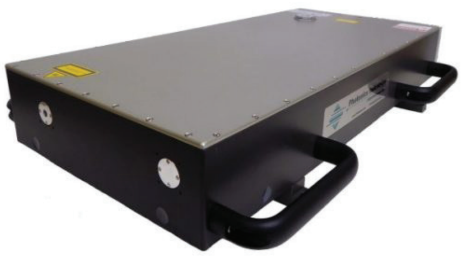
Physik Instrumente, a global leader in the design and manufacture of high precision motion control systems has launched the L-505 compact linear stage.

The L-505 linear stage family with four-row ball guides designed for comparatively high load ratings, exceptional stiffness and smooth running is ideally suited for industrial and scientific applications. With options for flange-mounted or folded drivetrains the L-505 is a compact linear stage platform that can easily be combined for X, Y and Z axis applications. Key features include:

- 13 or 26mm travel range
- Stepper or DC motor with and without gearhead
- Incremental linear encoder with a resolution of 5nm (stepper) or 50nm (DC)
- Backlash-compensated preloaded leadscrew



Ultra-efficient ns and ps solid stage lasers



Photonics Industries' (PI), the pioneer of intracavity solid-state harmonic lasers, has introduced its new DX Series, the highest wall plug efficiency nanosecond (ns) laser:

- ~17% for green
- ~10% for UV

and the most compact, most efficient air-cooled laser with the highest wall plug efficiency:

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- ~6% for UV

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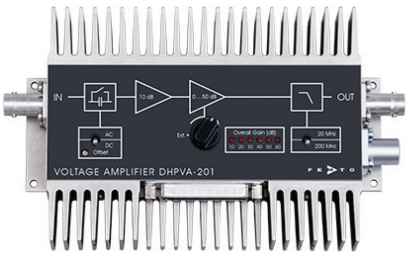

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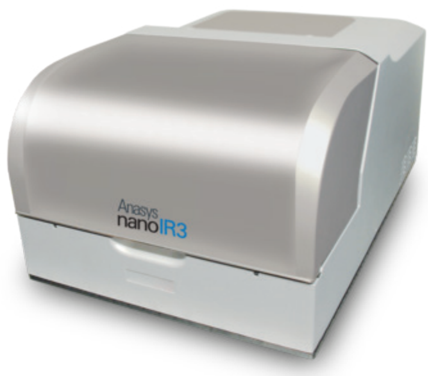

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Tunable Metasurfaces: Building Blocks of Modern Optics

by Mohsen Rahmani, Khosro Zangeneh Kamali, Lei Xu, Dragomir Neshev and Andrey E Miroshnichenko

Dielectric metasurfaces, i.e. arrays of subwavelength dielectric nanoparticles with negligible losses, have recently emerged as a successful concept for efficient wavefront shaping. They have been established as a platform for realising miniaturised optical meta-devices, such as holograms, flat lenses and deflectors. The applications of dielectric metasurfaces can be greatly expanded if one can tune the metasurface optical response in a controlled, reversible and reproducible fashion. Adaptable optical components are of high interest in many optical systems, ranging from camera lenses and beam scanners to flat displays and projectors. Here we discuss thermo-optical tuning, as a robust mechanism of tuning for dielectric metasurfaces. Subsequently, we demonstrate control of the contrast of metasurface images as a practical application for this tuning technique and provide an outlook on upcoming research directions.

Nanophotonics is the science of light emission, detection, modulation, control and/or amplification at the nanoscale. The building blocks of nanophotonics are thin and flat arrays of subwavelength nanoparticles, so called-metasurfaces, enabling control over the polarisation, phase, amplitude, and dispersion of light. Metasurfaces are a subject undergoing intense study, as their optical properties can be adapted to a diverse set of applications across the electromagnetic spectrum, including super-lenses, tunable images and holograms[1]. One unique possibility that metasurfaces can offer is the dynamic control of light-matter interaction. This is one of the prominent advantages of using metasurfaces over bulk optical components[1].

Tuning capabilities have been introduced via various techniques, such as phase-change media[2], the use of liquid crystals[3], doping[4], stretchable substrates[5], and mechanical tuning[6]. However each of these methods suffer from the following disadvantages: Changing the phase state of nanostructured materials by laser illumination is mostly limited to two states: amorphous and crystalline, i.e. achieving intermediate states is challenging [2]. Covering the metasurface with liquid crystal revokes access to the surface[3] of nanostructures that forbids some applications, such as sensing. Doping is not reversible[4], and altering the spacing between nanoparticles on a stretchable substrate by a physical force requires manipulating the physical conditions of the system[5]. Therefore, finding a tuning technique that is reversible, can cover the intermediate regions and does not require permanent alterations to the system or the environment is a subject of substantial research.

Our groups at The Australian National University and The University of New South Wales - Canberra have recently demonstrated a novel tuning technique that overcomes all the aforementioned disadvantages. This tuning technique exploits thermo-optical effects of materials, which can be used to alter the refractive index and subsequently optical responses of metasurfaces[7-9]. Silicon is an ideal material for thermo-optical tuning because of its high refractive index[10] and pronounced thermo-optical properties[11]. Thermal tuning fulfils all the requirements for proper tuning: it is reversible and covers intermediate regions. Moreover, this technique does not require external stimulators, such as altering the polarisation direction, angle of the illumination or refractive index of the environment.

Macro to Nano Scale: Bulk silicon has previously been used to realise modulation in optical modulators[11]. The thermal modulation time constant is typically on the order of 10 μs to 1 ms[11]. As the first step, we proved the extensibility of the thermo-optical characteristics of bulk silicon to silicon nanostructures and metasurfaces[7]. Figure 1(a) shows the experimentally measured reflection spectra of a 525 nm thick crystalline silicon slab on a sapphire substrate versus sample temperature. By using a Cryogenic chamber for measurements at

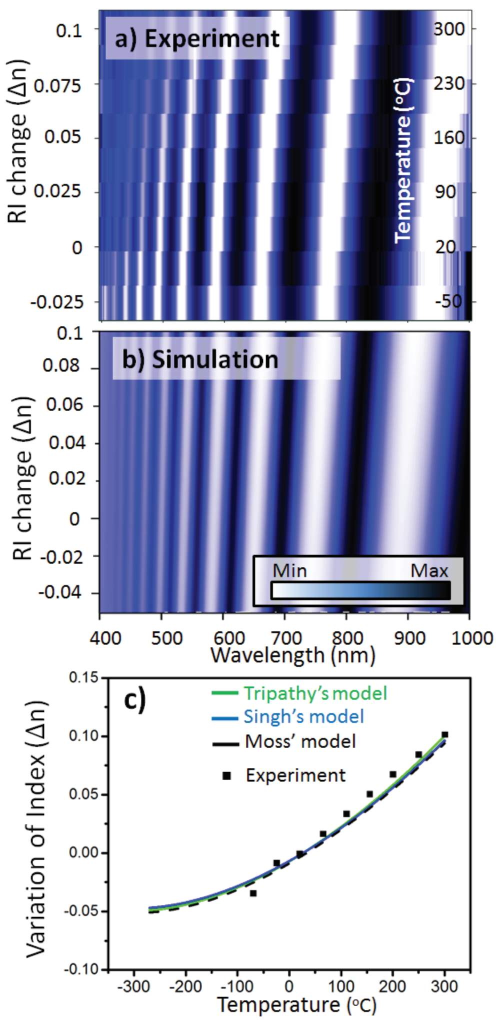

Figure 1. a) Experimentally measured and b) simulated reflection spectra from a crystalline silicon slab of thickness 525 nm on a sapphire substrate versus the sample temperature and refractive index (RI) variations. c) Temperature dependence of the variation of index, calculated via Tripathy's, Singh's, and Moss' models, compared to our experimental results [7].

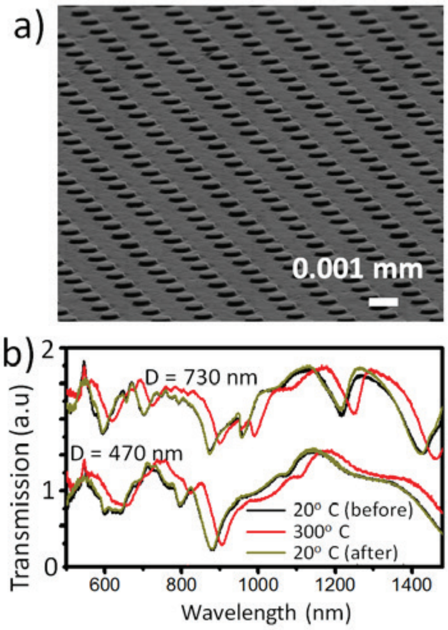

Figure 2. a) SEM image of the metasurfaces containing nanodisks with 470 nm diameter and 1 μm separation. b) Experimentally measured transmission spectra of metasurfaces composed of nanodisks with diameters of 470 and 770 nm[7].

low temperatures and a modified home-made setup for measurements at high temperature, the optical properties of the sample were measured from -70°C to 300°C. As can be seen in this figure, the exhibited Fabry-Perot resonances get redshifted linearly as temperature changes, demonstrating that a temperature increase leads to raising the refractive index of the slab. In this case, thermal phonons govern the thermal properties, influencing thermal and optical properties simultaneously. This induces thermal phonon-photon interactions. Figure 1b gives the corresponding theoretical results, which agree well with the experimental results. Importantly, these experimental results show very good agreement with theoretical models available in the literature at the macroscale, including Tripathy, Singh, and Moss models (see figure 1c)[7].

Subsequently, we successfully extended this concept to metasurfaces. In metasurfaces, changing the refractive index of the nanoresonators alters the resonance wavelength of the metasurface directly. To investige the effect of temperature on the optical output of a metasurface we designed, fabricated and measured a set of various metasurfaces at different temperatures. A scanning electron microscopy (SEM) image in figure 2a shows the arrangement of the metasurfaces consisting of nanodisks with 470 nm diameter. Figure 2b shows the transmission spectra for two silicon metasurfaces with nanodisks of diameters 470 and 730 nm, both on a sapphire substrate. As can be seen, when the temperature of the metasurfaces increases from 22˚C to 300˚C all resonance wavelengths experience about 30 nm redshift. It is indeed in line with the behaviour of bulk silicon- a nearly linear variation for the refractive index vs temperature. Importantly, after measuring the spectra at high temperatures, all resonances go reversibly back through a 30 nm blueshift. Solid black curves in figure 2b show the transmission before heating the sample and green curves represent the spectra after cooling the sample down.

Real-World Applications: After proving the thermo-optical tuning concept at the nanoscale, we employed this phenomenon for reversible image contrast manipulation[9]. For simplicity and a full demonstration of the concept, a Yin-Yang image was chosen, as it contains a binary region: bright and dark (see the inset of figure 3a). By controlling the spatial distribution of light passing through the metasurface we managed to control the contrast of different parts of a Yin-Yang image[9]. Two Types of silicon nonconcentric disk and hole nanostructures[12, 13], with slightly different geometries, were designed and fabricated as the building blocks of the Yin-Yang pattern (figure 3a). These building blocks exhibit sharp Fano resonances at the wavelengths of 772 nm and 784 nm, respectively (figure 3b). The nature of these resonances can be explained by symmetry-protected bound-state-in-the-continuum (BIC))[14, 15], i.e., a bound state of one symmetry class is embedded in the continous spectrum of another symmetry class. Due to high-quality factor resonances, one can introduce significant changes to the contrast with minimal alteration in the resonance wavelengths.

Through the exploitation of the thermo-optical properties of silicon, full control of the contrast was demonstrated by altering the metasurface temperature by ΔT ≈ 100˚C. Transmission spectra were recorded experimentally at a number of points, when heating or cooling the metasurface, and are shown in figure 3c. The reversible nature was observed for all measured points during the experiment. Images of the Yin-Yang pattern at a wavelength of 784 nm, at 22˚C and 125˚C can be seen in figure 3d. As expected, by changing the temperature, dynamic reversible image contrast manipulation can be observed, sweeping itself from one state to another. The left image is recorded at 22˚C, where building block Type A is opaque, while building block Type B transmits light, therefore the contrast is very clear. The right image shows the case where one can see the opposite contrast when building block Type A is transparent and the building block Type B is opaque. This is the first demonstrated technique to control image contrast via temperature.

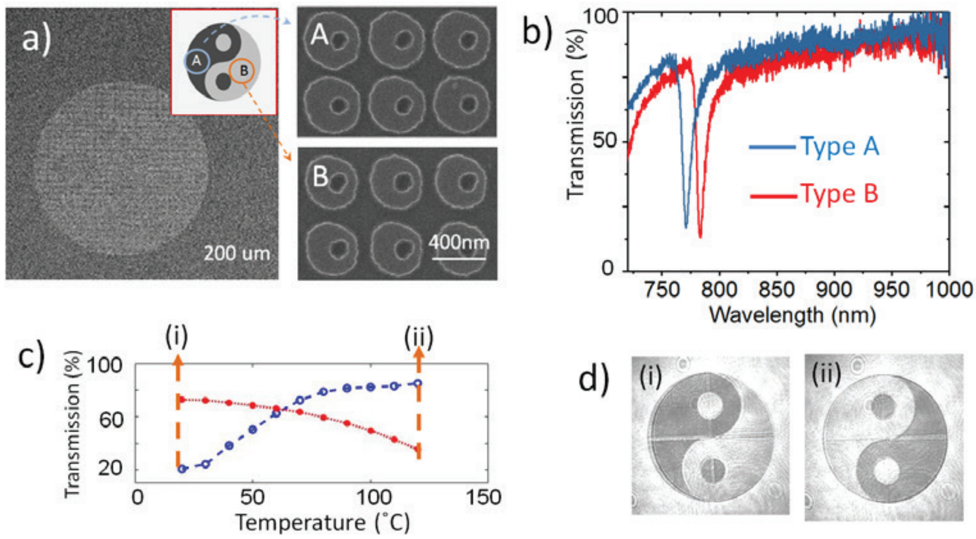

Figure 3. a) The SEM image of a nanostructured Yin-Yang pattern, accompanied by magnified SEM images of building blocks of Types A and B. Experimentally measured transmission spectra of b) block Types A and B at room temperature and c) the Yin-Yang pattern at λ = 784 nm at different temperatures. d) The experimentally recorded images from the pattern obtained at (i) 22˚C and (ii) 125˚C[9].

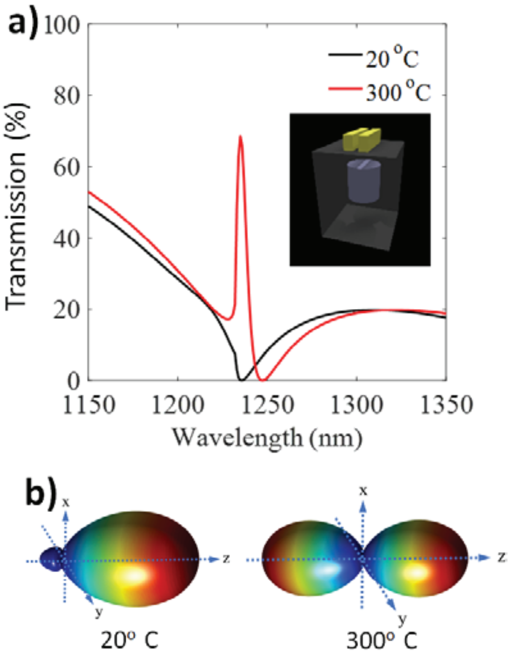

Figure 4. a) Simulated transmission of silicon with two gold bars, as illustrated in the inset. b) The far-field radiation pattern of the hybrid configuration at room temperature 20°C and 300°C, respectively[8].

Hybrid Systems: Additionally we have shown that hybrid metal-dielectric nanostructures allow the combination of the thermo-optical properties of both metallic and dielectric nanostructures simultaneously[8]. By taking advantage of the different thermo-optical properties of metals and dielectrics, novel hybrid metasurfaces can be designed that provide a unique platform to tune the excitation of electric and magnetic modes and their interference in parallel. Interestingly, thermal tuning is only applicable to dielectric metasurfaces, as the low thermo-optical coefficient of most of the noble metals, such as gold[16], makes metallic metasurfaces insensitive to variations in temperature. Such differences between dielectrics and metals provide a unique platform for active control of the excitation and interference between electric and magnetic resonances by heating the metasurface.

As an example, we examined the Kerker condition, a well-known effect in metasurfaces as a result of the interference between magnetic and electric modes[1]. The Kerker condition is mostly observed through a directive radiation pattern with zero backscattering. This leads to a unique capability to tune the Kerker condition when forward and backward scattering (i.e. transmission and reflection) can be turned on and off in a completely reversible way. Figure 4a shows the transmission spectra of the hybrid unit-cell, consisting of two gold bars, which are located on top of a silicon disk embedded in the glass. The electric resonance of metallic metasurfaces is essentially insensitive to heating, and magnetic and electric resonances of the dielectric component shift together during heating, with negligible change in the interference regime. Such a difference leads to a remarkable variation in optical scattering properties. As a result, around 70% tunability of transmission can be achieved at 1235 nm wavelength via the heating process (figure 4a). Therefore, at 20°C, light scattering is completely suppressed in the forward direction since its electric and magnetic responses are of the same order and the Kerker condition is satisfied. However, this equilibrium breaks at higher temperatures (i.e. 300°C), and this hybrid configuration scatters light in the forward direction (figure 4b).

Future Developments: Dynamic tuning can lead to very promising effects in the nonlinear regime too, such as second and third harmonic generations (SHG[17, 18] and THG[19], respectively). As can be seen in figure 5, the BIC state can dramatically enhance nonlinear emission from the nanostructures[14]. To demonstrate this effect, we encoded two images into the metasurface using resonances at different wavelengths. We defined two patterns of arrows ↑ and ↓ with building blocks (silicon nonconcentric disk and hole nanostructures) that are resonant at neighbouring wavelengths (i.e. 1325nm and 1355 nm). The width and length of the arrows were 20 and 90 µm, respectively. With this strategy, we tuned the THG image by tuning the fundamental wavelength (see figure 5a). Such a nonlinear tuning can be extended to III-V semiconductors with larger nonlinear susceptibilities.

We have recently invented a technique to fabricate III-V semiconductor nanocrystals on any transparent substrate, by embedding them within transparent polymers (see figure 5b) [20]. This technique has cracked a puzzle that had dogged scientists for over 50 years: how to fabricate III-V semiconductor nanocrystals on ultra-thin and fragile surfaces. This invention has enabled our team to demonstrate the potential for changing the colour of the light via III-V nanocrystals[17, 18]. This platform can realise many real-life applications, such as night-vision, where nanocrystals can capture short-wave infrared (SWIR) light, which is invisible to the naked eye, and re-emit it within the visible range. The thermal tunability, presented in this article, can further enhance the performance of dielectric and III-V nanostructures in the nonlinear regime for cutting-edge applications, such as nanoscale light routing, light sources, as well as multifunctional holograms and flat optical elements.

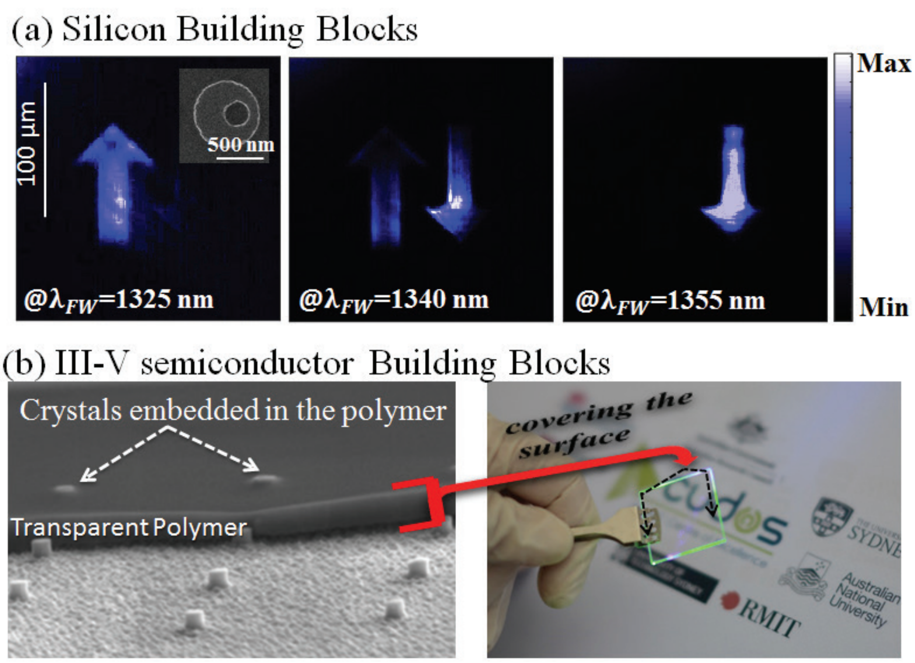

Figure 5. a) Nonlinear image tuning of a designed metasurface by tuning the fundamental wavelength (λ_{FW})[14]. b) Left: SEM image of AlGaAs nanocrystals embedded in a transparent polymer, before releasing from the handle wafer. Right: The polymer layer placed on a glass substrate[20].

Concluding Remarks: In summary, thermal tuning is a versatile method for dynamically and reversibly tuning the optical properties of dielectric and hybrid metasurfaces. The temperature dependence of the refractive index of dielectric materials provides a powerful tool to tailor the optical properties of metasurfaces, including transmission, reflection and absorption. Moreover, thermal tuning of hybrid metallic-dielectric metasurfaces enables complex mode interactions, which is not achievable with either dielectric or metallic metasurfaces alone. Importantly, thermal tuning has the promising potential to be extended to the nonlinear regime.

Acknowledgements

The authors acknowledge the contributions of Jonathan Ward to Refs [8,9] and useful discussions of Yuri Kivshar in Ref [7]. The authors acknowledge funding support provided by the Australian Research Council (ARC) (DP170103778, DP190101559). M.R. sincerely appreciates funding from ARC Discovery Early Career Research Fellowship (DE170100250). The authors acknowledge the use of the Australian National Fabrication Facility (ANFF)-the ACT Node.

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Nonlinear Photonics meets Topology

by Daria Smirnova, Sergey Kruk, and Yuri Kivshar

Recently discovered topological phases of light provide many novel opportunities for creating photonic devices robust against scattering losses and disorder. The combination of topological properties with nonlinear effects in photonic structures is anticipated to unlock advanced functionalities such as nonreciprocity and active tunability. Here we introduce the emerging field of nonlinear topological photonics and highlight some recent developments in bridging nonlinear optics with the physics of topological phases, including third-harmonic generation from nanoscale topological edge states and lasing in topological cavities.

Introduction

Topological phases of light provide unique opportunities to create photonic systems immune to scattering losses and disorder [1, 2]. Motivated by optical on-chip applications, there have been recent efforts towards bringing topological photonics to the nanoscale. Nanostructures made of high-index dielectric materials with judiciously designed resonant elements supporting Mie-type resonances [3] show a special promise for practical implementations of the topological order for light. This approach bridges the fundamental physics of topological phases with resonant nanophotonics and multipolar electrodynamics. Such high-index dielectric nanostructures possess optical nonlinearities enhanced near various geometric resonances.

Merging topological photonics with nonlinear optics suggests many novel opportunities since nonlinearity enables tuning and controlling topological properties of optical structures with intensity of light [4], and it can break optical reciprocity to realise full topological protection.

The nonlinear regime is natural to consider at laser optical powers and the fundamental question arises: what effects do nonlinearities have on topological phases and edge states, and vice versa? In particular, the concept of band topology is inherently tied to linear systems - the existence of a bandgap structure - and must be generalised to nonlinear systems.

The nonlinear response in photonics is expected to open the door towards advanced functionalities of topological photonic structures, including active tunability, genuine nonreciprocity, frequency conversion, and entangled particle generation. Such studies are still in their initial stages.

Here, we introduce this recently emerged novel direction in nonlinear photonics, focusing on the interplay between topological phases and nonlinear optics. We base this brief article on the recent results from our team in Canberra that demonstrated topological nanostructures which support subwavelength edge states and convert infrared radiation into visible light [5, 6].

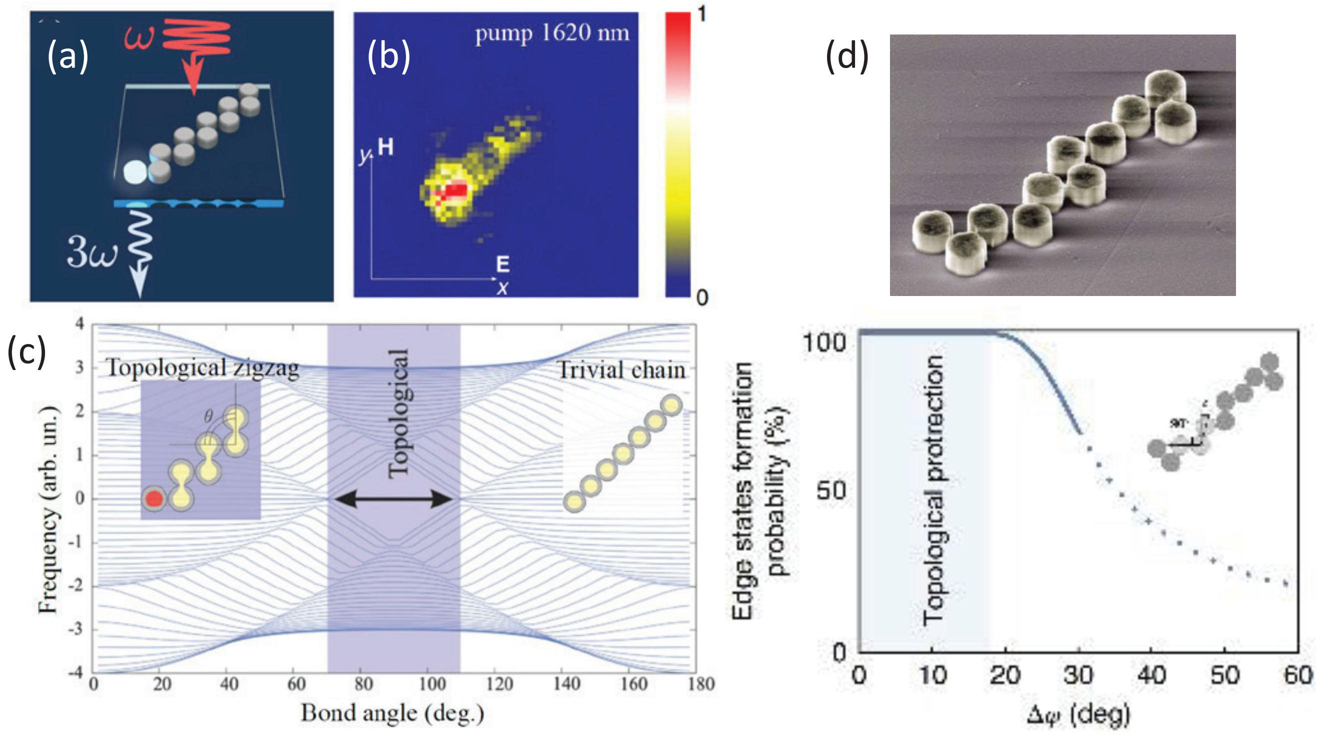

Figure 1. Nonlinear frequency conversion in topological arrays of nanoparticles. (a) Concept of THG in a zigzag array of nanoscale resonators: third-harmonic light (frequency 3ω) is generated by the topological edge state. (b) Experimentally measured distribution of the third-harmonic field in an 11-nanodisk zigzag array of Mie-resonant dielectric nanoscale dielectric disks. (c) Spectrum of the zigzag array calculated as a function of the bond angle. Shaded area is the region where the topological edge states can exist. (d) Robustness of the topological state to disorder. Top: an example of a fabricated disordered chain of nanoparticles. Bottom: the persistence of an edge state for a random change of the bond angle up to 20 degrees (Adopted from [5]).

Nonreciprocity in nonlinear topological arrays

For one of our experiments, we fabricated topologically nontrivial zigzag arrays of silicon nanodisks on a glass substrate, as shown in figure 1(a). This structure is described by a polarisation-enriched generalised Su–Schrieffer–Heeger (SSH) type model. Similar to the conventional SSH model, alteration of strong and weak dipole-dipole couplings in zigzag geometries leads to the edge state being localised at the edge, where the last dipole-dipole coupling is weak. A straight line chain is topologically trivial as it has a vanishing parity of the winding number. For a zigzag chain this topological invariant is nonzero, indicating the presence of a pair of edge states at both edges of the chain. The topological phase transition can be illustrated by plotting the energy spectrum of a finite chain as a function of the zigzag angle, see figure 1(c).

Due to the intrinsic nonlinearity of silicon, the topological edge state facilitates resonant generation of third-harmonic radiation, as shown in figure 1(b). Remarkably, the observed third-harmonic radiation switched from one edge of the array to the other, depending on the direction of illumination: from the substrate or from air. Such asymmetric generation induced by nonlinearity, bianisotropy and topology is a signature of the nonreciprocal behaviour being a fundamental requirement to realise nanoscale topological optical diodes. To verify the robustness of our structures to disorder, we fabricated a number of arrays with randomly generated bond angles between the disks. In full agreement with theory, for a disorder angle less than a critical value of 20°, the edge states were observed in all cases (see figure 1(d)).

Nonlinear edge states in topological metasurfaces

Going to two dimensions, topology-controlled nonlinear light generation was demonstrated [6] in a nanostructured metasurface with the domain wall supporting two counter-propagating spin-polarised edge waves (see figure 2). We fabricated waveguiding domain walls between topologically trivial and nontrivial metasurfaces (see figure 2(a-c)) and employed nonlinear imaging to make the first direct observation of nanoscale helical edge states passing sharp corners (see figure 2(d)). We further demonstrated geometry-independent photonic topological cavities with an Australia-shaped contour (see Figure 2(e)).

These recent experiments have established topological dielectric nanostructures as a promising platform for robust generation and guiding of photons at the nanoscale. The topological all-dielectric platform can be used to build tunable and active topological photonic devices with integrated light sources. Novel strategies to create integrated functional elements for advanced photonic circuitry (unidirectional waveguides, miniature topological cavities, low-power nanoscale lasers) are to be developed and tested. In turn, nanofabricated topological photonic cavities of arbitrary geometries may be employed as nonlinear light sources, with tunability of near and far field characteristics governed by the topological band inversion, and intrinsic protection against fabrication imperfections. This opens prospects for singular optics and frequency mixing driven by topological effects.

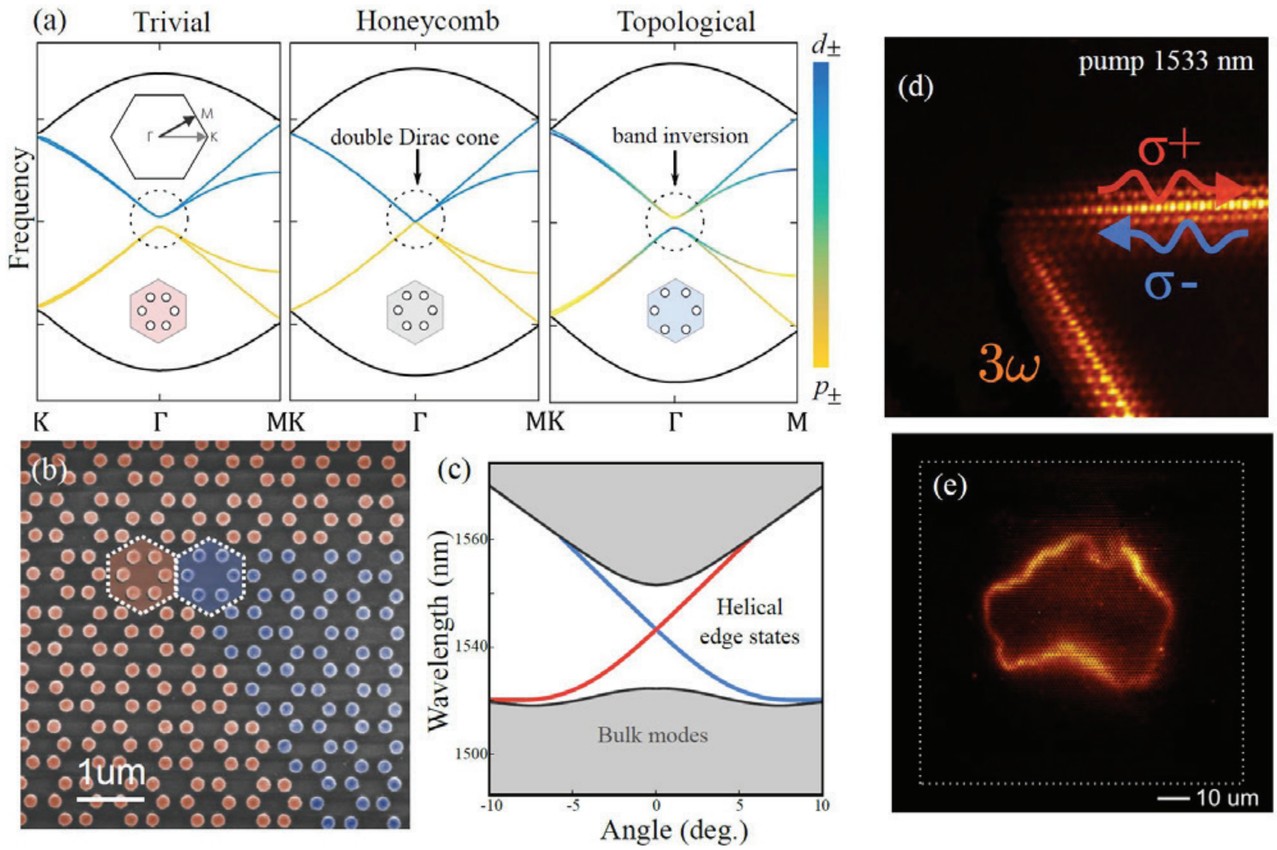

Figure 2. Third-harmonic generation from nanoscale helical edge states. (a) Topological transition due to clustering the hexagonal unit cell. Band structures for shrunken (left), unperturbed (middle), and expanded (right) lattices of hexamers. Colour of the bands encodes polarisation ranging from pure c.p. dipolar p± to pure c.p. quadrupolar d± states. (b) SEM of the fabricated metasurface. (c) Calculated band diagram featuring gapped bands of bulk modes and Dirac-like crossing for the edge states. (d,e) Experimental images of third-harmonic generation by the edge states at the sharp-corner domain wall (d) and Australia-shaped contour (e). (Adopted from [6]).

Lasing in topological cavities

Given that optics offers an ideal ground where gain and/or loss can be physically implemented, an important research direction is to investigate light dynamics in non-Hermitian topological systems. The synergy between non-Hermiticity and topology in active photonic systems ultimately promises single-mode lasers with topological robustness to disorder.

Next, we explored lasing operation in active topological metasurfaces. We designed a small-scale topological cavity based on the closed valley-Hall domain wall created by inversion of a staggered sublattice potential in a honeycomb lattice. The cavity supports quantised spectrum of confined modes within the topological bandgap. We studied its lasing characteristics and the spatial structure of the emitted beam.

We fabricated our topological cavities using electron beam lithography. We nanopatterned a 250 nm-thin InGaAs slab incorporating three InGaAsP quantum wells. The resulting structure is a free-standing patterned membrane positioned 1 μm above an InP handle wafer. Figure 3(a) shows the electron microscope image of the sample. We pumped the sample with 1030 nm wavelength by 6ps laser pulses with 5 MHz repetition rate. The illuminated area is approximately two times larger than the sample size. An image of the sample is built in reflection with a X100 0.7NA lens also filtering out the pump. The observed light above the lasing threshold emission is depicted in figure 3(b). Triade corner mode facilitates lasing due to its high quality factor and small mode volume.

To verify lasing experimentally, we first observed a narrow spectral line depicted in figure 3(c), and then studied the emission intensity vs. pump intensity, which exhibits a characteristic threshold dependence plotted in figure 3(d). We proved the coherence of the emission by introducing a 4-edge field diaphragm into the setup for real-space filtering. When two emission spots are isolated in real space, we observe an interference pattern in Fourier space suggesting that the emission is coherent. With this, we consistently confirmed that the observed signal corresponds to lasing. Finally, we isolated an individual lasing spot and measured its directionality diagram in Fourier space (see figure 3(f)). We observed a donut-shape beam hosting a singularity that agrees with the computed distribution of the Poynting vector in the vicinity of the lasing corner as shown in figure 3(e). These findings step towards topologically controlled lasing with nontrivial radiation characteristics.

Concluding remarks

We have described a few examples of photonic systems which combine topological phases with nonlinear optical effects. While the study of electronic topological states has a long history, topological photonics is a comparatively young field of research, and its links to nonlinear optics have been developed only in the last two years. A pressing question is how to harness this newly discovered degree of freedom of topological phases in practical optical devices, for example to achieve disorder-immune components for high-speed information transfer and processing, as well as robust nonlinear switching. In particular, topological metasurfaces could form the platform for a new class of ultrathin devices with

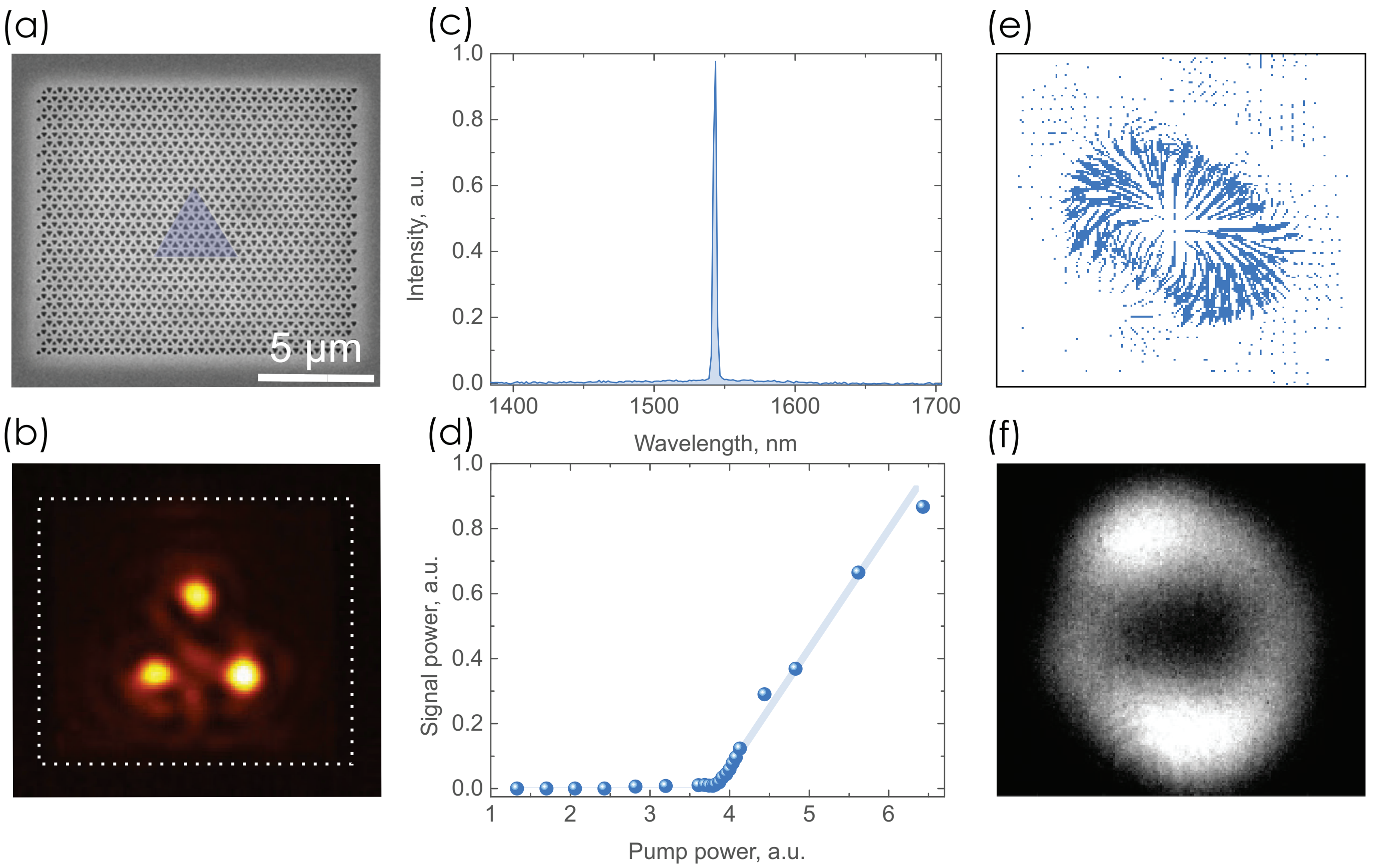

Figure 3. Lasing in topological cavities. (a) Electron microscope image of the fabricated topological structure. False-colour triangle marks the interior of the topological cavity. (b) Experimental emission image from the sample at around 1550 nm when pumped with 1030 nm. (c) Narrow spectral line of the emission above the lasing threshold. (d) Emission power vs. pump power showing a threshold transition to lasing. (e) Numerically calculated distribution of the Poynting vector, plotted as arrows around an isolated lasing cavity corner, indicates a singularity point. (f) Fourier-space emission directionality from an isolated cavity corner.

functionalities based on novel physical principles.

We envision that nonlinear topological photonics may provide novel tools and approaches for the study of interesting problems at the borderland between nonlinear dynamics and topology, and it may serve as a route towards unconventional designs for disorder-robust photonic device applications, such as high-speed routing and switching, nanoscale lasers, and quantum light sources.

Acknowledgements

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Optics in Everyday Life: Tidal Disruption

by Tony Klein

After my previous column on Aperture Synthesis, which showed the first image of a black hole, I came across some more remarkable pictures of black holes, showing the effects of them devouring stars by the phenomenon of tidal disruption. Since optics is essentially about images, I thought that these pictures may be of some interest, not only to astrophysicists, but to the optical community as well.

The sequence of pictures, starting with figure 2[1], show the effect of the gravitational gradient surrounding a super-massive black hole having the effect of completely shredding a nearby star. This is the phenomenon of tidal disruption, shown in a spectacular way as a video clip of the phenomenon as a function of time[2].

By observing the light given off during this process, which increases to a peak brightness and then tapers off, astronomers can better understand the physics of the black hole and the forces driving these phenomena.

This particular picture, taken as part of a continuing series, was taken in January 2019, by the NASA Satellite TESS – the Transiting Exoplanet Survey Satellite[3], which contains a telescope that continually observes the sky as it orbits the Earth, and detects the most minute changes in its brightness. In this way it showed the unexpected glimpse of an increase in light intensity as the black hole began the violent process of ripping apart of a Sun-sized star – an incredibly rare event.

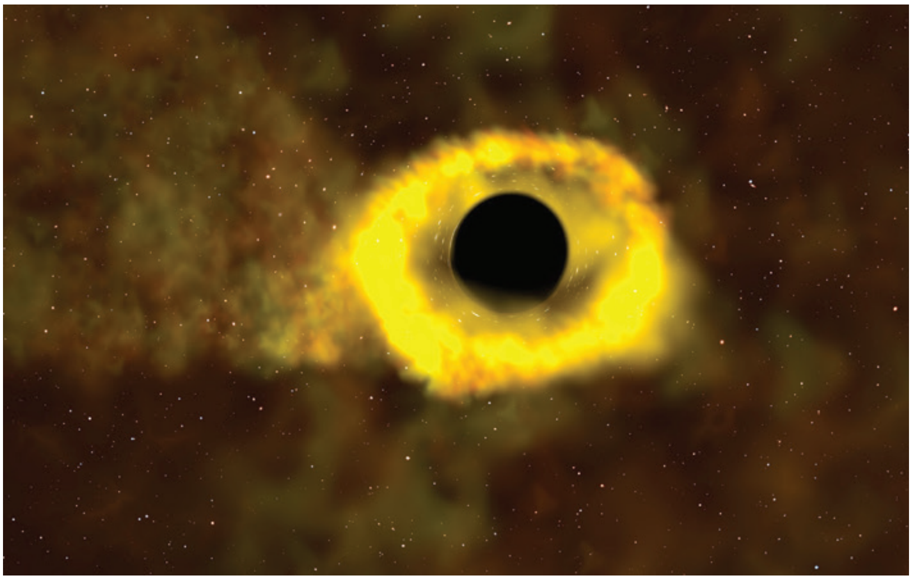

Figure 1. Image of a star completely disrupted by the tide surrounding a black hole, finally forming an accretion disk. Image Credit: NASA's Goddard Space Flight Center.

In fact, these cataclysmic events are said to occur only once every 10,000 to 100,000 years in a galaxy the size of our own Milky Way. In total, astronomers have observed only about 40 tidal disruptions so far, and scientists predicted TESS would see just one or two in its initial two-year mission. Because the event that we are talking about, named ASASSN-19bt, was rapidly identified by TESS, ground based telescopes such as the All-Sky Automated Survey for Supernovae (ASAS-SN)[4], were alerted and able to follow its evolution using multi-spectral observations, adding further to our knowledge of black holes.

Note that this (and other ground-based telescopes) were primarily designed to detect supernovae and other transient

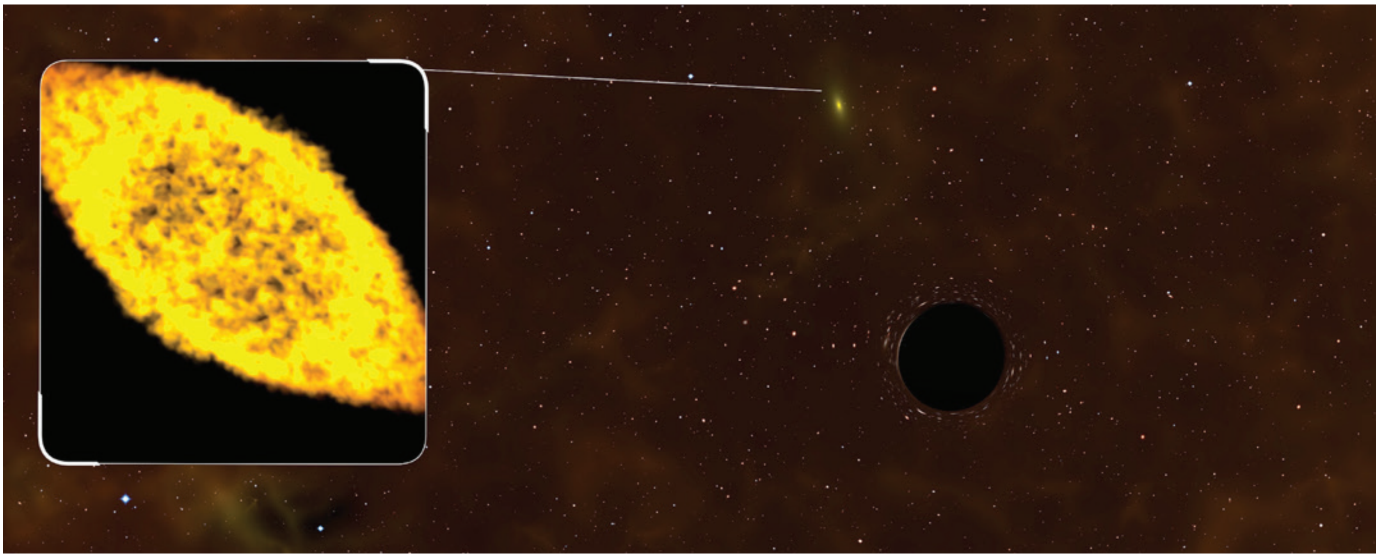

Figure 2. The star, passing near the super-massive black hole, breaks up into a stream of gas, forming a tidal bulge. Image Credit: NASA's Goddard Space Flight Center.

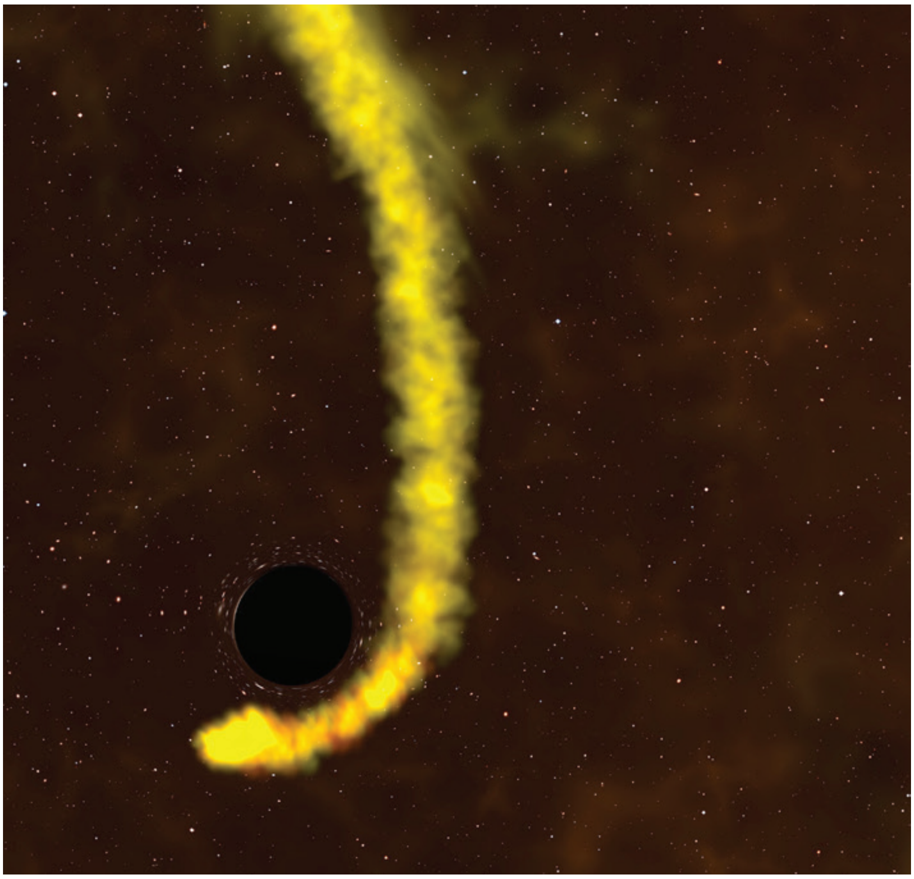

Figure 3. Some of the material of the star gets flung out into space. Image Credit: NASA's Goddard Space Flight Center.

phenomena and were only fortuitously involved with this discovery. The same is true for TESS: The extraordinary observation of the phenomenon of tidal disruption was not the primary purpose of this space telescope. As its name indicates, it was designed to detect the tiny diminution of the light from a star as one of its satellites crosses its disk, effectively eclipsing it during its orbit. Another technique used in the finding of exoplanets consists of detecting the slight Doppler shift caused by the wobble of the star, caused by the motion of the exoplanet.

That such phenomena should be detectable at all, was in fact, the subject of half of the Nobel Prize in Physics for 2019, shared by Michael Mayor of the University of Geneva and Didier Queloz of the Universities of Geneva and Cambridge. (The other half went to James Peebles, of Princeton, one of the founders of Physical Cosmology).

In recent times, hundreds of exoplanets have been discovered by TESS and by other telescopes, using these techniques. As a matter of fact, today, we know that there are at least 4,000 planets around stars in the Milky Way galaxy alone, with countless more waiting to be discovered.

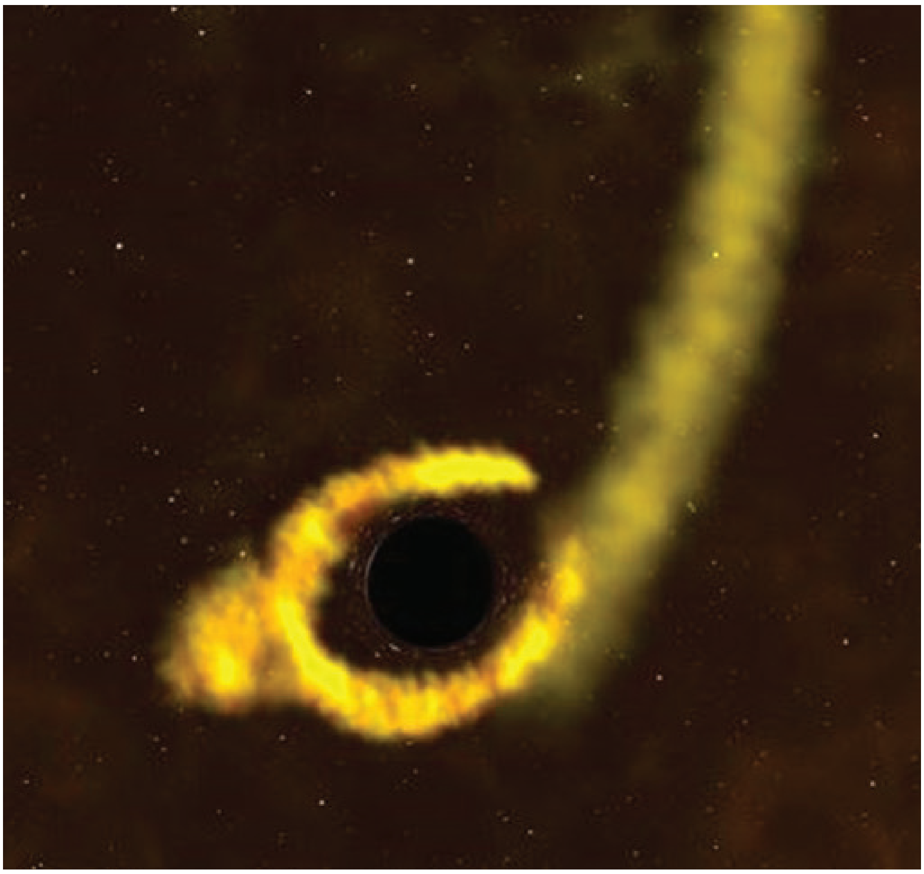

Figure 4. The rest falls back into the black hole and forms a disk of hot, bright gas as it is consumed, ending up as the accretion disk, shown in figure 1. Image Credit: NASA's Goddard Space Flight Center.

Then there is also the observation of supernovae, including the long-awaited (and long–overdue) appearance of a supernova in our own galaxy which should produce further fantastic pictures, as did 1987A the supernova in the neighbouring galaxy, the large Magellanic Cloud which caused quite a stir in 1987.

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