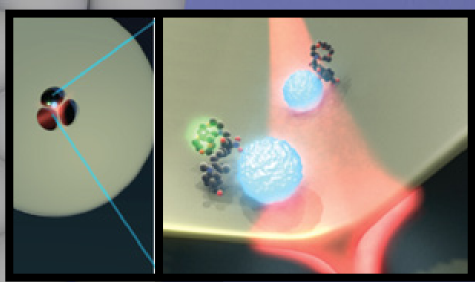
AOS News

Volume 30 Issue 2
July 2016
ISSN 1832-4436
Registered by
Australia Post
Publication No:
233066 / 00030

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.

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.

Advertising:
Potential advertisers in AOS News are welcome, and should contact the editor.
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Copy Deadline
Articles for the next issue (September 2016) should be with the editor no later than 22 August 2016, advertising deadline 15 August 2016.

Editor
Jessica Kvansakul
La Trobe Institute for Molecular Science
La Trobe University
Melbourne VIC 3086
jk.aosnews@gmail.com

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.

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Cover Pictures:
- Depiction of a scanning probe quantum microscope imaging the properties of individual molecules. Elements of the image are: diamond probe (transparent grey) containing a defect with an optically addressable spin (red arrow), microwave coil (copper) for quantum control of the spin, and interaction between the spin and molecule (blue spiral), see page 23. Image created by Michael Barson.
- Insets (left to right)
  - Upconversion nanocrystals within suspended core optical fibres can be used for biosensing applictions, see page 17.
  - Solar halos can be seen when cirrus clouds of ice crystals are present as they can act like prisms, bending sunlight into a halo shape around the sun, see page 30. Image credit: Gustavo Asciutti.

AUSTRALIAN OPTICAL SOCIETY

AOS Executive

PRESIDENT
Stephen Collins
Eng & Sci - Footscray Park campus
Victoria University, PO Box 14428
MELBOURNE VIC 8001
Telephone: 03 9919 4283
stephen.collins@vu.edu.au

VICE PRESIDENT
Simon Fleming
School of Physics (A28)
University of Sydney
Institute of Photonics and Optical Science, SYDNEY NSW 2006
Telephone: 02 9114 0581
Fax: 02 9351 7726
simon.fleming@sydney.edu.au

PAST PRESIDENT
Ann Roberts
School of Physics
University of Melbourne
MELBOURNE VIC 3010
Telephone: 03 8344 5038
Fax: 03 9347 4783
ann.roberts@unimelb.edu.au

HONORARY SECRETARY
Dragomir Neshev
Nonlinear Physics Centre, RSPE
Australian National University
CANBERRA ACT 2601
Tel: 02 6125 3792
Fax: 02 6125 8588
dragomir.neshev@anu.edu.au

HONORARY TREASURER
Baohua Jia
Centre for Micro-Photonics
Swinburne University of Technology
VIC 3122
Tel: 03 9214 4819
Fax: 03 9214 5435
bjia@swin.edu.au

AOS Councillors

Ken Baldwin
Atomic and Molecular Physics Labs
ANU, RSPSE
Canberra ACT 0200
Tel. (02) 6125 4702
Fax. (02) 6125 2452
kenneth.baldwin@anu.edu.au

Maryanne Large
Innovation and Commercialisation
Faculty of Science
University of Sydney
Sydney NSW 2006
Tel. (02) 9114 0850
maryanne.large@sydney.edu.au

John Harvey
Department of Physics,
University of Auckland,
Private Bag 92019,
Auckland 1010, New Zealand
Tel: (+64 9) 373 7599
Fax: (+64 9) 373 7445
j.harvey@auckland.ac.nz

Ben Eggleton
Director, CUDOS
School of Physics,
University of Sydney
Sydney NSW 2006
Tel: 02 9351 3604
Fax: (02) 9351 7726
egg@physics.usyd.edu.au

Halina Rubinsztein-Dunlop
Department of Physics,
University of Queensland,
Brisbane, QLD 4072
Tel: (07) 3365 3139
Fax: (07) 3365 1242
halina@physics.uq.edu.au

Robert McLaughlin
Chair of Biophotonics
Centre for Nanoscale Biophotonics
University of Adelaide, SA 5005
Tel: 08 8313 9942
Fax: 08 8313 4380
robert.mclaughlin@adelaide.edu.au

Peter Veitch
Department of Physics,
University of Adelaide, SA 5005
Tel: (08) 8313 5040
Fax: (08) 8313 4380
peter.veitch@adelaide.edu.au

John Grace
INDUSTRY REPRESENTATIVE
PO Box 958
NEWPORT BEACH NSW 2106
Tel:(02) 9979 7646
Fax: (02) 9979 8207
johng@raymax.com.au

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President's Report

It's always good to begin my report with some good news. On 23 May, the Australian Academy of Science announced the election of 21 new Fellows for their outstanding contributions to science and scientific research. Two of these awardees are former AOS presidents and members of the current AOS Council, and many AOS members would be well aware of their contributions to optics and photonics. Halina Rubinsztein-Dunlop, at the University of Queensland, works in laser physics, linear and nonlinear high resolution spectroscopy, laser micromanipulation, atom cooling and trapping and nano-optics. Ben Eggleton, at the University of Sydney, researches integrated nanophotonics and nonlinear optical physics with applications to ultrafast and ultra-broadband and energy efficient information signal processing. On behalf of the other Council members I warmly congratulate Halina and Ben.

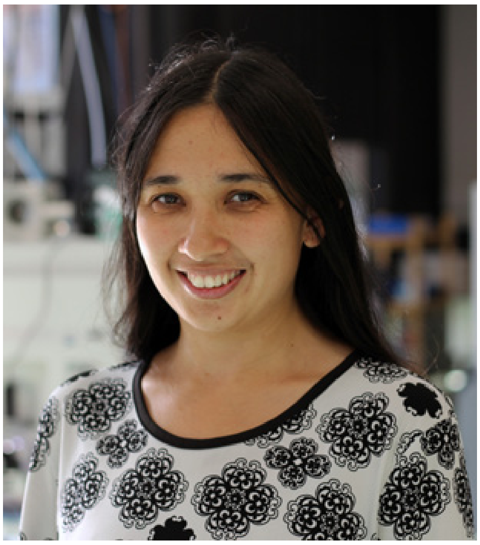
The Australian government's budget now seems long ago. Science & Technology Australia (STA), of which AOS is a member, stated "It is no surprise that there is little new for science in tonight's Federal Budget. After the announcement of the $1.1 Billion National Innovation and Science Agenda (NISA) last December, it was unlikely additional measures would follow." No doubt members are interested in the policies being promoted around research, and also the cutbacks and reorganisations in certain areas of CSIRO. STA has various initiatives to help promote the importance of science and research. Late last year they organised a Science meets Business event in Sydney, at which one of our Council members, John Grace, attended. A similar event is being planned for Monday, 24 October 2016 in Melbourne, with by-invitation attendance by business and science leaders, with speakers from both sectors and from the Government and Opposition, with support by the Federal Department of Industry, Innovation and Science. There is likely to be an opportunity for AOS participation; anyone interested should contact me.

Plans to marks the centenary of the birth of Aleksandr Prokhorov, in the Atherton Tablelands region, who was one of the co-winners of the 1964 Nobel Prize in Physics for the invention of the laser, are now well-advanced. Through National Science week funding AOS, with the support of the AIP, will be running a version of the LaserShow, a two-person show, presented by Prof Hans Bachor (of ANU) and Patrick Helean (of Questacon – the National Science and Technology Centre, Canberra), in Townsville (17 August) and Cairns (18 August) with a major public event to be held in Atherton on Saturday 20 August. These shows will be accompanied by some hands-on activities. I am very grateful for the fulsome support of a number of organisations including universities and a local secondary school physics teacher. We are seeking other ways of marking this centenary, and I encourage members planning Science Week activities, or similar, to at least make mention of the story of Prokhorov.

As we pass the middle of the year I trust many AOS members are planning to participate at one or both of our 2016 meetings. The organising of OSA Photonics and Fiber Technology conference, 5-8 September in Sydney (incorporating the BGPP (Bragg Gratings, Photosensitivity and Poling in Glass Waveguides), NP (Nonlinear Photonics) and 41st ACOFT conferences) is well underway, with Ben Eggleton as the Congress Chair. The AOS annual meeting is to be held 4-8 December in Brisbane, as part of the 22nd Australian Institute of Physics Congress (in conjunction with the 13th Conference of the Association of Asia-Pacific Physics Societies). Halina Rubinsztein-Dunlop and the current AIP president, Warwick Couch, are Conference Co-Chairs. In addition AOS Council has provided technical co-sponsorship to a number of other meetings being held in Australia. Beyond this year, another ANZCOP is likely to be held at the end of 2017.

Stephen Collins
AOS president

Editor's Intro



Welcome to another issue of AOS News. We have a range of articles for this issue, with a report on some of the international outreach that took place last year as part of the Year of Light and an article from the winner of the 2015 Geoff Opat Early Career Award, Marcus Doherty, on quantum microscopes. Other items in this issue include a summary of the challenges involved in bringing new optical devices into surgery and an article on using optical fibres for medical sensing. Our 'Optics in Everyday Life' section looks at solar halos and how they are formed, and there is also an article describing the use of nanophotonics to colour surfaces. I hope you enjoy reading them all. As usual, please let me know if you have any suggestions for anything you would like to see in AOS News or have any articles or other items you would like to submit.

The way that science appears in the news is something that affects all of us, whether it is an article directly reporting on our own work or area of expertise or just items that add to the scientific understanding and awareness of the general public, making science communication an important issue. There has been a decline in the number of specialised science journalists and editors in recent years due to the loss of advertising revenue and poor sales for print media. This means that science stories are covered by general interest journalists rather than dedicated science writers who may not have the same contacts, knowledge and understanding of the area. There has also been a shift to more science communication rather than science journalism (defined as 'objective', critical reporting and analysis). With newspapers relying on more online content it has changed the way news is reported in mainstream media. There is more and more of a push for faster coverage of stories that means that there isn't always the same rigour applied to science articles that there used to be and there is concern that there is much less fact checking and balance for stories that appear. These are now often mainly based on press releases and end up being sensationalised click-bait rather than an accurate analysis of an issue.

Journalists have faced declining wages with pay rates stagnating over the last few years and many unable to make a living through their writing and having worries about job security. This also affects the type of science stories that are able to be covered. There is less opportunity to work on longer, well-researched pieces and even pitches to editors are becoming much shorter and less well-developed than in the past. Freelance budgets at many news outlets were reduced as well as science editorial staff being cut even though with lower rates the editors have more work to do as writers spend less time on articles. As there is less time all round this leads to a reduction in relationship-building and mentoring so that any changes that editors do make aren't explained to writers so that they can improve.

There is still a large amount of high quality science communication out there with experienced people who do present stories in context (which is what a lot of the former science journalists are doing now). Much of this is now coming from different areas and in new formats compared to before. It does mean that there is less critical, independent reporting and analysis of the science, however, which now only happens in science magazines rather than in mainstream media. This also leaves the possibility for those with an agenda or who simply take a story at face-value to have misleading conclusions or slants on stories, as well as the prospect of a single researcher who disagrees with scientific consensus being given as much weight as the rest of the scientists in a given area. Optics is generally non-controversial (unlike, say climate science or genetically modified organisms), which makes it easier for our field in general to be less likely to suffer this misrepresentation, but it is still possible. There is a strong need for journalists to provide appropriate balance and take consideration of expert opinion. With a scientifically literate general public these changes would be less of an issue, but there is often little understanding that scientists differ in opinion due to different interpretations of results or even personal rivalry, and that generally scientific knowledge is subject to change with new evidence.

With untrustworthy science coverage people become confused and start ignoring everything as well as it undermining public confidence in science and the scientific process. There is also the issue that science in the media does affect the public attitude to science and trust in research institutions if people stop trusting scientists due to what they see in the media. We just have to hope that more of the new web-based science communication manages to address some of these issues. I did hear recently about a website (understandinghealthresearch.org) that has been set up to help people understand the quality of particular health research articles as this is one area where conflicting information is constantly given in the media. This helps people weigh up the evidence from a given study to see how reliable and useful it may be. Hopefully people will use this when reading about the latest fad or food concern and in the process learn more about critical appraisals of research. Perhaps more ideas like this to help educate and inform the public are the way forward.

Jessica Kvansakul
Editor

PHOTON SCIENTIFIC

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'Spectral Products' is an industry leader in the design and manufacture of optical instruments including spectrometers, monochromators, spectrographs, spectrophotometers, spectrum analysers, detection systems, light sources as well as fiber optic cables and couplers. Spectral Products introduced the first total microprocessor-controlled, direct drive scanning monochromator in 1987. The award-winning design eliminated the commonly used, but costly and unreliable, sine-bar drive for wavelength control. Today, the Spectral Products' Digikröm line of monochromators combines microelectronics with precision optics while featuring computer control, direct digital drive, automatic grating changes and motorized slits. This careful marriage of microcomputers with precision opto-mechanics is an example of why Spectral Products are now the world leader in low-cost high performance spectroscopic systems.

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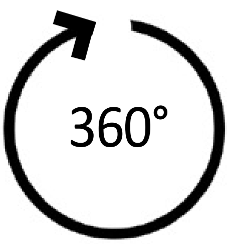

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Year of Light Brings ANU Scientists to the Philippines

The International Year of Light (2015) has brought scientists from the Australian National University (ANU) in Canberra to the Philippines to conduct a series of workshops on optics to science teachers.

by Vincent Daria and Hans Bachor

The workshops aim to enhance the knowledge of science teachers on the nature and role of optics through hands-on experimentation using readily available materials. The Optics Workshop also served to initiate and strengthen linkages between scientists from the Australian National University and the public and private high schools participating in the workshop.

The workshops were partially supported by the Optical Society of America Foundation (which provided optics kits), and the Philippine government through the Philippine Council for Industry, Energy and Emerging Technology Research and Development (PCIEERD). ANU physicists, Hans Bachor and Vincent Daria conducted the seminar/workshops in coordination with local educators, Chris Bernido, Marivic Bernido and Ann Go.

Two workshops were conducted, one at the Research Centre for Theoretical Physics, Central Visayan Institute Foundation (CVIF), Jagna, Bohol and the other at the Philippine Science High School Western Visayas Campus, Leyte. The CVIF is managed by Chris and Marivic Bernido, who are both physicists by training. Ann Go, on the other hand, was at the time teaching at the Philippine Science High School after completing her PhD in Neuroscience at the ANU.

The first workshop assisted secondary schools that are implementing the CVIF Dynamic Learning Program (DLP). The CVIF-DLP is a teaching method geared towards developing each child to his or her fullest potential. The method has already shown to improve student performance. As a measurable outcome, the participants were asked to design DLP Learning Activities based on the workshop so that the knowledge gained can be directly translated into the classroom.

The two workshops combined gathered around 100 high school science teachers representing more than 50 schools around central Philippines. The majority of the schools participating in the two workshops have already been implementing the CVIF-DLP for several years. The emphasis was on low cost demonstrations that can be repeated with locally available equipment – and thus can be scaled to a large number of students. The 100 science teachers together educate more than 15,000 students in each school year. The impact, therefore, of the hands-on and minds-on activities at the workshop cannot be underestimated.

Hans Bachor demonstrating projected laser patterns caused by vibrations from blowing an improvised didgeridoo made from a PVC pipe.

Teachers watch as Hans Bachor demonstrates the principle of superposition and interference of waves.

Vincent Daria demonstrates the optical waveguiding effect using a low-cost laser pointer and a fishing line.

Vincent Daria is with the John Curtin School of Medical Research, The Australian National University, and Hans Bachor is with the Research School of Physics and Engineering, The Australian National University.

Nanophotonic 'Plasmonic Pixels' for Robust Surface Colouration

Of all the properties of light, colour is the one that most captures the public imagination. Here we demonstrate using nanoscale patterns to colour aluminium surfaces without the need for pigments or dyes.

by Timothy D James, Paul Mulvaney and Ann Roberts

Throughout human history, we have used colour for coding information, differentiating between objects and, of course, purely for aesthetic purposes. Artists have always manipulated colour to achieve particular emotional and visual impacts and fireworks and lighting displays are a riot of colour.

Most manufactured objects we perceive as possessing a particular colour have been coated with a pigment or impregnated with a dye. A significant issue with this approach to colouration, however, is the fact that they are, to a greater or lesser degree, fugitive – they fade over time. Furthermore, many pigments are toxic and, even for harmless colourants, their presence adds an additional layer of complexity to manufacturing and subsequent recycling of materials. As a consequence, there is considerable interest in being able to replicate the colour spectrum without the introduction of additional materials.

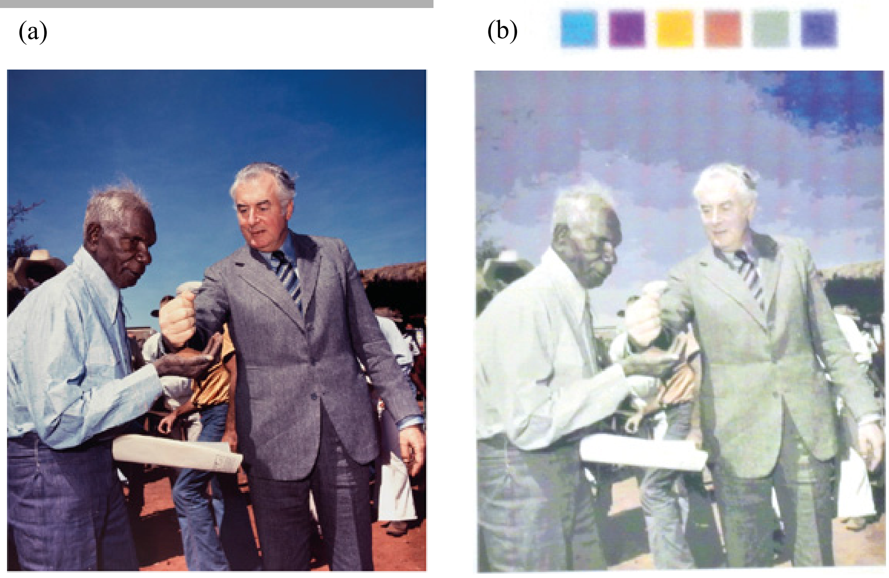

Figure 2. (a) Original photograph (b) rendering in plasmonic pixels. Image is 1.25 x 1.5 cm. The small squares above the image show (left to right) display rendering of cyan, magenta, yellow, red, green and blue. Note that the image in (b), whilst close to full colour, is composed using only aluminium and polymer.

Animals regularly take advantage of 'structural colour' [1]. The morpho butterfly and the deadly blue-ringed octopus are just two creatures that use submicron scale texturing or layering to achieve striking diffractive colour effects. From a technology viewpoint, diffraction gratings and photonic crystals are well-known for their ability to produce colour effects, albeit with a strong sensitivity to angle of incidence.

There is a rapidly emerging interest in using localised plasmonic resonances on the surfaces of nanoscale features in metals to produce chromatic effects and the field has progressed to a point where industrial scale fabrication using conventional embossing techniques has been demonstrated [2]. A review of recent progress in the field can be found in [3]. Australian groups have contributed to this effort. In work led by Duk-Yong Choi at ANU, arrays of aluminium patches have been shown to produce colour filtering [4] and a recent paper led by researchers at Latrobe University [5] demonstrated polarisation-tunable colour pixels based on cross-shaped apertures in a thin film of silver.

A key challenge in producing structural colour effects is to generate a broad colour-gamut whilst suppressing diffractive

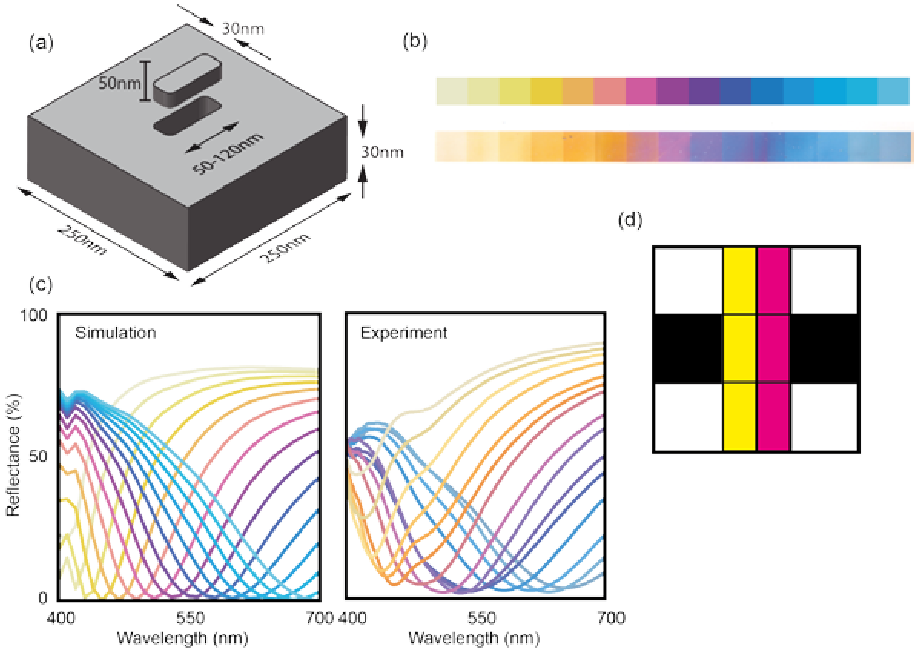

Figure 1. (a) Schematic showing the building block of the plasmonic pixel where an Al nanorod floats above its complementary nanoslot in an Al film; (b) shows simulated (top) colour and photographs of fabricated 200 µm x 200 µm dipole arrays; (c) shows the reflectance calculated using the Finite Element Method implemented in COMSOL Multiphysics on the left and experimental results on the right; (d) layout of the plasmonic pixel showing the creation of a particular hue and brightness by controlling the number of 'colour', 'white' and 'black' pixels.

effects that become apparent with periodic structures at larger viewing angles. We have recently demonstrated non-diffractive structural colour using an approach taking advantage of localised plasmonic resonances in aluminium [6]. The nanoscale structures correspond to characteristic resonances in the visible part of the electromagnetic spectrum. Furthermore, these individual elements can be combined to produce subtractive colour in a 'plasmonic pixel'.

The basis for the colour effects is a unit cell consisting of an aluminium nanorod 'floating' a distance 50 nm above its complementary nanohole (Figure 1a) in a film of aluminium. This can be used to generate a basis CMY colour palette as shown in Figure 1b. Note that the colours obtained experimentally are in excellent apparent agreement with the design colour. To generate a wide palette of colours with a range of available saturation and lightness levels, the CMYK colours need to be combined intelligently to produce the colours we require. We achieve this by creating a plasmonic pixel, 30 µm on each side, made up of a 3x3 array of 10 µm sub-pixels. Each of these sub-pixels can be colour, black or white, and the combination of sub-pixels creates a pixel of varying colour, saturation and brightness (Figure 1c). The colour sub-pixels consist of 10 x 1 µm strips of CMY, each consisting of arrays of floating dipole elements with different lengths. The number of strips of C (dipole length 120 nm), M (90 nm) or Y (70 nm) is determined by the desired hue. The brightness is adjusted by changing the numbers of 'white' and 'black' sub-pixels. White cells are untextured and have uniform reflectance. Black (K) cells are created by including not one, but two floating dipoles of different lengths (70 nm and 110 nm). The saturation is controlled by varying the number of colour sub-pixels within a pixel, where a fully saturated pixel has all 9 sub-pixels as colour. The overall structure is embedded in polymer and the geometry is compatible with scalable embossing approaches to fabrication.

As a demonstration of the potential for the plasmonic pixel to produce large area colouration, we have produced a replica of an iconic Australian photograph showing then Prime Minister Gough Whitlam handing back Wave Hill Station to Vincent Lingiari (Figure 2a) in 1975. The resulting image, 1.25 cm x 1.5 cm, is polarisation-dependent, opening up potential methods for dynamic colour modulation. The colour was designed to be produced when the polarisation was parallel to the long axes of the nanorods (Figure 2b) and it is apparent that there is good replication of the original colour palette. Note that the small squares above the image show (left to right) display rendering of cyan, magenta, yellow, red, green and blue using nanorod arrays. As the incident light polarisation is changed, the colouration changes and the image becomes a uniform dull brown when the polarisation is orthogonal to the long axis of the rods. For the design polarisation, however, the colour quality persists to large viewing angles.

In conclusion, we have demonstrated nanoscale structural colour utilising the unique properties of localised plasmonic resonances. The spectral dependence of these resonances produces colouration that can be integrated into a unique pixel design that generates a broad colour palette in aluminium that is independent of the viewing angle. Approaches such as this lay the foundations for next-generation colouration of consumer products and may also find application in displays and colourimetric sensors.

References

[1] S Kinoshita, *Structural Colours in the Realm of Nature*, World-Scientific (2008).

[2] X Zhu, C Vannahme, E Højlund-Nielsen, NA Mortensen and A Kristensen, *Plasmonic colour laser printing*, Nature Nanotechnology **11**, 325 (2016)

[3] Y Gu, L Zhang, JKW Yang, SP Yeo and CW Qiu, *Color generation via subwavelength plasmonic nanostructures*, Nanoscale, **7** 6409 (2015).

[4] VR Shrestha, S-S Lee, E-S Kim, and D-Y Choi, *Aluminum Plasmonics Based Highly Transmissive Polarization-Independent Subtractive Color Filters Exploiting a Nanopatch Array*, Nano Lett, **14**, 6672, (2014).

[5] E Balaur, C Sadatnajafi, SS Kou, J Lin & B Abbey, *Continuously Tunable, Polarization Controlled, Colour Palette Produced from Nanoscale Plasmonic Pixels*, Sci Rep, **6**, 28062 (2016).

[6] TD James, P Mulvaney and A Roberts, *The Plasmonic Pixel: Large Area, Wide Gamut Color Reproduction Using Aluminum Nanostructures*, Nano Lett **16**, 3817 (2016).

Timothy D James and Ann Roberts are with the School of Physics, The University of Melbourne and Paul Mulvaney is with the Bio 21 Institute and School of Chemistry, The University of Melbourne.

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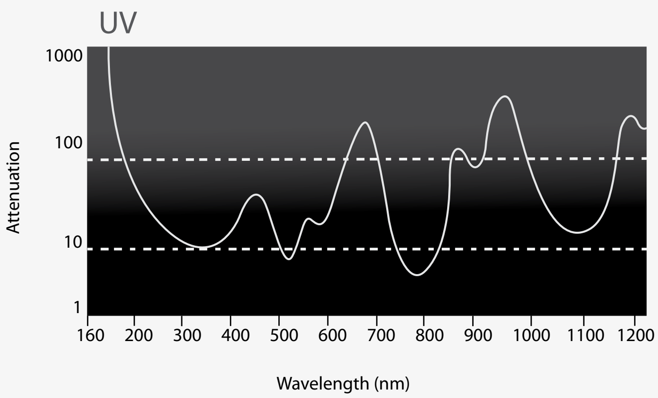

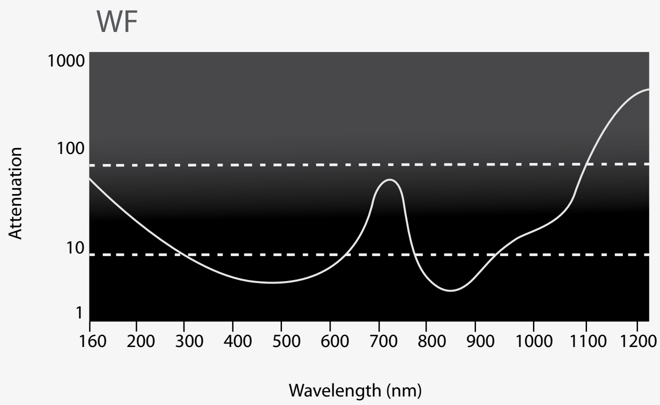

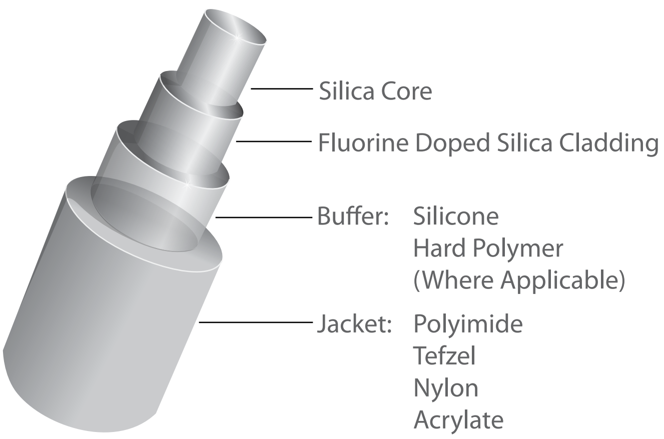

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Bringing Optical Innovation into Surgery

by Robert McLaughlin

An optical coherence tomography needle probe, capable of high resolution imaging deep in tissue.

Bringing a new medical technology from the lab and into the hospital is a complex journey. Over the past nine years, our team at the University of Western Australia, and now also at the University of Adelaide, have worked to develop a new type of medical imaging probe from its early days on the optics bench, through to initial human trials.

The miniaturised fibre-optic probe uses precision splicing and cleaving of a range of fibre types to fashion a small lens onto the end of a length of single-mode fibre. Each stage of the fabrication involves splicing only a few hundred microns of optical fibre, painstakingly building a composite that can focus a light beam, and that is then encased inside a hypodermic needle.

For our work, the probe is attached to an optical coherence tomography (OCT) scanner, using near infrared light to acquire high-resolution images of tissue up to 1mm away from the needle tip.

These highly miniaturised OCT needle probes open exciting new possibilities to guide doctors in treating diseases deep inside the body by inserting the needle far beyond the depth penetration limits of the light – all thanks to the creativity and ingenuity of a large team of engineers, physicists, computer scientists and medical clinicians. The efforts of this team were recognised when they became recipients 2014 WA Innovator of the Year Award, and the 2015 Australian Innovation Challenge award.

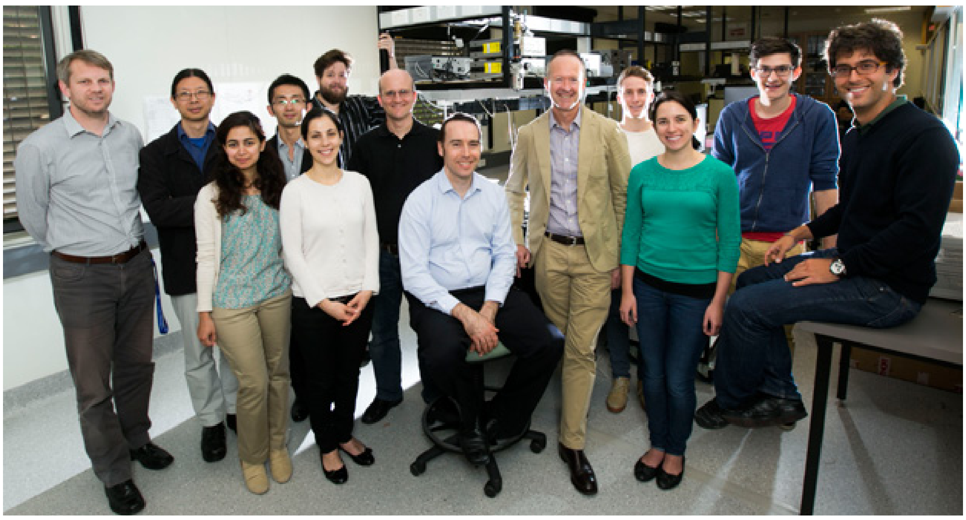
We are currently preparing for our first in vivo human trials, where the needle probe has been integrated into a brain biopsy needle. We have the potential to enable safer brain biopsies, providing the neurosurgeon with an early warning of any blood vessels near the needle as it is inserted.

What we hadn't anticipated was that making this technology suitable for use in humans requires far more than high-precision optics.

Defining a clinical protocol that minimises the risk to patients has taken close collaboration between the neurosurgeons and engineers. The surprise for us was that these two professions speak very different languages and often focus on completely different aspects of the problem.

Our team have also had to change many of the components from the original bench-top prototypes, sourcing suppliers of biocompatible materials from all over the world that adhere to the appropriate ISO and regulatory standards.

Gaining approval from hospital ethics and governance committees has required a change in mindset, taking the technical questions we are familiar with as engineers, and rephrasing them from an ethical and patient-risk point-of-view.


Part of the team responsible for development of the needle probes, led by Prof. Robert McLaughlin and Prof. David Sampson (both centre).

However, the greatest realisation has been just how much work and how many dedicated people it takes to bring a technology to initial human trials. Funding that process is an on-going challenge, and we have been fortunate to have long-term support from organisations such as Cancer Council WA, The National Breast Cancer Foundation, The Raine Medical Research Foundation, ARC, NHMRC, and South Australian and Western Australian state governments.

Australia is well-positioned to undertake this type of clinically focused development, with well-established Universities and a sophisticated medical system. But successful clinical translation lies beyond the expertise of any single discipline. If you want to deliver clinical innovation, I would recommend that you start developing your multi-disciplinary networks early.

Professor Robert McLaughlin is the Chair of Biophotonics with the ARC Centre of Excellence for Nanoscale Biophotonics, Institute for Photonics and Advanced Sensing, University of Adelaide.

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News

Congratulations to Halina Rubinsztein-Dunlop and Ben Eggleton, Fellows of the AAS
The AOS is delighted that two of our Councillors, Professors Halina Rubinsztein-Dunlop and Benjamin Eggleton, were made Fellows of the Australian Academy of Science on 23 May.

Halina Rubinsztein-Dunlop is recognised internationally for her achievements in laser physics, linear and nonlinear high resolution spectroscopy, laser micromanipulation, atom cooling and trapping and nano-optics. She is one of the originators of laser enhanced ionisation spectroscopy, and is a pioneer of laser micromanipulation and transfer of angular momentum of light and all optical drive micromechanics. She initiated the experimental programs in laser micromanipulation and atom optics at the University of Queensland that culminated in the demonstration of dynamical tunnelling in a Bose Einstein Condensate (BEC) in a modulated standing wave. She led the team that observed dynamical tunnelling in quantum chaotic systems.


Professor Halina Rubinsztein-Dunlop.

Ben Eggleton is a leader in integrated nanophotonics and nonlinear optical physics and has made seminal contributions to the fields of optics, photonics and optical communications technology. He has made significant advances in nonlinear optics, waveguides, soliton physics, and fundamentals and applications of slow light. He has made important contributions to optical communications technology with applications to ultrafast and ultra-broadband and energy efficient information signal processing devices that are chip-based. He established and shaped the research directions of the highly successful Centre of Excellence, CUDOS, and is working on creating a revolutionary photonic chip. He received the 2011 Eureka Prize for Leadership in Science.

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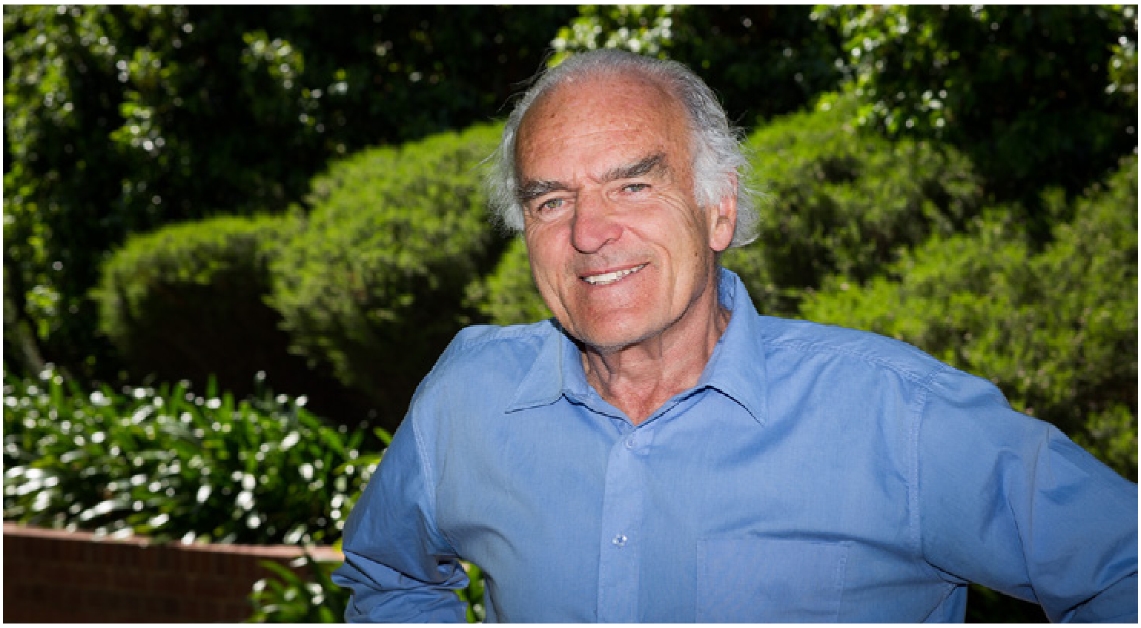
Professor Ben Eggleton.

Vale Professor John Love

Professor John Love passed away on 19 June 2016. He was surrounded by loving friends in Canberra hospital on his last day.

Born in England 2nd October 1942, John Love was a Life Member of the Australian Optical Society and winner of the prestigious Beattie Steel medal. His career in optics and photonics began when he arrived in Australia in 1973. Over the following forty plus years he made a major impact on the field. He is widely known for the definitive textbook, Optical Waveguide Theory, with 5500 citations and translated into Russian and Chinese. John was an enthusiastic champion of many important research and educational initiatives in Australia, including being a stalwart of the ACOFT conference, the world's second longest running photonics conference. He also leaves a much more direct and personal impact on the very many students and young academics he mentored, who will remember him with love and respect, especially for how generous he was with his time and knowledge.


Professor John Love. Photo by kind permission of the Australian National University.

Fibre Sensors for Chemical and Medical Sensing – New Tools for Old Problems

by Erik Schartner

New applications are guiding the development of upcoming optical fibre sensors, aiming to better understand the complex biological processes within the body.

Introduction

In recent years, optical fibres have expanded beyond their typical use in communications, to alternate applications in active devices and sensors. While the majority of the work in this field has focused on the development of structural health monitoring tools for civil engineering and aviation, an ever increasing interest has developed in the use of optical fibres for both chemical and biosensing applications.

The unique guiding properties of optical fibres, combined with the ability to use them in previously inaccessible locations has allowed for the use of these fibres in widely varied applications. By adding functionality to the fibre, typically through the use of a fluorophore layer or resonant feature, the fibre can be sensitised to a particular parameter such as temperature, pH or chemical concentrations.

There are a number of methods that can be employed for the sensing of these parameters. The suitability of a particular method generally relies on a range of parameters, such as the need for point or distributed measurements, the type of sample being measured, and the maximum size of the sensing element.

Sensors can be created either to be sensitive at the end face of the fibre, as a tip sensor, or alternatively the signal can be integrated/interrogated along the fibre's length. Generally, tip sensors are fabricated from the more standard core/clad optical fibres, where the interaction of the light with the sensing occurs entirely at the end face. Fibres used for these applications can range from single mode fibres, with cores as small as 2-3 µm, through to large diameter (>500 µm) multi-mode fibres which act to increase the signal collection efficiency by increasing the interaction area at the tip.

For sensing along the length of the fibre, the range of potential fibre geometries expands considerably. Initial work in this field began by removing a portion of the cladding, creating what's commonly referred to as a "D fibre". This allows a portion of the guided mode, known as the evanescent field, to interact with the surrounding medium. While the strength of this evanescent interaction was extremely limited in these initial demonstrations, it was sufficient to demonstrate that these fibres had potential for measurements of properties such as the absorption of gases or emissions from fluorescent molecules.

Tapering of fibres was also investigated as a potential for sensing, as tapering allows for the evanescent interaction to be enhanced, such that at extreme tapering levels the majority of the guided mode exists as an evanescent field, available for interaction with the surrounding medium. While these tapers allow for a large interaction, they are limited both in the possible length that can be made, and the practicality of handling a fibre of such small dimensions that can easily be degraded or destroyed by dust or physical contact.

Microstructured Optical Fibres

Over the past two decades microstructured optical fibres (MOFs) have evolved to present a strong alternative to the conventional core-clad optical fibres for sensing applications. These fibres possess a complex transverse structure, which can be controlled to allow for modifications to the guidance properties of the fibre. Initially these fibres were based on a photonic crystal structure, where the cladding consisted of an array of small air holes, giving an effective cladding index between that of the pure silica and air. These fibres did show some prospects for sensing applications, however the small size of the air holes somewhat restricted the practical applications of the fibres.

Later developments allowed for the realisation of hollow-core structures, in which the fibre is designed such that the

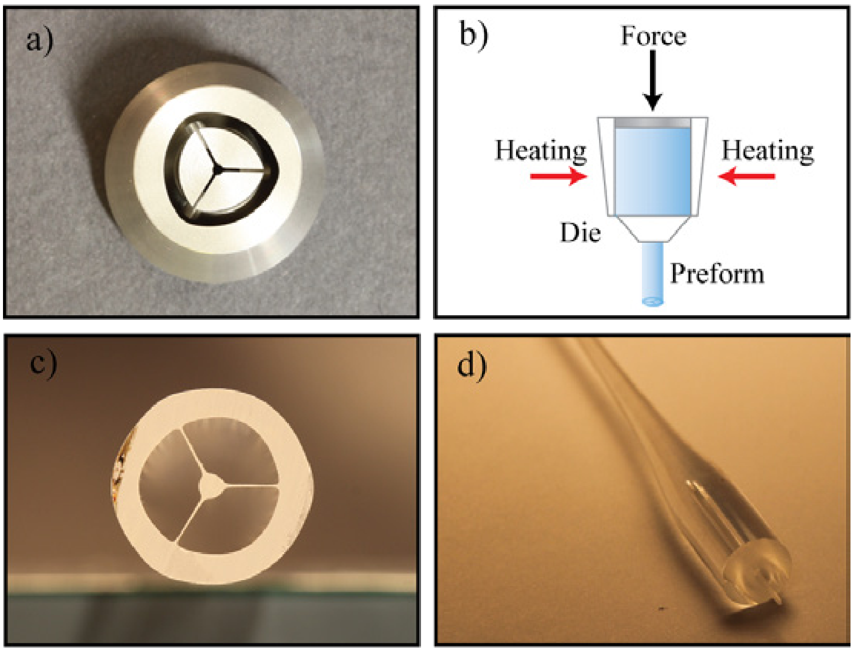


Figure 1. Schematic of the extrusion process for the fabrication of MOFs. A glass billet is heated and forced through an extrusion die (a,b), producing a preform (c) that is effectively the inverse of the initial die structure. For small core structures the preform is caned and inserted into an outer jacket (d) to increase the strength of the fibre.

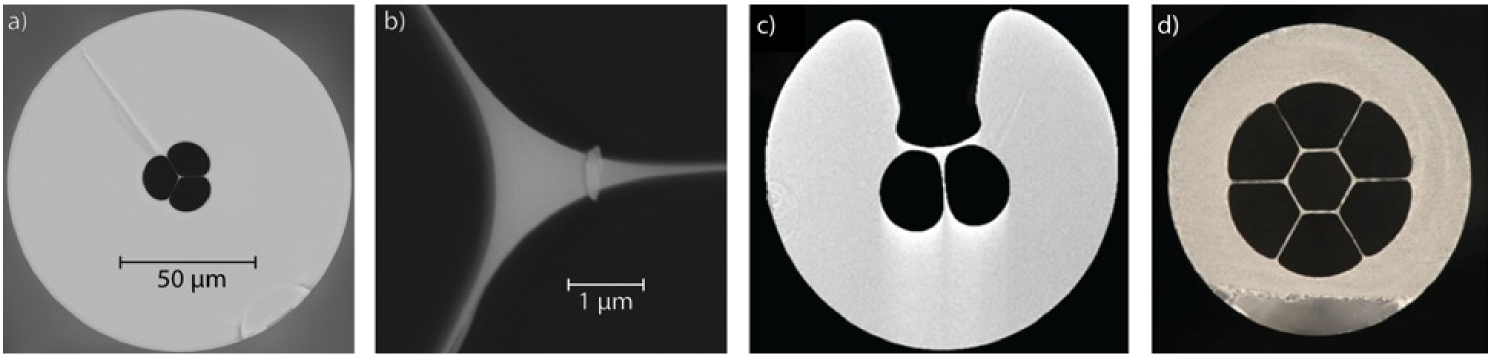


Figure 2. MOF structures. (a,b) Soft glass SCF (c) Silica ECF (d) Soft glass HCF

mode is confined to the air region at the centre of the fibre. As such, the guided light has effectively a 100% overlap with gases or media within the central hole, allowing for large improvements in sensitivity. Early bandgap fibres showed a restricted bandwidth over which they transmitted light with low-loss, with later developments in non-bandgap air-guiding fibres such as Kagome fibres allowing for broadband transmission.

An alternative to this geometry, the suspended core fibre (SCF), which is conceptually somewhat similar to tapered fibres has found extensive use for sensing applications. This fibre can be thought of as a suspended nanowire structure, where the central core region in which the light is guided is supported by a web of surrounding struts inside a robust outer jacket. This jacket allows the fibre to be handled much like a conventional telecoms fibre, while the small core and surrounding ring of air holes allow for a controlled interaction of the evanescent field with analytes filled within the holes of the fibre. Modifying the fibre geometry to open up one of the holes along the length of the fibre, creating an exposed core fibre (ECF) then allows for interaction between the guided mode and the environment along the entire length of the fibre. This can then be employed either for distributed sensing, to identify where along the length of the fibre an interaction is occurring, or to greatly increase response speed as the fibre holes do not need to be filled for a measurement to be performed.

Fabrication

Various methods for the fabrication of MOFs have been explored to create the widely varied structures that are in use today for sensing applications. These include stacking, in which an array of thin rods or tubes is assembled into a macroscopic version of the desired final structure that can then be drawn down to fibre on a drawing tower. Drilling directly into the glass rod has also found use for fabrication of MOFs, where an ultrasonic drill is employed to directly drill holes into a solid rod. Both of these methods are somewhat limited in the final geometries that can be created, as generally only circular features are possible, either by stacking cylindrical rods/tubes, or by drilling circular holes. Stacking generally can produce more complex structures, with longer preform lengths than drilled preforms, however the process is time consuming compared to the relatively automated drilling method.

An alternative to these methods is called the extrusion technique, in which the almost arbitrary features can be fabricated in the initial preform in a single step. This technique involves first fabricating a metal or ceramic die, with approximately the final structure on the output face of the die. This geometry is essentially a scaled-up version of the final desired geometry, typically with a diameter of 10-20 mm. The glass billet is then heated beyond its softening point, and forced through the die. By controlling the temperature and the force during this process, the emergent preform displays uniform dimensions along its length, and can then be pulled down into fibre using standard methods.

Fluorescence sensing

Previous work with SCFs has primarily looked at sensing for various chemicals through the use of fluorescent dyes. The fluorophore is chosen to react with the desired target of interest, and when it does so it either results in an increase or decrease in the fluorescent signal. By monitoring the change in the fluorescence, the detected signal intensity can then be correlated to the quantity of the chemical present.

These fluorophores can be combined with the suspended core fibres either by directly filling the mixed solution into

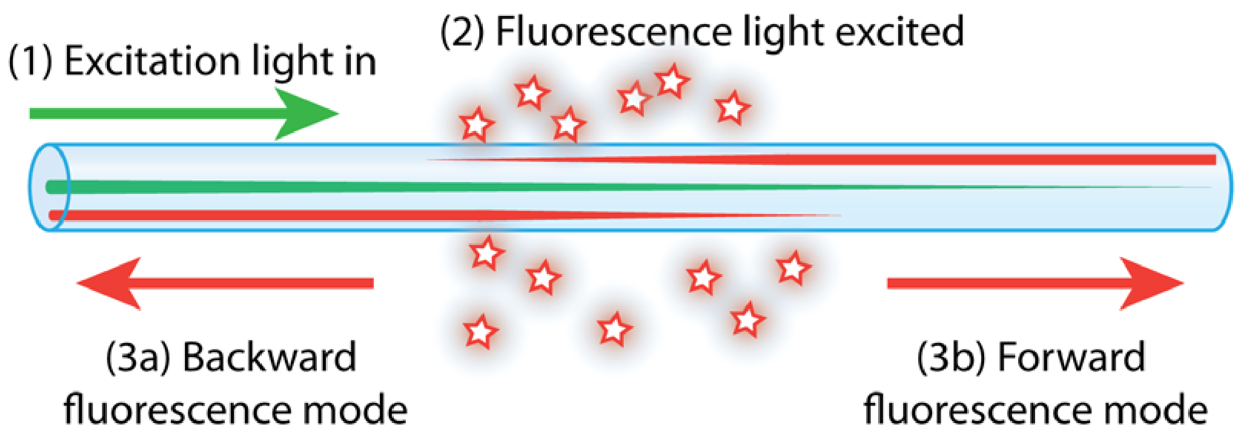


Figure 3. Schematic of fluorescence sensing using MOFs. The excitation light is guided along the fibre core (1), and interacts with fluorescent molecules filled within the holes (2). A portion of this light is then captured into both a forward (3a) and backward (3b) propagating mode within the fibre for detection at either end.

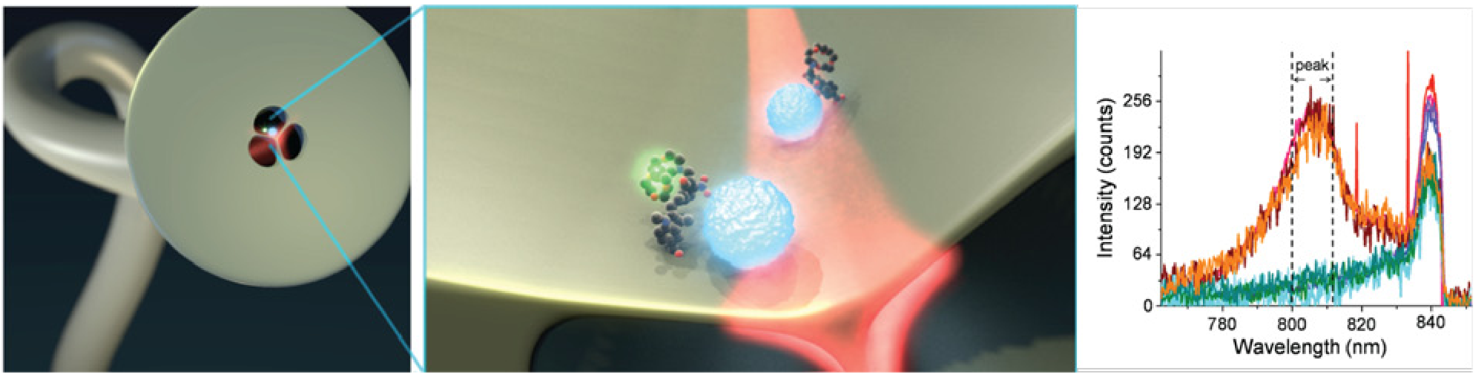


Figure 4. Upconversion nanocrystals within a SCF, and the fluorescence signal resulting from the detection of individual nanocrystals within the fibre.

the voids along the length of the fibre, or alternatively by attaching the fluorophore to the internal walls of the fibre using covalent or electrostatic functionalisation methods. This newly functionalised fibre can then be dipped directly into the sample, which then fills up the length of the fibre via capillary action. Biosensing can be performed through a similar method, in which fluorophores are attached to antibodies then used as fluorescent labels.

Work using organic dyes is typically limited in sensitivity, as one of the primary advantages of the SCFs, in their small sampling volume, also leads to an inherent weakness in photobleaching rates. The high intensity of the excitation light, and the lack of diffusion within the holes acts to rapidly bleach the fluorescence signal. In recent years there has been considerable interest in the development of alternative labels to standard organic dyes which circumvent many of the issues faced with traditional dyes.

Filling the fibres with quantum dot (Qdot) labels allows for the effects of photobleaching to be minimised, with background signals from the glass becoming the primary limitation for sensitivity. Replacing the Qdot labels with upconversion nanoparticles allows for the sensitivity to be further improved, with single particle detection possible from the combination of high emission intensity, and virtually zero background signal from the fibre. These nanocrystals, doped with rare earth ions such as erbium, thulium or ytterbium can be excited using near-infrared sources, and produce visible light through upconversion processes. By carefully controlling the synthesis process these nanocrystals can be fabricated with a uniform size distribution, and through further processing can then be attached to antibodies for use as fluorescent labels.

One interesting application of these fibres involves their use for detection of gold nanoparticles within liquid samples, which is important in mining. Conventional methods rely on complex lab-based readings, and by examining either the direct absorption of gold nanoparticles within the fibre, or through the use of a fluorescent dye, the levels of gold within samples can be observed using a comparatively simple measurement technique.

Another example using SCFs is in fertility applications. For conditions such as endometriosis various parameters have been shown to be linked in laboratory studies with unexplained infertility, however there is currently no reliable method for measuring these in real world samples. SCFs have been shown to be useful for enzyme activity assays, where they have been able to detect the enzyme PC6 down to 50 U/mL using a sample size of 210 nL. This is particularly important for potential *in vivo* applications, where the difficulty of removing larger samples restricts the total available volume, leading to a particular advantage in using MOFs for these applications.

While SCFs show a high signal collection efficiency allowing extremely sensitive measurements to be performed, they are also somewhat limited as the fibre needs to fill with the analyte before measurements can be performed. As previously mentioned this can be avoided through the use of an ECF, but if a particular application requires measurements to be performed at a specific spatial location then a fibre optic tip sensor presents an ideal solution. Attachment of a single layer of fluorophores through covalent or electrostatic attachment produces only a small fluorescence signal, so methods to increase the available signal have been explored in detail.

One such method involves deposition

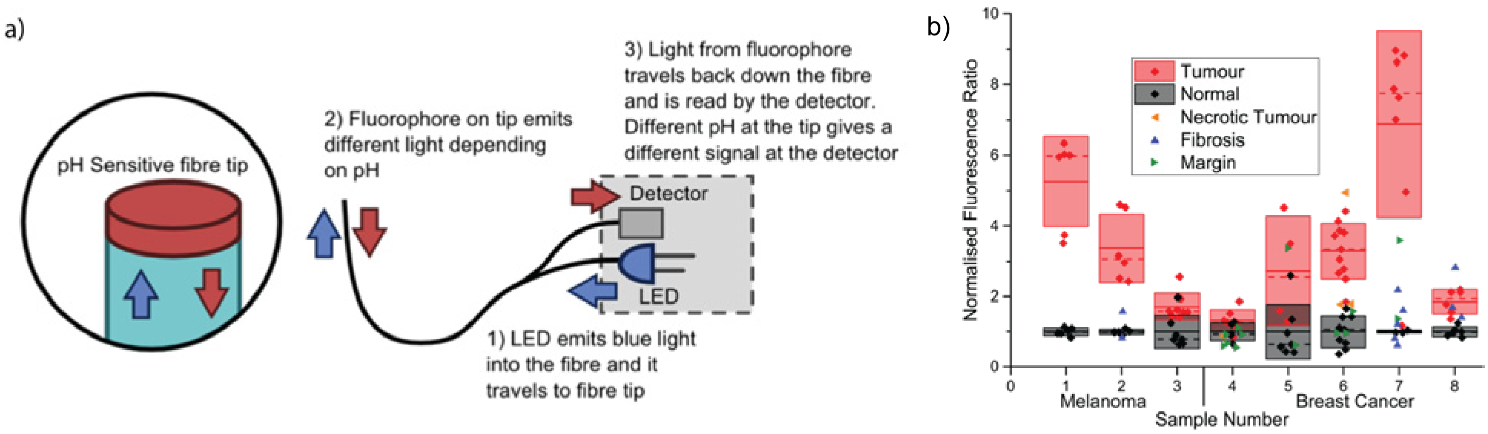


Figure 5. a) Method for margin detection in human cancer samples using an optical fibre tip (b) Results for the use of the probe across eight human tissue samples, covering both breast cancer and melanoma.

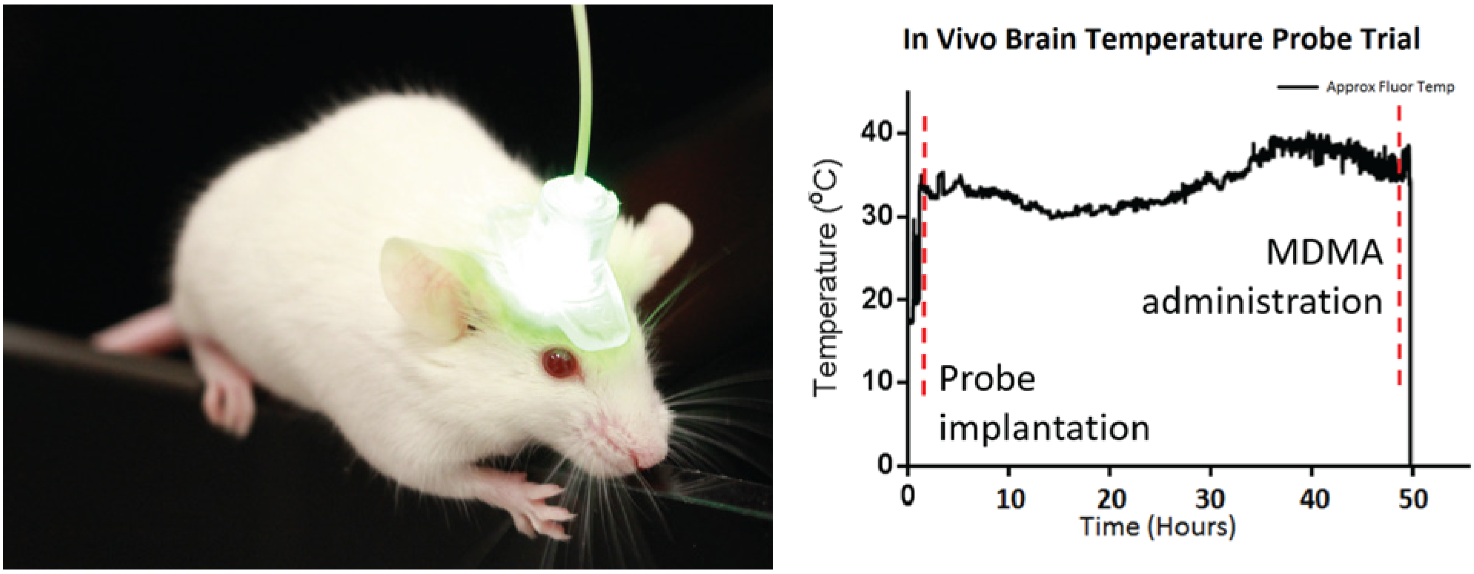


Figure 6. In-vivo data collected during MDMA administration of brain temperature in an ambulatory mouse

of a polyacrylamide layer on the tip of the fibre that has the desired fluorophore embedded within the polymer matrix. Since the quantity of fluorophores on the tip can be varied by changing the thickness of the polymer layer the sensors can be rapidly optimised for a given application. Multiple fluorophores can even be embedded within the polymer, allowing for several parameters to be measured with a single fibre simply through the use of multiple excitation wavelengths. Using this method, a sensor for both hydrogen peroxide and the pH of a solution has been fabricated, which has strong potential for applications in embryology.

An interesting application that is being explored with tip sensors based on this method is in oncology, to identify cancerous tissue. By embedding a pH indicator with the polymer coating, the fibre sensor was able to rapidly identify the pH of the surface of an excised human tissue sample. Comparisons between the results from the probe and post-operative pathology measurements showed that simply by observing the pH of the sample the tissue type could be accurately identified in >90% of measurements. This has strong potential for intraoperative use in breast cancer cases, where limitations in current methods result in up to 20% of patients requiring an additional follow-up surgery. Using the probe during surgery could give an indication to the surgeon that cancerous tissue remains within the tumour cavity, necessitating the removal of additional tissue to ensure that the entire tumour is removed in the initial surgery.

Tip sensors have also found use for in-vivo measurements of brain temperature for medical research applications. A thin layer of rare earth doped tellurite glass is deposited on the end of an optical fibre by dipping the tip into the glass melt. The temperature of the fibre tip can be measured by observing the ratio of two upconversion emission bands. This method gives precise measurements of temperature, and as it relies on upconversion emission is virtually insensitive to autofluorescence which commonly presents issues for in-vivo measurements.

Summary

These examples show the strong potential over the coming years of fibre sensors for chemical and medical sensing applications. Further developments in surface chemistry and fabrication techniques will allow for the scope of these applications to be broadened, while improvements to the practicality of the measurement systems will enable the use of these technologies outside of conventional optics laboratories. Using these fibres in medical research will hopefully allow for new parameters to be measured, increasing our understanding of complex biological processes within the body.

References

[1] MR Henderson et al., SPIE Optics+ Optoelectronics, (pp. 950611-950611) 2015.

[2] MS Purdey et al., Sensors 15.12 (2015): 31904-31913.

[3] EP Schartner et al., International Journal of Applied Glass Science 6.3 (2015): 229-239.

[4] S Musolino et al., *A portable optical fiber probe for in vivo brain temperature measurements*, Optics Express (2016) In press

[5] J Zhao et al., Nature nanotechnology 8.10 (2013): 729-734.

[6] A Zuber et al., Sensors and Actuators B: Chemical 227 (2016): 117-127.

Erik Schartner is with the Centre for Nanoscale BioPhotonics, University of Adelaide.

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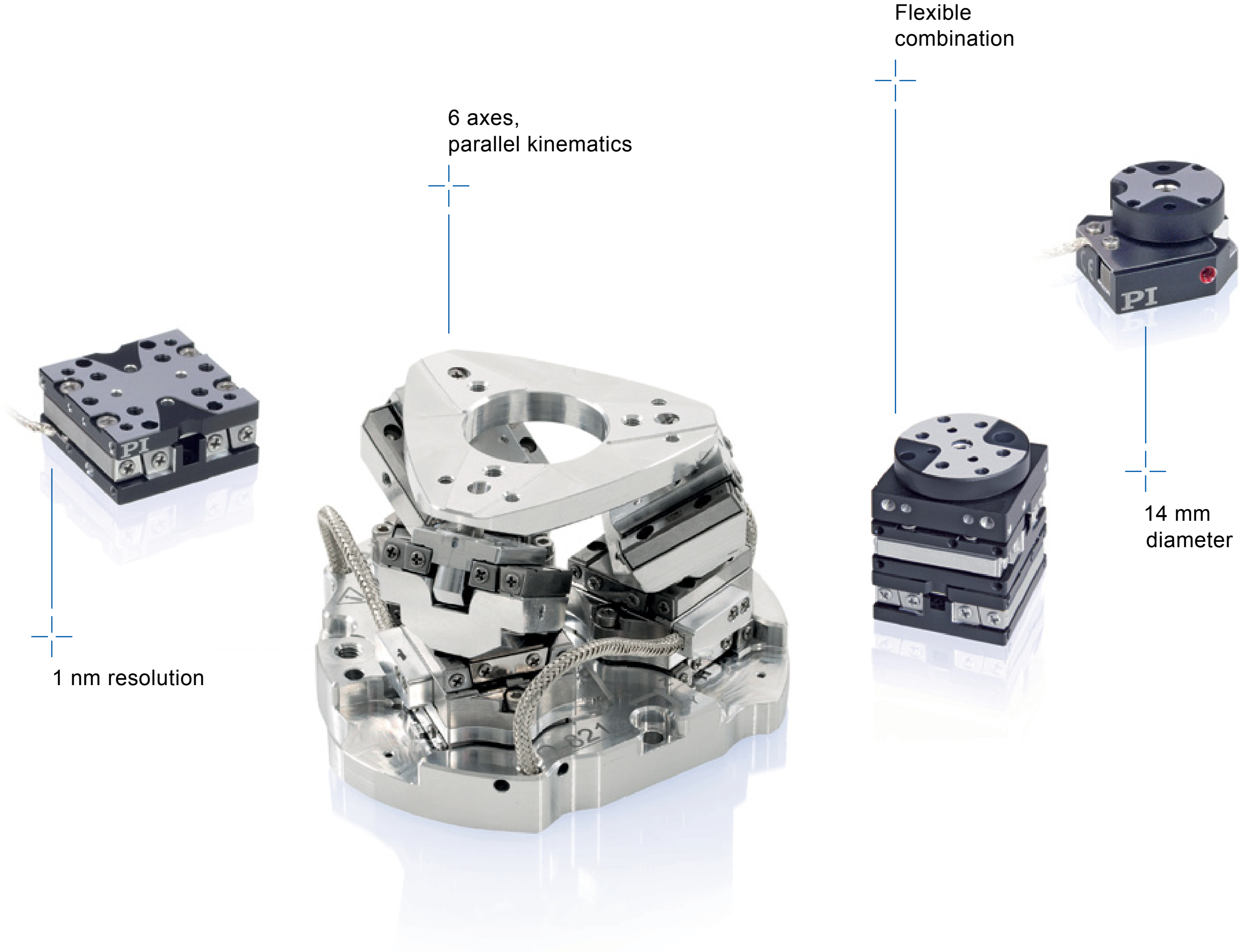

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MOTION | POSITIONING

The Quantum Microscope

by Marcus W Doherty

The quantum microscope represents the next microscopy paradigm where controlled quantum probes are used to directly image the quantum nature of matter at the scale of individual molecules and atoms. Optical defects in diamond are leading the development of quantum microscopes and have already found impressive applications in fields such as cellular biology, nanomaterials and single-molecule nuclear magnetic resonance spectroscopy. The author is the recipient of the 2015 Geoff Opat Early Career Award.

Introduction

The invention of the optical microscope in the 17th century provided the first window into the hidden microscopic world that surrounds us all [1]. It enabled early scientists to discover that plants and animals were composed of tiny cells and, in doing so, created microbiology and revolutionised medicine. However, there was essentially no fundamental change to the microscope until the invention of the electron microscope at the beginning of the 20th century [2]. This was stimulated by the discovery of wave-particle duality; that electrons can behave like visible light waves, although with much shorter wavelengths. As per Abbe's diffraction limit, this reduction in wavelength allows electron microscopes to resolve much smaller objects, which led to the first images of molecules, bacteria and viruses. The third fundamental change to the microscope occurred in the 1980s with the invention of the scanning probe/atomic force microscope (AFM) [3]. Unlike the electron and optical microscopes, the AFM does not involve waves, but instead scans a very sharp mechanical probe to measure forces with nanometre resolution. Different probes can be chosen to image the forces produced by different sample properties (i.e. electric and magnetic). This additional information provided by the AFM has particularly advanced material science and nanotechnology.

It is clear that each fundamental advance in microscopes over the centuries has enabled smaller objects or different properties of objects to be viewed. The ultimate end to this progression is the invention of a microscope that provides a window into the quantum world of individual molecules, atoms and elementary particles. In this world, the 'classical' laws of physics that appear to govern our everyday lives are replaced by strange 'quantum' laws, which seemingly allow particles to be in two places at once (i.e. superposition) and act upon each other from a distance (i.e. entanglement), but also constrain our knowledge of the particles at any one instance (i.e. Heisenberg's uncertainty principle). To view this strange world, the microscope must itself behave according to the quantum laws. This realisation led to the invention of the quantum microscope at the beginning of the 21st century [4, 5].

The quantum microscope uses a quantum object as a probe. The probe may be scanned over, embedded in or assembled into an array underneath the sample. The demands on the probe are that it is sensitive to the properties of the sample and that its quantum state can be prepared, manipulated and measured with high precision. The probe can be an atom or molecule or similar system. Thus far it has been found that atom-sized defects in diamond make the most versatile probes [6-15]. These defects behave like molecules, but with the advantages that they can be engineered into diverse microscope structures and are sufficiently robust to operate in a wide range of conditions. As a consequence, there are amassing international efforts to design and build diamond quantum microscopes to solve major questions in science.

The purpose of this article is to provide a timely brief to the multidisciplinary Australian Optics community on the development of quantum microscopy. I first outline the design and operating principles of diamond quantum microscopes. I then highlight recent microscopy achievements before proposing several new directions and opportunities for quantum microscopy. I finally identify what I perceive as the major challenges that face quantum microscopy and its adoption by the wider scientific community.

Quantum microscopy with diamond defects

The NV centre in diamond The negatively-charged nitrogen-vacancy (NV) centre [16] is the main diamond defect in current use. It consists of a substitutional nitrogen atom adjacent to a carbon vacancy in the diamond lattice (see figure 1). The NV centre occurs in natural diamonds, but can also be created in synthetic diamonds using either nitrogen ion implantation or the introduction of nitrogen during crystal growth. The NV centre is distinguished by three key properties: (1) bright fluorescence, which enables single centres to be optically detected with diffraction-limited resolution; (2) a mechanism of optical spin polarisation and readout, which enables high-fidelity initialisation and measurement of the centre's spin state; and, (3) long-lived ground state spin coherence (longest of any solid state spin at room temperature), which enables

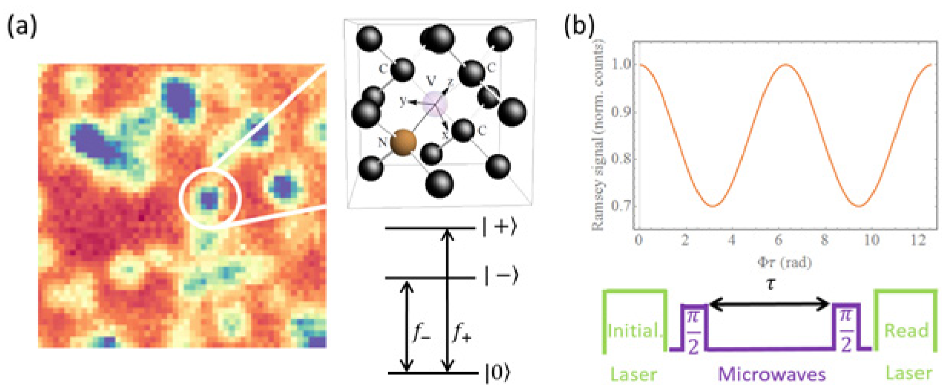


Figure 1. (a) left - confocal image of NV centres in diamond (courtesy of M. Barson), upper right - the NV centre structure and coordinate system, lower right - electronic ground state fine structure and spin resonances. (b) Ramsey interferometry pulse sequence and signal as described in the text.

small changes in its spin resonances to be spectrally resolved. Thus, the spin of the NV centre presents as an ideal optically addressable quantum probe.

The NV centre's spin resonances are susceptible to various quantities in addition to magnetic fields, including electric fields, temperature and mechanical stress/strain [16]. This is the case because the NV centre's ground state is a spin-triplet (S=1), rather than a simple spin-doublet (S=½), and these other quantities modifying the triplet spin-spin interactions. A static bias magnetic field can be used to selectively condition the spin resonances to the desired sensing mode [17]. For a B_Z bias magnetic field, the spin resonances $f_\pm = D + k_\parallel \delta E_Z \pm \gamma_e (B_Z + \delta B_Z)$ are most sensitive to the perturbing magnetic field δB_Z, where D = 2.87 GHz is the zero-field spin-spin interaction, γ_e is the electron gyromagnetic ratio, δE_Z is the axial component of the perturbing electric field or effective electric field induced by mechanical stress/strain, and $k_\parallel$ is the corresponding ground state electric susceptibility parameter. For a bias field aligned in the transverse plane, the resonances become linearly dependent on $\delta\vec{E}$, $f_\pm = D + A_\pm + k_\parallel \delta E_Z \pm k_\perp[\delta E_X \cos 2\phi_B - \delta E_y \sin 2\phi_B]$, where $\tan\phi_B = B_y / B_x$ is the transverse orientation of the bias magnetic field, $A_\pm = (3 \pm 1)\,\gamma_e^2|\vec{B}|^2/2D$ only depends on the magnitude of the bias field and other parameters are defined similarly to before. Thus, by measuring one of the spin resonances at three different bias field orientations (e.g. ϕ_B = 0, $\pi/4$, $\pi/2$), each vector component of the electric field can be measured [8,17]. Vector magnetometry can be performed by either rotating the diamond or using multiple NV centres with different orientations to measure the same field [7].

Quantum sensing using the NV centre Quantum sensing is performed using the NV centre by repeating the following procedure until sufficient measurement statistics are accumulated [6]: (1) applying an optical pulse to initialise the spin in $|0\rangle$, (2) applying a sequence of microwave contol pulses that includes periods for the spin state to evolve under the influence of the environment, and (3) applying a second optical pulse to readout the final probability that the spin was in $|\pm\rangle$ or $|0\rangle$. The frequency of the microwave pulses is typically chosen to be near resonant with one of the spin resonances. The sequence of microwave pulses is chosen to filter the susceptibility of the spin resonance to a desired spectral band of the environment. Many of the pulse sequences employed have been long utilised in electron paramagnetic resonance (EPR) and nuclear magnetic resonance (NMR) spectroscopy [6].

The Ramsey interferometry sequence is the simplest example of a microwave pulse sequence [6]. It consists of two microwave $\pi/2$-pulses separated by a period τ of evolution subject to the environment (see figure 1). For the microwave frequency tuned to the f_- spin resonance, the first $\pi/2$-pulse creates the superposition state $1/\sqrt{2}(|0\rangle + |-\rangle)$ of $|0\rangle$ and $|-\rangle$. This state then evolves $1/\sqrt{2}(e^{-i\phi t/2}|0\rangle + e^{i\phi t/2}|-\rangle)$ subject to the environment, such that $|0\rangle$ and $|-\rangle$ accumulate a relative phase $\phi = 1/\tau \int_0^\tau \delta f_-(t)\, dt$, where $\delta f_-(t)$ is the environment's perturbation of the spin resonance f_-. The second $\pi/2$-pulse projects the relative phase into a probability difference $\alpha \cos\phi\tau$ between $|0\rangle$ and $|-\rangle$. The readout optical pulse thereby provides a measure of the probability difference, and thus ϕ for a known τ. A Fourier transform allows the phase $\phi = \int_{-\infty}^{\infty} \delta f_-(v) F(v)\, dv$ to be interpreted in terms of the spectrum $\delta f_-(v)$ of the interactions with the environment and the spectral filter function $F(v) \propto \mathrm{sinc}\, v\tau$ of the Ramsey sequence. The latter is broad band, spanning DC to AC frequencies $\sim 1/\tau$. More complicated microwave pulse sequences (e.g. Hahn-echo, CPMG, XY8 etc) have filter functions that can be tailored to be narrow band at desired frequencies in order to provide better spectral filtering/resolution. The minimum spectral width is limited to $\sim 1/T_c$ by the relevant spin coherence time T_c.

The coherence time also limits the minimum detectable frequency shift $\delta f_-^{min} \approx (T_c\sqrt{CN_{ph}N_m})^{-1}$ after a total of N_m measurement repetitions, where $C \approx 1/3$ is the NV centre's optical spin readout contrast and $N_{ph} \approx 1/3$ is the mean number of emitted photons that are detected per measurement shot [6]. It follows that the minimum detectable change in a quantity δF (e.g. $\delta F = \delta B_Z$) is $\delta F_{min} = \left(\frac{d\delta f_-}{d\delta F}\right)^{-1} \delta f_-^{min}$, which may also be defined $\delta F_{min} = \eta_F/\sqrt{T}$ in terms of the sensitivity $\eta_F \approx \left(\frac{d\delta f_-}{d\delta F}\sqrt{CN_{ph}T_c}\right)^{-1}$ and the total measurement averaging time $T \approx N_m T_c$ [6]. Table 1 lists indicative sensitivities to different quantities together with physical examples, which demonstrate that the NV centre has sufficient sensitivity to probe various elementary systems at the nano/atomic scale.

From sensing to imaging To go from sensing at a single atomic-sized location to imaging over a wide field, the NV centre must be incorporated into a microscope architecture. There are four main architectures (see figure 2): (1) fluorescent tracking of nanodiamonds distributed into/on the surface of a sample [10,11], (2) wide-field imaging of an array of NV centres in a diamond chip [7], (3) scanning a diamond nanoprobe containing an NV centre [12,13], and (4) magnetic resonance imaging (MRI) using a proximal NV centre for detection [14,15]. The choice of architecture is largely determined by the nature of the sample to be imaged and the desired measurement. For example, fluorescent tracking of nanodiamonds is more suited to biological applications, whereas scanning probe microscopy is more suited to nanomaterials.

Quantity	DC (AC) sensitivity	Example
Electric field	20 (2) $\frac{mV}{\mu m}/\sqrt{Hz}$	Static elementary charge at a distance of ~120 nm. Fluctuating molecular electric dipole (1 Debye) at a distance of ~15 nm.
Magnetic field	110 (11) nT/√Hz	Static electron spin at a distance of ~25 nm. Fluctuating proton spin at a distance of ~7 nm.
Temperature	40 (4) mK/√Hz	Temperature variations inside living cells.
Force	300 (30) pN/√Hz	Force applied by a living cell during migration.

Table 1. Indicative sensitivities of the NV centre to different quantities, including examples of nano/atomic scale systems that can be detected after 1 second of measurement. Force estimates correspond to the response of an NV centre located at the base of a 0.1×0.1×1 μm diamond nanopillar when a force is applied to the pillar's tip.

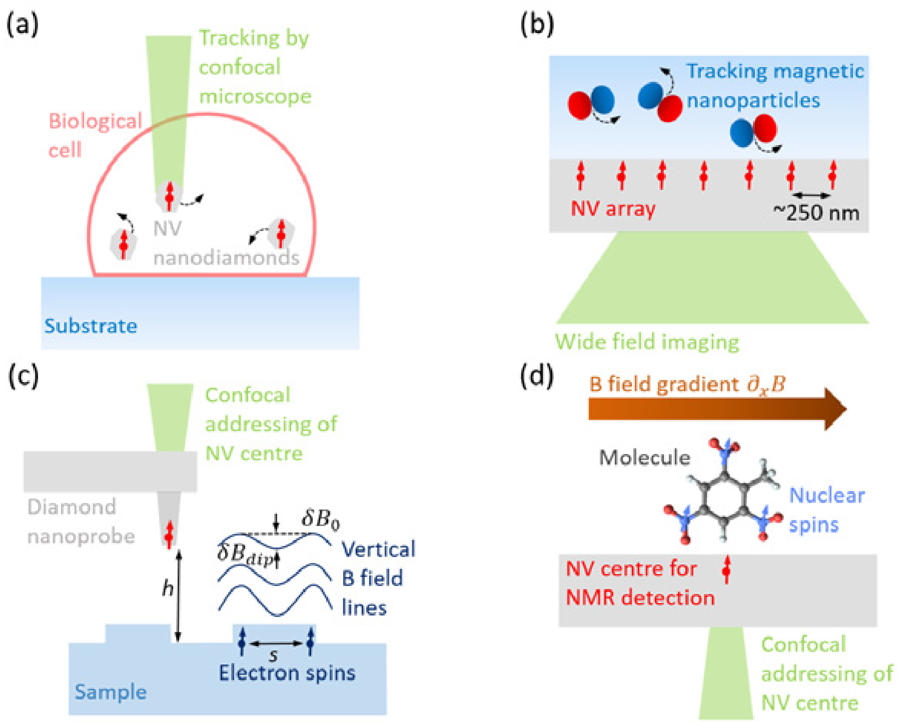


Figure 2. Example quantum microscopy architectures: (a) fluorescent nanodiamond tracking, (b) tracking magnetic nanoparticles via wide-field imaging of an array of NV centres, (c) scanning diamond nanoprobe, and (d) MRI using a proximal NV centre. (c) also depicts the example of geometry-limited resolution that is described in the text.

The spatial resolution of the architecture depends on the implementation and the *a priori* knowledge of the sample. Without the application of optical super-resolution techniques, like STED [18], the spatial resolution of fluorescent tracking of nanodiamonds and the wide-field imaging of NV arrays is limited by the standard optical diffraction limit to ~250 nm. With the addition of optical super-resolution techniques, these architectures join the scanning probe architecture in being limited by the geometry of the interactions between the sample and the NV centre. For example, consider an NV centre scanned at a height h above two identical and coplanar electron spins in a sample (see figure 2c). The criterion for spatially distinguishing the two spins is that the depth of the central dip δB_{dip} of the net vertical magnetic field produced by the two spins must be greater than the minimum detectable change in magnetic field $\delta B_{min} = \eta_B \sqrt{T} < \delta B_{dip}$, after a given measurement time at each step in probe position (assuming step size is smaller than the separation of the spins). For this criterion, the minimum detectable separation of the spins, and thus resolution, is $s_{min} \approx h(\delta B_{min} / \delta B_0)^{½}$, where δB_0 is the net vertical magnetic field directly above one of the spins. Hence, the height h between the NV centre and the spins principally determines the spatial resolution and is ultimately limited by how small nanodiamonds, nanoprobes and array depths can be made before the NV centre's properties (i.e. η_B) degrade due to surface induced charge, noise or chemical instabilities. Current fabrication experience suggests that the minimum size is $h_{min} \approx 5$ nm, which for electron spins corresponds to a spatial resolution of $h_{min} \approx 3$ Å for 1 second of measurement at each position step.

This geometric limit to resolution is surpassed by the fourth architecture by applying the principles of MRI. Given the known gyromagnetic ratios of nuclei γ_n, a bias magnetic field gradient $\partial_x B$ or rotation of magnetic field can be used to spatially distinguish nuclei by detecting their spin resonances using a proximal NV centre [14,15]. In which case, the spatial resolution is limited to $x_{min} \approx \Delta f_{NMR} (\gamma_n \, \partial_x B)^{-1}$, where Δf_{NMR} is the NMR spectral resolution as obtained by the NV centre for the adopted microwave pulse sequence. The field gradients ($\partial_x B \approx 0.1$ mT/μm) and NMR spectral resolutions ($\Delta f_{NMR} \approx 1$ kHz) that have been demonstrated [14,15] to date are insufficient to spatially distinguish nuclear spins in a single molecule. However, it is foreseeable that advances in magnetic microstructure fabrication will provide three orders of magnitude larger field gradients, in which case, the resolution of nuclei will approach the ultimate goal of a single molecular bond length ≈1 Å.

Recent highlights in quantum microscopy

Out of the many recent advances, the following three specifically highlight each of the microscopy architectures as well as the diversity of their applications.

Tracking and thermometry within living cells The positions and rotations (relative to a bias magnetic field) of nanodiamonds containing NV centres have been fluorescently tracked inside living cells [10]. Since nanodiamonds can be functionalised, nanodiamond tracking provides information about cellular processes. However, the distinct advantage of NV nanodiamonds over many competing biomarkers is rather their ability to combine tracking with *in situ* sensing. A remarkable realisation of this potential was the combining of NV nanodiamonds with gold nanoparticles to respectively perform thermometry and laser heating within biological cells [11]. Such a combination could eventually be used for the *in vivo* identification and thermoablative therapy of malignant cells with minimal damage to surrounding tissue.

Imaging magnetic memories and superconducting vortices A scanning diamond nanoprobe has been used to image the nanoscale magnetic domains in racetrack magnetic memories [12] as well as the formation of magnetic vortices during superconducting phase transitions [13]. The images of domain wall dynamics provided new insight into their underlying mechanisms that will aid the advanced design of racetrack magnetic memories. The imaging of magnetic vortices demonstrated the capability of the scanning diamond nanoprobe to observe dynamic phenomena at cryogenic temperatures. Consequently, these measurements demonstrate the versatility of quantum microscopy to address topical questions in materials science and technology.

Towards MRI of single molecules The spin resonances of nuclei in single

molecules have been detected with chemical contrast by NV centres in a diamond substrate [14]. Magnetic field gradients have also been incorporated into microscope architectures to gain high spatial resolution [15]. Thus, it appears that soon, these two feats will be combined to perform MRI of single molecules as described above. This will have substantial implications for the study of complex molecules, such as those of interest to structural biology.

Future directions and possibilities

The current international focus is predominately on the applications I have described thus far. However, there are many other exciting possibilities for diamond quantum microscopes and I would like to take this opportunity to propose the three that I find most interesting and promising.

Unification with nanomechanical sensing Nanomechanical sensors are a technology that has been developing rapidly in parallel with quantum microscopes. Nanomechanical sensors have diverse interdisciplinary applications in biological and chemical analysis and microscopy. For example, nanomechanical sensors based upon nanoelectromechanical systems (NEMS) have demonstrated chip-scale mass spectrometry capable of detecting single biomolecules [19]. Since diamond is an extreme mechanical material, there is a clear opportunity to combine nanomechanical sensing and quantum microscopy in the form of diamond nanomechanical structures with embedded NV centres. This combination could yield an unrivalled chip-scale device capable of both mass spectrometry and magnetic resonance imaging of single molecules.

Imaging nanoelectronics and molecular polarisation To my knowledge, the NV centre is the only known electrometer capable of locating a single electron with nanometre resolution in ambient conditions [20]. Despite this unique capability, the nanoelectrometry applications of the centre are comparatively much less developed than its applications in nano-magnetometry and –thermometry. There is thus a clear opportunity to develop diamond quantum microscopes for unprecedented imaging of processes in nanoelectronics and, potentially, the electric polarisation fields of individual molecules. Polarisation fields govern molecular dynamics and their understanding is vital to unravelling complex chemical processes, such as the details of active sites of biomolecules.

High pressure science The behaviour of materials under high pressure is routinely investigated by applying pressure using a diamond anvil cell (DAC) and performing optical microscopy of the sample through the diamond anvils [9]. *In situ* sensing is difficult and any form of imaging is nearly impossible using existing techniques. An immediately apparent solution is to embed an array of NV centres into one of the diamond anvils and use the NV centres to perform *in situ* quantum microscopy. This has the potential to yield significant advances in the understanding of high pressure phenomena like superconducting and ferroelectric phase transitions.

Challenges ahead

The rapid development and application of quantum microscopy has been impressive. However, there are several challenges that must be met before the promise of a new microscopy paradigm can be fulfilled. I identify three of the challenges here.

Beyond the NV centre and diamond The success of the NV centre thus far can be primarily attributed to the simplicity and versatility of its implementation in quantum microscopy. There are no strong arguments that it is the optimum quantum probe and that there do not exist other systems with superior properties, or at least, superior properties for specific applications. For quantum microscopy to substantially advance, superior systems need to be discovered. Since the NV centre is one of the most extensively studied solid state defects, the substantial knowledge of the centre's structure and mechanisms can be used to guide the discovery of new defects or to engineer the enhancement of the NV centre.

Putting the 'quantum' in quantum microscopy Whilst the implementations I have described above employ quantum superposition, their sensitivity is still ultimately limited by classical shot noise. For a microscope to be truly 'quantum', it must use entanglement and quantum measurement protocols to surpass the classical limit. This entanglement can extend between multiple quantum probes or between the quantum probe and the sample. Furthermore, a quantum microscope should be able to interrogate the entanglement intrinsic to a sample. Generating entanglement between multiple systems is a challenge shared with the quantum computer. Consequently, I expect that advances in quantum computing and microscopy will be complementary in this respect.

Breaking out of the physics lab Most importantly, the quantum microscope is not an instrument for the self-gratification of physicists, but is one to aid advancement across science. The widespread adoption of quantum microscopy requires physicists to raise awareness by first engaging interdisciplinary scientists and identifying opportunities to service the solution of major disciplinary problems. The knowledge and apparatus of quantum microscopy will then need to be refined to enable transfer of the technology to other disciplines. As exemplified by the current implementations using the NV centre, the refined apparatus should seek to augment conventional microscopy equipment as much as possible, thereby reducing the barriers to transdisciplinary adoption.

Acknowledgments

I am sincerely honoured by the Geoff Opat Early Career Award and the AOS Committee's invitation to contribute to AOS News. I thank Prof Neil Manson and A/Prof Matthew Sellars for their excellent feedback and guidance on this article. I acknowledge funding support from the Australian Research Council (DP120102232 and DP140103862) and the DAAD-Go8 Cooperation Scheme.

References

[1] R Hooke, "*Micrographia*", (London: J Martyn and J Allestry, 1665).

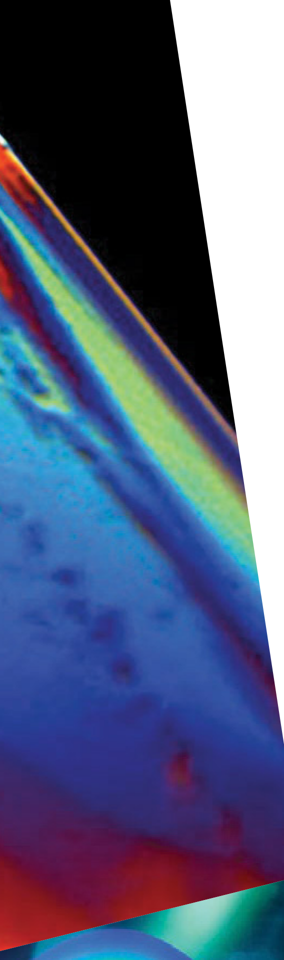
[2] E Ruska in "*Nobel Lectures: Physics 1981-1990*", Editor-in-Charge Tore Frängsmyr, Editor Gösta Ekspong, (Singapore: World Scientific Publishing Co., 1993).

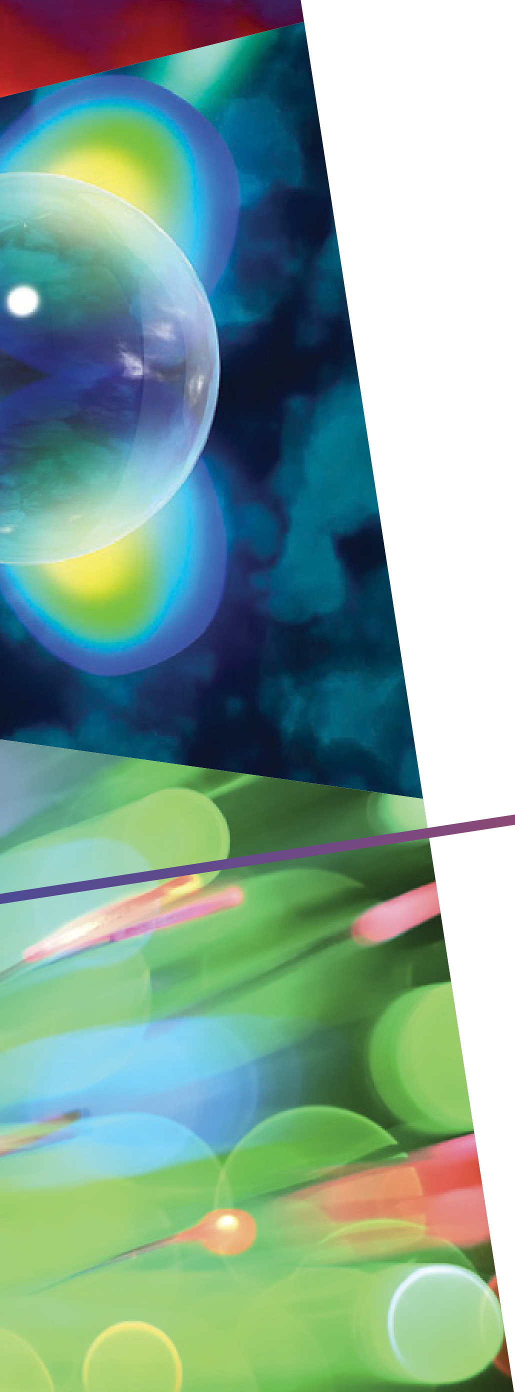
[3] G Binnig and H Rohrer, "*Scanning tunneling microscopy*", IBM Journal of Research and Development **30**, 355 (1986); G Binnig, CF Quate, C Gerber, "*Atomic-Force Microscope*", Phys. Rev. Lett. **56**, 930 (1986).

[4] BM Chernobrod and GP Berman, "*Spin microscope based on optically*

detected magnetic resonance", J. Appl. Phys. **97**, 014903 (2005).
[5] CL Degen, "*Scanning magnetic field microscope with a diamond single-spin sensor*", Appl. Phys. Lett. **92**, 243111 (2008).
[6] L Rondin, JP Tetienne, T Hingant, JF Roch, P Maletinsky and V Jacques, "*Magnetometry with nitrogen-vacancy defects in diamond*", Reports of Progress in Physics **77**, 056503 (2014).
[7] S Steinert et al, "*High sensitivity magnetic imaging using an array of spins in diamond*", Rev. Sci. Inst. **81**, 043705 (2010).
[8] F Dolde et al, "*Electric-field sensing using single diamond spins*", Nature Physics **7**, 459 (2011).
[9] MW Doherty et al, "*Electronic properties and metrology applications of the diamond NV−center under pressure*", Phys. Rev. Lett. **112**, 047601 (2014).
[10] LP McGuinness et al, "*Quantum measurement and orientation tracking of fluorescent nanodiamonds inside living cells*", Nature Nanotechnology **6**, 358 (2011).
[11] G Kucsko et al, "*Nanometre-scale thermometry in a living cell*", Nature **500**, 52 (2013).
[12] J-P Tetienne et al, "*Nanoscale imaging and control of domain-wall hopping with a nitrogen-vacancy center microscope*", Science **344**, 1366 (2014).
[13] L Thiel et al, "*Quantitative nanoscale vortex imaging using a cryogenic quantum magnetometer*", Nature Nanotechnology, DOI: 10.1038/NNANO.2016.63 (2016).
[14] T Häberle, D Schmid-Lorch, F Reinhard and J Wrachtrup, "*Nanoscale nuclear magnetic imaging with chemical contrast*", Nature Nanotechnology **10**, 125 (2015).
[15] K Arai et al, "*Fourier magnetic imaging with nanoscale resolution and compressed sensing speed-up using electronic spins in diamond*", Nature Nanotechnology **10**, 859 (2015).
[16] MW Doherty, NB Manson, P Delaney, F Jelezko, J Wrachtrup and LCL Hollenberg, "*The nitrogen-vacancy colour centre in diamond*", Phys. Rep. **528**, 1 (2013).
[17] MW Doherty, J Michl, F Dolde, I Jakobi, P Neumann, NB Manson and J Wrachtrup, "*Measuring the defect structure orientation of a single NV− centre in diamond*", New Journal of Physics **16**, 063067 (2014).
[18] E Rittweger, K Young Han, SE Irvine, C Eggeling and SW Hell, "*STED microscopy reveals crystal colour centres with nanometric resolution*", Nature Photonics **3**, 144 (2009).
[19] MS Hanay et al, "*Single-protein nanomechanical mass spectrometry in real time*", Nature Nanotechnology **7**, 602 (2012).
[20] F Dolde et al, "*Nanoscale detection of a single fundamental charge in ambient conditions using the NV− center in diamond*", Phys. Rev. Lett. **112**, 097603 (2014).

Dr Marcus W Doherty is with the Laser Physics Centre, Research School of Physics and Engineering, Australian National University.





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Optics in Everyday Life: Halo Around the Sun

by Tony Klein

Solar halos are one of the commonest phenomena of atmospheric optics – yet not many people have seen one, or know what causes it.

A rainbow around the Sun, often a complete circle but very commonly just a smaller segment, is visible all over the world but most commonly at higher latitudes, especially in Antarctica. It is caused by high-altitude cirrus clouds of ice crystals, all acting like 60-degree prisms of ice, more or less like the way in which rain droplets of water form rainbows, except that the reflection of sunlight on the back of water droplets result in rainbows having their centres at 42 and 51 degrees away from the anti-solar point, whereas solar halos are at 22 degrees (and sometimes 46 degrees) away from the Sun.

That's about a hand-span away from the centre, with the outstretched hand, so that with the thumb covering the Sun, the tip of the little finger will point at the halo – or just a piece of rainbow when the halo is not a complete ring. That, by the way, is the way to observe it, and it appears surprisingly often – if one knows where to look! Alternatively, better to look with an obstacle such as a lamp post or another person's head blocking out the Sun.

An ordinary camera, with a 45 degree field of view will just about be able to photograph a complete 22 degree halo, but the direct sunlight can produce a blinding image which could wreck a film camera. Better to put the Sun behind an obstacle, as described above – and in Figure 1. Halos are sometimes seen around the moon at night, also at 22 degrees, and one can then look directly into their centre, without one risking one's eyesight.

The simple cause of the 22 degree halo is a cloud of needle-shaped ice crystals pointing randomly in all directions, acting as 60-degree prisms, as shown in Figure 2, which also shows the much fainter 46 degree halo. Quantitative agreement with the refractive index and the dispersion of ice crystals confirms these observations.

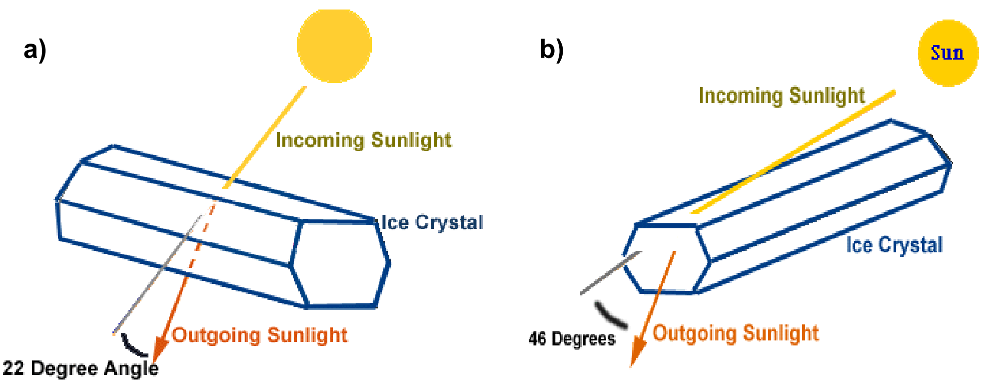
Tiny high-altitude snowflakes would produce the same effect. But sometimes the wispy, thin cirrus clouds contain platelet-shaped hexagonal ice crystals which tend to lie flat as they fall vertically. This produces bright spots of rainbow at 22 degrees from the Sun, in a horizontal plane as seen in Figure 3.

A somewhat rarer occurrence, they are called "Sun dogs" and one can see them if one knows where to look. (Usually when the Sun is low on the horizon. I happened to see a magnificent halo, with Sun dogs, driving home from Adelaide to Melbourne in the morning once, when one can't but help but look in the direction of the Sun!).

The fact that they are visible as "spots" rather than continuous horizontal lines is because they are what is known as "points of accumulation" as the refracted light is strongest at the extreme angle before the prism starts to produce total internal reflection. But there are other refractive effects to be seen, produced by other parts of ice crystals, e.g. from pyramidal ends of the hexagonal prisms and also from multiple reflections and refractions. They are harder to see because they are less bright. The place to see these beautiful

Figure 1. Solar halo in Corrientes, Argentina. Image credit: Juan Marcelo Coronel.

phenomena is where ice clouds are more abundant. A spectacular photograph of this is shown in Figure 4, taken at a higher latitude. More frequently such spectacles are seen in Antarctica (see figure 5). Their explanations and computer simulations are to be found in the wonderfully illustrated books in References 1 and 2.



c)

Figure 2. a) 22 degree halo b) 46 degree halo c) both halos. Images from the University of Illinois WW2010 Project.

Figure 3. "Sun dogs" in North Dakota. Image credit: Gopherboy6956

References

[1]Robet Greenler: "Rainbows Halos, and Glories" (CUP, 1980)

[2]M Minaert "The Nature of Light and Colour in the Open Air" (Dover, NY, 1954)

Emeritus Professor Tony Klein is a Foundation Member and Past President of the AOS. Tony is with the School of Physics, University of Melbourne.

Figure 4. Complex halo sometimes visible at high latitudes. Image credit: A. James Mallman.

Figure 5. Lora Koenig, of NASA's Goddard Space Flight Center, blocks the sun for a better view of a spectacular sundog on the West Antarctic Ice Sheet. Image credit: NASA/Lora Koenig.

Figure 6. Solar halo in Cordoso Island, Brazil. Image credit: Gustavo Asciutti.

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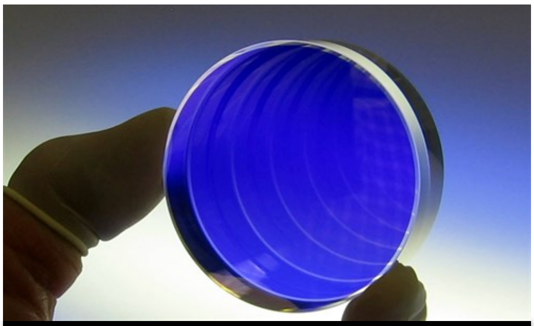

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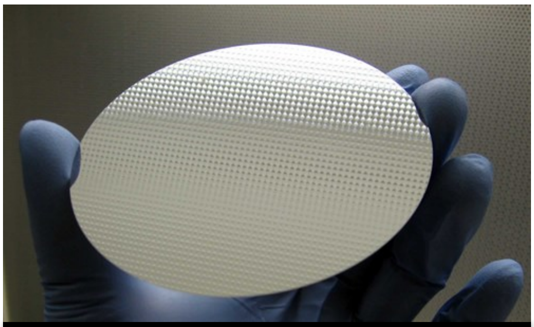

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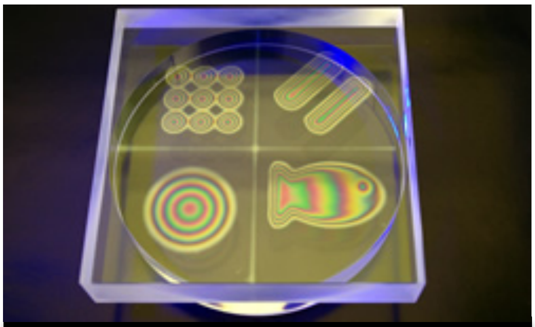

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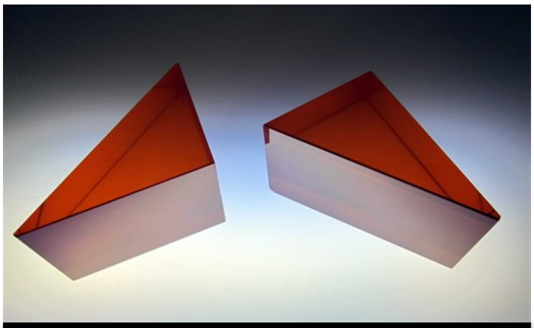
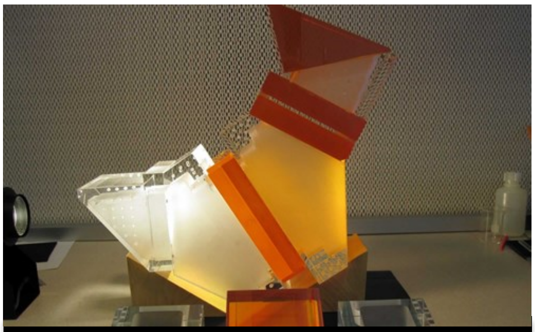


Zinc Selenide wedges for SWIFT, an IR doppler asymmetric spatial heterodyne Michelson interferometer for measuring upper atmospheric winds and ozone concentration. This is a very large, heavy instrument, the wedges are about 4" long.



This is the complete instrument prior to adding the last prism and the gratings.

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The OSA Photonics and Fiber Technology Congress will be held in Sydney from Monday 5 to Thursday 8 September 2016, consisting of The Bragg Gratings, Photosensitivity and Poling in Glass Waveguides (BGPP), Nonlinear Photonics (NP) and Australian Conference on Optical Fibre Technology (ACOFT) meetings. The congress covers multiple aspects of the latest results in the fields of data transfer and optical effects in guided wave optics and materials. Glasses play a central role in photonics; papers will be presented that cover many physical phenomena in glasses including the fundamentals of photosensitivity, glass relaxation and poling, the fabrication and properties of grating structures, and the numerous applications to which these glasses are being applied. osa.org/FiberandPhotonicsOPC

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Lens Design Cloud

Thin Film Cloud -This thin film coating design software is becoming very powerful with very fast optimization. Keep checking back for further enhancements

More Optical Design Tools

- **Dual Etalon Designer** -For when etalons don't quite cut it
- **Etalon Tuning** -How fast will my etalon peaks move with temperature? Also a useful chart view of material parameters.
- **Fizeau Wedge Designer** -A simple wedge interferometer, adjust the parameters and observe the expected output
- **Frequency Conversion** -Conversion for the various units of wavelength, frequency and energy
- **Fresnel Rhombs** -An unusual polarization component, the Fresnel Rhomb can act like a waveplate but works without birefingent materials.
- **Gaussian Beam Propagation** -Gaussian beam propagation through lens systems, this is a very useful and versatile tool for designing laser beam delivery systems
- **Grating Spectrometers** -LightMachinery does not manufacture grating based spectrometers but we thought this would be interesting to add so that performance can be compared to VIPA and etalon based spectrometers.
- **Laser Beam Shaper** -Design an aspheric surface to modify a gaussian beam into a top hat beam
- **Laser Resonators** -Adjust resonator parameters to determine mode size and stability
- **Index & Reflection** -A summary of material properties, index and Fresnel reflection at various angles
- **Percent vs dB** -Convert Percentage to dB (power or amplitude)
- **Simple Lens Designer** -A thick lens simulation gives a very nice approximation to actual lens performance at low angles
- **VIPA Designer** -VIPA etalons are becoming the new standard for hyperfine spectral analysis. This design tool allows users to investigate the properties of VIPA's (Check the user's guide as well)
- **Waveplate**

For more information please contact Raymax at info@raymax.com.au or 02 9979 7646

Scientific CMOS Cameras

Scientific CMOS (sCMOS) is a breakthrough technology that offers an advanced set of features making it ideal for high fidelity, quantitative scientific measurement. The multi-megapixel sensors offer a large field of view and high resolution, without compromising read noise, dynamic range or frame rate. Andor's Zyla and Neo cameras offer 4.2 and 5.5 megapixel formats with the following impressive specifications:

Peak QE: 82% (Zyla)
Read noise: 1e- (Neo)
Frame rate: 100fps at full resolution

These capabilities make sCMOS a compelling alternative to CCD cameras in many applications, especially as prices start below A$20,000.

We currently have a demonstration Zyla 4.2P camera available for trial in your lab. Please contact us to arrange a demo.

Compact Spectrometer with Automated Focus

Andor has released the Shamrock 193i compact spectrograph with Adaptive Focus Technology. This latest addition to Andor's portfolio of modular spectrographs complements their existing range of longer focal length Czerny-Turner, broadband Echelle and high throughput transmission spectrographs.

The new adaptive focusing automatically provides the best spectral resolution for any combination of grating, camera or wavelength range, with unmatched repeatability. The F/3.6 aperture, combined with Andor's range of ultra-sensitive CCD, ICCD, EMCCD and InGaAs detectors offers a "workhorse" spectroscopy platform with superb photon collection efficiency, ideal for challenging low-light applications or routine spectroscopy.

A wide range of accessories is available integrating the spectrograph with microscopes, optical fibre setups or other experiments.

We currently have a demonstration system available (with iDUS CCD detector) for trial in your lab. Please contact us to arrange a demo of this versatile and affordable system!

Energetiq – The Innovators in Light

Coherent Scientific is pleased to announce it is now distributing Energetiq's products throughout Australia and New Zealand. Energetiq is a developer and manufacturer of advanced light sources that enable the manufacture and analysis of nano-scale structures and products. Used in complex scientific and engineering applications, Energetiq's light products are based on new technology that generates high brightness and high power light in the 170nm to 2100nm range with high reliability, high stability and long life, all in a compact package.

For further information please contact Coherent Scientific at sales@coherent.com.au or 08 8150 5200

Spherical piezo elements enable use in 360° ultrasonic applications

PI (Physik Instrumente) Ceramic now manufactures piezo components as hemispheres and hollow spheres. These types of components are particularly suitable for use as 360° transmitters such as those used in sonar technology. The outside diameter is between 10 and 60 mm. Larger diameters are available on request. The minimum wall thickness is 1 mm and other dimensions are also possible on customer request.

Thanks to their design, the components are generally suitable for applications which function as 360° sound transducers with a high bandwidth. Therefore, these spherical piezo components can be used in many different sonar application areas such as underwater communication, underwater monitoring, depth and underground relief measuring or for locating swarms of fish.

The components are manufactured from ferroelectric soft or hard piezo materials according to the application range. This enables optimum setting with respect to the coupling factor and acoustic impedance. The spheres can be made with a hole or groove for easy mechanical integration.

For more information, contact Warsash Scientific on +61 2 9319 0122 or sales@warsash.com.au

Compact and robust linear stages at an affordable price

Warsash Scientific is pleased to announce the new linear stages in the L-406 series from PI (Physik Instrumente) which offer very good performance on compact installation space. Despite the narrow width of only 65 mm, travel accuracies up to only 0.5 µm are possible over a travel range of 25 mm. PI is able to supply inexpensive solutions in conjunction with PI motor controllers at very short notice.

The linear stages are equipped with recirculating ball bearings and leadscrews, and were conceived for loads up to 10 kg. The stress-relieved aluminium base ensures high stability.

The L-406 is available for strokes of 26 mm, 52 mm, and 102 mm. In addition, they can be easily mounted to XY set-ups without using an adapter or operated vertically using a bracket.

A high-resolution, integrated rotary encoder takes care of the position metrology in the versions with DC gear motor. The noncontact, optical limit switches and reference point switches with direction sensing in the middle of the travel range simplify use in automation tasks.

For single-axis control, PI offers the easy-to-operate C-863 digital Mercury motion controller for DC servo motors and the C-663 for stepper motors. DC motor control of up to four axes is possible with the C-884. Using the PIMotionMaster, it is possible to use the L-406 in a networked group to control up to 40 axes with different drive technology.

For more information, contact Warsash Scientific on +61 2 9319 0122 or sales@warsash.com.au

Ezzi Vision Announces The Distributorship Of The New HELIOT 900 Series Leak Detectors

Improved Evacuation Capability and Usability for Faster Testing

EZZI VISION is pleased to announce the addition of the (ULVAC) HELIOT 900 Series leak detectors for sale in its existing product range.

Background

Leak detectors are test equipment designed to measure the amount of leakage and locate leaks during helium leak testing, a method of testing leaks using helium gas. Helium leak testing provides higher sensitivity than any other leak test method and enables fast and accurate testing, even for minor leaks. Due to these advantages, helium leak testing is used in a wide range of industries that require leak testing, including production lines for various piping components, electronic devices, air-conditioners, chillers, and automobiles, as well as food/drug packaging and medical equipment.

ULVAC has been selling leak detectors since the 1960s, and since 1995, the name of these products has been the HELIOT Series. They have fully upgraded their time-tested HELIOT 710 Series products to launch the brand-new HELIOT 900 Series.

Overview

The HELIOT 900 Series consists of the following four models:

(1) Portable/901: Suitable for stationary installations (on the table, floor, etc.)

- (a) HELIOT 901W1: Equipped with an oil-sealed rotary vacuum pump, 30 L/min
- (b) HELIOT 901D2: Equipped with a scroll dry pump, 90 L/min

(2) Mobile/904: Cart-mounted type with ease of moving to support large work pieces

- (a) HELIOT 904W2: Equipped with an oil-sealed rotary vacuum pump, 135 L/min
- (b) HELIOT 904D3: Equipped with a scroll dry pump, 250 L/min

Features

(1) The products provide a helium pumping speed of 5 L/sec, which is two to three times higher than competing models in the same class.

To meet today's ever-demanding helium leak testing requirements, such as shorter test times and higher responsiveness, stability and detection sensitivity, we have dramatically improved helium evacuation capability while increasing the sensitivity of the detection unit.

(2) Tablet-type controller as a standard feature

The display is no longer fixed to the detector body, eliminating operational constraints and greatly improving usability. The 7-inch capacitance touch panel allows operators to work with the detector more intuitively and promptly while holding it in hand. The controller comes standard with wireless remote connection to enable remote control operation. The display supports seven languages.

(3) Advanced mobile cart

To ensure safe movement - even through narrow passages - the cart embodies numerous features requested by professionals in laboratories, such as a compact body, large wheels, a flat panel cover, and the ease of moving and placing.

(4) Improved user serviceability

The service panel can be removed without tools. The internal structure provides good serviceability. Maintenance can be performed in accordance with a step-by-step video that can be displayed on the controller.

(5) The products are interchangeable with existing models to enable a smooth transition.

About Ezzi Vision Pty Ltd.

EZZI VISION is a Melbourne based leading provider of high-quality Vacuum products and systems, along with Glove box & Thin Film Technology. With over 30 years of combined vacuum, thin film technology and ophthalmic experience, Ezzi Vision provides products, service, training, and customer support like no other supplier. We offer this solution composed of equipment, materials, analytic evaluation, vacuum components and other various services, for flat panel displays, solar cells, semiconductors, electronic components, and many other general industrial equipment.

For more information, contact Ezzi Vision on 1800 46 3994 or ezzivision.com.au

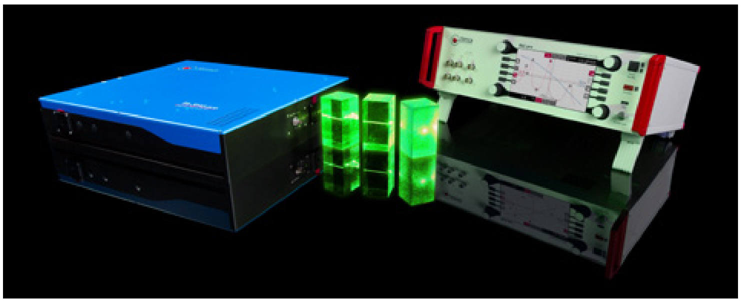
2 W of high power tunable green-yellow lasers available from TOPTICA!

TOPTICA has released a new class of multi-Watt laser sources for use in the laboratory but also opening up opportunities for future OEM integration. Based on the TA-SHG pro product line, a resonantly frequency-doubled tapered amplified diode laser, more than 2 Watts of single frequency output covering the spectral range from 550 nm to 565 nm are now available. The dramatic leap towards higher power levels is possible due to proprietary tapered amplifier technology, modified electrical & thermal management and further improvements of the frequency-doubling resonator technology.

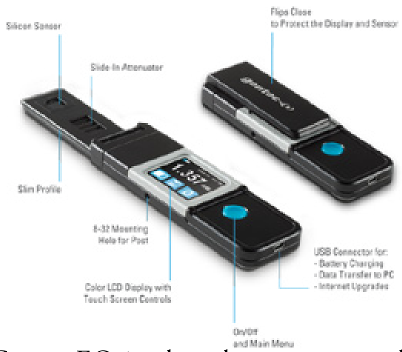
With a tunability of several nanometres, mode-hop-free scanning of 30 GHz and a linewidth of less than 100 kHz, the novel laser source allows numerous applications in quantum technologies. Similar performances are achieved around 400 nm, 430 nm and 480 nm.

The TA-SHG pro product line covers a wavelength range of 316 nm to 675 nm with only few gaps and maximum power levels ranging to more than 2 W. The digitally controlled version DLC TA-SHG pro offers remote control via PC, touch screen operation, automatic alignment and active output power stabilisation.

For further information please contact our Toptica Product Manager Jessica Mackintosh on 08 8443 8668 or jessica@lastek.com.au.



New compact laser power meter for low power measurements from Gentec-EO



Gentec-EO is pleased to announce the addition of a new member to the pronto family of compact laser power meters. As its name indicates, the Pronto-Si presents a large 1 cm^2 silicon sensor, the largest in its category, perfect for measuring very low powers. When combined with the integrated slide-In OD1 attenuator, the total power range of the Pronto-Si extends from 0.3 nW to 800 mW. The measurements are done in continuous mode, so you can install the pronto in the laser beam path and leave it there indefinitely. The internal memory also allows you to acquire data and transfer it to a PC for further analysis. The sensor part has a very slim profile of only 6 mm, allowing it to be used in very tight spaces.

Features:

- Pocket-sized
- Colour touch screen display
- Screen and sensor are protected when you flip it close
- Extend your power range with the slide-In OD1 attenuator (0.3 nW to 800 mW)
- Use it in very tight spaces (Only 6 mm at the Sensor)
- Set the wavelength, brightness and screen orientation
- Advanced features like data logging and data transfer to PC

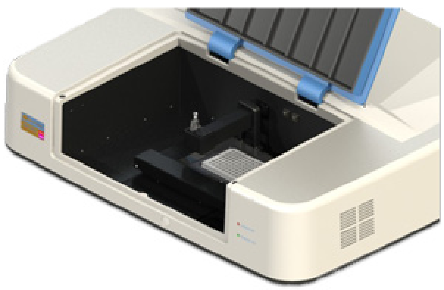
Bayspec RamSpec™ Deep-Cooled Benchtop Raman Spectrometer

BaySpec's RamSpec™ series Raman spectrometers are turn-key solutions designed for best-in-class performance and long-term reliability. Integrating an ultra-sensitive, deep-cooled transmission spectrometer, a class 3B laser source, an optional integrated computer and fibre connectivity, the RamSpec™ offers a high-performance scientific-grade Raman system in a rugged, portable benchtop platform.

The RamSpec™ employs a highly efficient volume phase grating (VPG®) as the spectral dispersion element and a deep-cooled, ultra-sensitive CCD or InGaAs array detector, thereby providing high-speed parallel processing and continuous spectral measurement. As an input, the device uses a fibre optic bundle or slit based on customer preferences. The included Spec 2020 software platform allows full control of spectral acquisition as well as library search functionality. The new-generation RamSpec™ has optional dual excitation wavelengths and automatic mapping function for well-plates.

Key features:

- 532, 785, and 1064 nm lasers (custom wavelengths available), single or dual
- Ultra-sensitive, deep-cooled CCD or InGaAs detector
- High-throughput, fast (f/2) spectrograph
- Automatic well-plates sampling (optional)



For more information please contact Lastek at sales@lastek.com.au or 08 8443 8668

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AFW Technologies Pty Ltd
First floor, No. 45, Star Crescent
Hallam, Victoria 3803
Tel: +613 9702 4402
Fax: +613 9702 4877
sales@afwtechnology.com.au
http://www.afwtechnology.com.au

BAE Systems
2-6 Ardtornish Street
Holden Hill, SA 5088
Tel: +618 8266 8284
peter.whitteron@baesystems.com
http://www.baesystems.com.au

Coherent Scientific Pty Ltd
116 Sir Donald Bradman Drive
Hilton, SA, 5033
Tel: (08) 8150 5200
Fax: (08) 8352 2020
sales@coherent.com.au
http://www.coherent.com.au

CUDOS
School of Physics,
University of Sydney, NSW, 2006
Tel: (02) 9351 5897
Fax: (02) 9351 7726
martin@physics.usyd.edu.au
http://www.cudos.org

Ezzi Vision Pty Ltd
Vacuum & Thin Film Coating
PO Box 206, Chirnside Park, VIC 3116, Australia
Office: 1 Dalmore Drive, Caribbean Business Park,
Scoresby, VIC 3179, Australia
Tel: +61 (0) 3 97270770
Fax: +61 (0) 3 86101928
adil.adamjee@ezzivision.com.au
www.ezzivision.com.au

Laser SOS Ltd
Unit 3, Burrel Road, St. Ives, Cambs,
PE27 3LE, United Kingdom
Tel: +44 1480 460990
Fax: +44 1480 469978
sales@lasersos.com
http://www.lasersos.com/

Lastek Pty Ltd
10 Reid Street
Thebarton, SA, 5031
Tel: (08) 8443 8668
Fax: (08) 8443 8427
sales@lastek.com.au
http://www.lastek.com.au

Photon Scientific
114 Albany Drive
VIC 3170
nish@photonscientific.com.au
http://www.photonscientific.com.au

Raymax Applications Pty Ltd
PO Box 958,
Newport Beach, NSW, 2106
Tel: (02) 9979 7646
Fax: (02) 9979 8207
sales@raymax.com.au
http://www.raymax.com.au

Warsash Scientific Pty Ltd
PO Box 1685, Strawberry Hills
NSW, 2012
Tel: (02) 9319 0122
Fax: (02) 9318 2192
sales@warsash.com.au
http://www.warsash.com.au

Wavelength Opto-Electronic Pte Ltd
Blk 2, Bukit Batok St 24
#06-09 Skytech Building
Singapore 659480
Tel: 65-65643659
Fax: 65-65649627
john@wavelength-tech.com
http://www.wavelength-tech.com

Sacher Lasertechnik Group

High Power, Low Linewidth Ridge Waveguide Laser

Stabilized by Volume Holographic Grating External Cavity at 780nm

Motivation

Sacher Lasertechnik Group

- **Focus:**
  - Highly stable external-cavity diode lasers (ECDL) with an output power of several hundred milliwatt
- **Applications:**
  - Optical cooling & trapping, Raman spectroscopy, LIDAR, time standards
- **Means:**
  - Feedback by volume holographic grating (VHG), compact packaging
- **Advantages:**
  - High mechanical stability, low manufacturing costs

CONTACT US

E-mail: info@photonscientific.com.au

Ph: +61 (0)411198392

Fibre Optic & Photonic products

Optical Fibre Delay Line / Spools

AFW can manufacture compact size, robust fibre delay lines to suit your space and budget. You no longer require large fibre spools with connectorised fibre pigtails. We can make customised fibre length solutions to suit your application. Suitable for optical network testing and analysis, time delay applications, fibre network simulations, research and development.

Key Features

- Insertion loss 0.3 ~ 0.5dB per km
- Customised fibre lengths: 50m,100m, 200m, 1km ~ 5km, 10km, 25km, 40km and 50km
- Operating wavelength range: 1260 ~ 1650nm standard
- Fibre type: G.652.D SMF
- Multiple fibre lengths in 19” 1U Chassis

AFW Technologies

Phone: +613 9702 4402
Email: sales@afwtechnologies.com.au
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