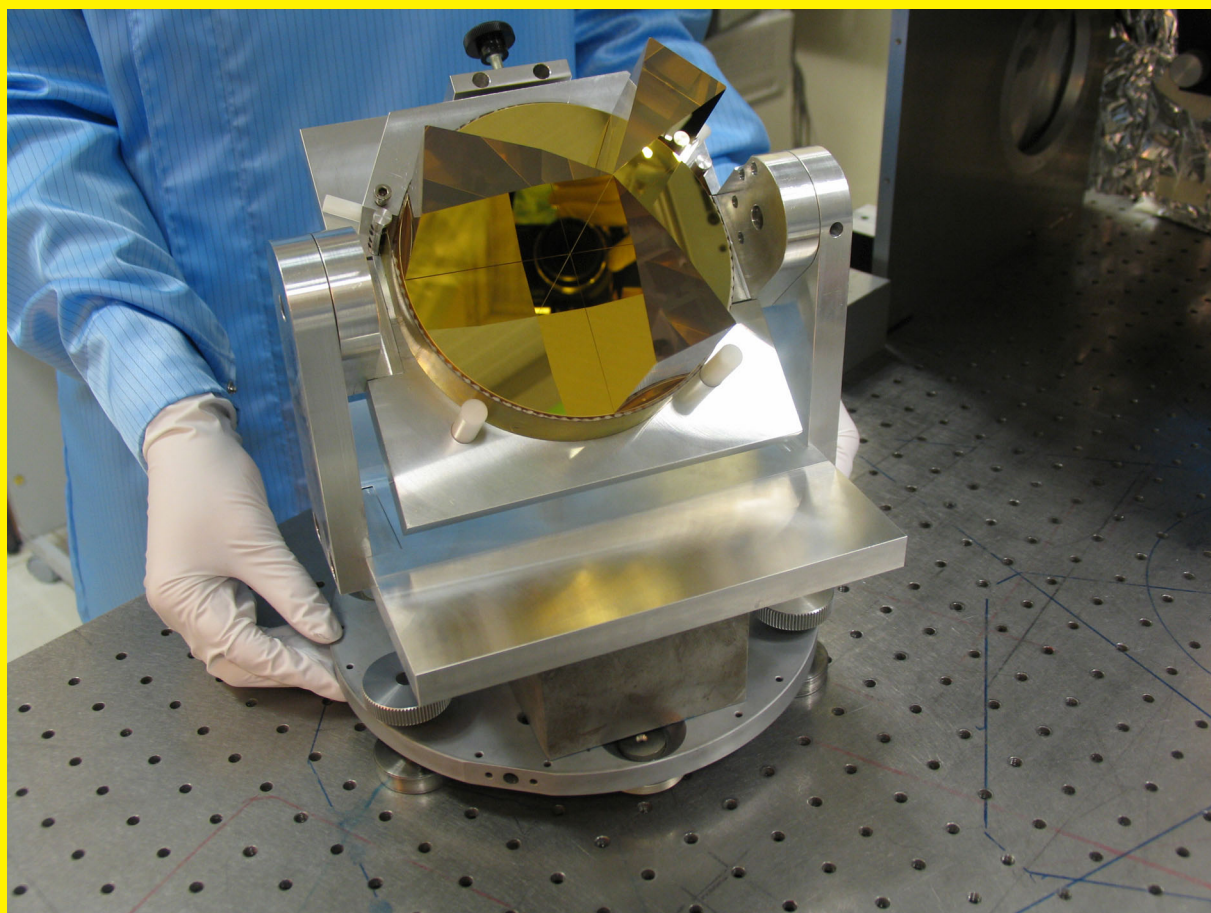


# Australian Optical Society

# NEWS



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December 2005

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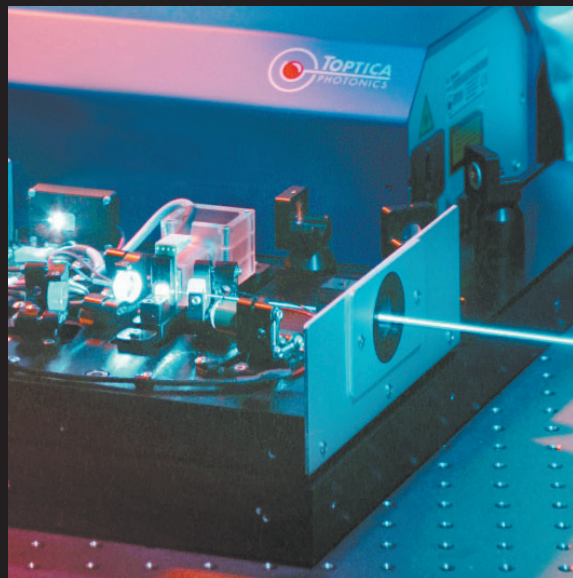
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# Optical Fibre Information and Communication Experiment System

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## LEOK-20 (7 experiments)

- Experiment of fundamental knowledge of optical fibre optics
- Experiment of coupling method between optical fibre and light source
- Multimode fibre numerical aperture (NA) measurement
- Optical fibre transmission loss property and measurement
- M-Z optical fibre interference experiment
- Optical fibre thermal sensing principle
- Optical fibre pressure sensing principle

## LEOK-21 (10 experiments)

- All the experiments on above *LEOK-20*
- Optical fibre beam splitter parameter measurement
- Adjustable optical attenuator and parameter measurement
- Fibre optic isolator and parameter measurement

## LEOK-22 (15 experiments)

- All the experiments on above *LEOK-21*
- Optical fibre optical switch experiment
- Wavelength division multiplexing (WDM) principle
- Optical transmitter's extinction ratio measurement
- Erbium-doped fibre amplifier (EDFA) principle
- Open circuit audio analog signal transmission experiment

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ABN 63 009 548 387

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### 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*

#### \* *News Item*

#### \* *Book Review*

#### \* *Cartoon or drawing*

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☞ 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, as well as copies of the diagrams in their original format in separate files.

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Where possible, diagrams should be contained within the document and sent as separate files. Figures on A4 paper will also be accepted. Note: all figures should be black & white or greyscale.

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Copy for the next issues to be sent by Feb 6 for Feb 26 print.

June 23 for June 30 print.

Sept 11 for Sept 29 print.

Nov 30 for Dec 11 print.

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<http://aos.physics.mq.edu.au>

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December 2005

Volume 19 Number 4

# AOS NEWS

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*Cover Picture: Multiple cube corner assembly(three retro-reflectors) made of precision gold coated Zerodur components, developed by CSIRO - ACPO for JPL/NASA. The assembly is one a number of such assemblies that will be used to measure the relative positions of a stellar interferometer telescopes (mounted on a 10 m truss in space) to within 50 pm accuracy. This is a crucial part of the Space Interferometer Mission which will detect tiny wobbles in stars which may have earth like planets orbiting.*





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ABN 63 009 548 387

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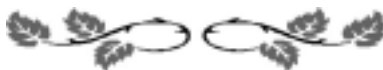
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## President's Report

Since the last issue of the News appeared the council has had three meetings – one face to face and two e-meetings. Probably the most far-reaching of the decisions made was that the AOS agree take on 50% of the ownership of the ACOFT series of conferences. From 2007 ACOFT meetings are to be held at the same time and place as the main AOS meeting in any particular year. Engineers Australia (the other 50% co-owner) is agreeable to this.

The council also agreed to hold a one-day AOS conference in July 2006, to be co-located with the 2006 ACOFT meeting. Ann Roberts (University of Melbourne) has kindly agreed to organize the program for the AOS meeting, which will be chaired by Arthur Lowery (Monash University), with Arnan Mitchell (RMIT) organizing the ACOFT program. The venue will be RMIT and the combined meeting will be in the second week of July.

This closer relationship between the AOS and the ACOFT community is a very positive step for the AOS in my opinion. There isn't really room in the year for more than one major AOS conference, given the funding and time constraints that most of us have. And many AOS members feel themselves more naturally a part of the ACOFT conferences, than of the AOS conferences, which of late have been either ACOLS or subsidiary to AIP congresses. Thus having the two, AOS and ACOFT, together helps keep the AOS together.

The ACOFT conferences (usually in July) have provided a vehicle for the AOS to run its AGM. The main AOS conferences (AOS, ACOLS, AIP) tend to be in December or February, with some exceptions. A consequence of the longer term arrangements vis-a-vis ACOFT is that we will need to give some thought as to how we are to manage AGMs in the future. Low attendance at the AGM has been a perennial problem and having an AOS conference in the July to October timeframe helps to keep the AGMs quorate.

In response to a request from the organisers of the AIP Congress in Dec 2006 (Brisbane), the council has agreed to participate financially in the congress, in much the same way as for the 2005 AIP Congress in Canberra. So for 2006 this will be the main conference for the AOS.

Further into the future, in 2007 there will be an ACOFT conference which is likely to be co-located with a COIN (Conference on the Optical Internet) conference. There will be no AOS meeting as such but at the second of the abovementioned e-meetings the council decided to host the ETOP conference at the ACOFT/COIN venue (same time too!) ETOP stands for Education and Training in Optics and Photonics, which is a subject that has in the past few years become well represented in Australia. The conference series has a steering committee with representation from the ICO, the OSA and SPIE (who are all permanent sponsors), so it is a serious international conference. The venue will most likely be Melbourne, but the timing is as yet unclear.

As I've mentioned (or maybe just implied) several times in past issue of the News, the next major AOS conference after 2006 will be the ICO congress, the plans for which are steadily crystallizing. It's definitely a done deal now, thanks to John Love and Chris Walsh. This will happen in Sydney in July 2008, along with an ACOFT meeting and probably an OECC meeting (the latter is a regular Eastern Pacific optoelectronics meeting, but I'm afraid I've forgotten exactly what the acronym stands for!!)

The AOS News has possibly found an editor to succeed me. Angela Bakonyi, a consultant with connections to the optical industry, has volunteered to try out the editorship provided that she can be given guidance, when necessary, regarding academic issues. She is based in Adelaide, so I will be the one to assist her while we try this arrangement. This issue is the first prepared by Angela!

It is pleasing to see AOS Council members representing Australian interests internationally, with John Love being voted in as a vice-president of the ICO, and Ken Baldwin as an OSA Director at large. Halina Rubinsztein-Dunlop has joined the OSA Member & Education Council. Congratulations to all three on these appointments.

So that wraps it up for another year. I wish you a productive festive season in the lab (if you can get away with it) and all the best for 2006!

*Murray Hamilton  
President, Australian Optical Society  
November, 2005*

## Stop Press !

Apologies for the late issue this time round. It has been delayed by the ACOLS 2005 conference, and software compatibility issues associated with the handover to the new editor.

The ACOLS 2005 conference was just held in Rotorua from the 6<sup>th</sup> to the 9<sup>th</sup> of December, and was a great success.

Several awards were presented or announced at the conference.

- Prof. Brian Orr of Macquarie University received the AOS Beattie-Steele Medal for 2005
- Aidan Brooks of the University of Adelaide received the AOS Postgraduate Student Award for 2005
- Vijay Sivan of RMIT University was awarded the AOS/Warsash Student prize for 2005
- Michael Ventura of Swinburne University received the 2006 SPIE Student Prize
- Nathan Langford of the University of Queensland received the 2006 Student Prize

The last two awards were for the two best student presentations at the ACOLS conference, and were presented by the OSA President Susan Houde-Walter. In addition to heartily congratulating all of the winners, I would like to thank the OSA/SPIE Student Award judging panel for their difficult decision making, and dedication in ensuring that they went to all student presentations. The panel was Ed Hinds, Dave Wineland, Crispin Gardiner, Andrew Truscott, Russell McLean and Stephane Coen. Photographs of the awards (i.e. the handshakes!) will be published in the next AOS News in March 2006.

Murray Hamilton - AOS President.





# Focus on Microscopy 2006

**Sunday 9th - Wednesday 12th April 2006**  
**Perth, Western Australia**

[www.FocusOnMicroscopy.org](http://www.FocusOnMicroscopy.org)

Focus on Microscopy 2006 is the continuation of a successful conference series presenting the latest innovations in optical microscopy and its applications in biology, medicine, material science, and information storage. 3D optical imaging and related theory are important subjects for the conference. The series is as relevant now as at any time in its history as the scientific and engineering communities strive to meet the needs of a surging life sciences sector as well as respond to the sustained pressure on miniaturisation in lithography and data storage.

The 2006 meeting will be held in Perth on Australia's western seaboard. The conference will be held in the nearby port city of Fremantle, at the scenic Esplanade hotel, close to the boat harbour and Perth's famous beaches. Perth's relaxed and outdoor lifestyle should prove an ideal setting for a stimulating and enjoyable meeting – see you there!

Dead-line for submission of abstracts will be 9 January, 2006.

We invite you to participate on behalf of the FOM2006 organising committee:

David Sampson, University of Western Australia  
G. J. (Fred) Brakenhoff, University of Amsterdam

Conference topics include:

- Confocal and multiphoton-excitation microscopies
- Novel illumination and detection strategies – selective-plane, extended depth of focus, 4pi, structured illumination
- Fluorescence – new labels, fluorescent proteins, quantum dots, single molecule, excitation-emission spectroscopy
- Time-resolved fluorescence – FRET, FRAP, FLIM, FCS
- Coherent non-linear microscopies – SHG, THG, SFG, CARS
- Scattering processes: Raman, light scattering spectroscopy, second harmonic
- Multi-dimensional imaging
- Sub-wavelength resolution – near field microscopy, total internal reflection
- Laser manipulation, ablation and microdissection, photoactivation
- Magnetic resonance and X-ray microscopy
- Image processing and visualisation
- Live cell and tissue imaging
- Whole tissue imaging - optical coherence tomography, endoscopy, whole animal fluorescence
- New tools in genomics, proteomics, phenomics, cytometry
- Lithography and data storage





the 7th International Conference on the Electrical, Transport and Optical Properties of Inhomogeneous Media

Conference website and on-line registration:

<http://etopim7.mtci.com.au>

**ETOPIM 7 conference is to be held in Sydney, Australia in July, 2006.**

ETOPIM stands for the ***Electrical, Transport and Optical Properties of Inhomogeneous Media***.

Composite materials draw on the native properties of their constituents and the microstructure of their amalgamation to realise new and often extraordinary properties. As a consequence, such designer materials find a vast range of applications, many of which were not practicable with traditional materials.

The study of composites is of importance in a range of academic disciplines, with examples in optics, physics, engineering, geophysics, defence sciences, medicine and biotechnology. Optical applications of composites include photonic crystals, meta-materials, selective surfaces for renewable energy applications, and control of reflection and transmission as a function of wavelength, angle of incidence or polarization.

The science of composite materials addresses issues such as the design of composites with specified properties from a knowledge of their constituents, and the inverse situation where the properties of the composite have been determined and it is desirable to know the geometry and constituents of the composite.

**ETOPIM is an inter-disciplinary conference where those from different application areas come together to exchange ideas on common theoretical, numerical and experimental techniques and solutions.**

The first meeting was held in 1977 in Columbus, Ohio. ETOPIIM 7 will be the first held in the Southern Hemisphere, at the exciting location of Cockle Bay Wharf, Darling Harbour, Sydney, Australia. The program of the main conference will run for four days from July 9-12, with mini-symposia on selected specialists topics on July 13th and 14th.

**The Conference has attracted strong financial support from a range of sponsors including:**

- \* The University of Sydney
- \* The University of Technology, Sydney
- \* The Australian Defence Science and Technology Organisation
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## Sharp and Fast: The unexpected story of how ultra-fast laser pulses delivered precision optical frequency measurement.

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*Frequency Standards and Metrology (FSM) Group, School of Physics,  
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A revolution has occurred over the last 5 years that is likely to lead us into a new era in which it is commonplace to measure the instantaneous phase of an optical wave. Instruments that are presently familiar in the audio, radio-frequency and microwave frequency ranges will soon become available for the optical domain in many laboratories: one thinks of frequency counters, synthesisers and network analysers for lightwaves. All of this is predicated on the existence of a device that can create a one-to-one correspondence between the phase of a lightwave signal, and the phase of some lower frequency signal that is suitable for use in conventional electronics. It is the development of just this device that we discuss in this article, along with the work that we have performed in our laboratory for delivering this capability to Australia. The development of this tool was recognised by the awarding of the Nobel Prize for Physics in 2005 to Theodor Hänsch and John Hall.

### I. INTRODUCTION

Most physics and electronic engineering laboratories would find it difficult to work without tools that can display and manipulate the instantaneous amplitude of a signal. More specifically, given a signal  $y(t) = A(t) \sin[\omega(t)t + \phi(t)]$ , one would like to be able to display  $y(t)$ . Until recently, however, this has not been possible for those working with optical signals because the frequency of optical signals falls well above the range of any electronic system. For example, optical signals have frequencies that range from around 200 THz (200 trillion cycles per second or  $2 \times 10^{14}$  Hz) in the near infrared up to 700 THz in the blue. On the other hand, the fastest electronic signal processing can occur at perhaps 100 GHz; a factor of more than 1000 times too slow.

The first team to effectively overcome this exceedingly difficult challenge (of following the phase of an optical signal) was at PTB (Physikalisch-Technische Bundesanstalt) in Braunschweig, Germany around 1996 [1]. The team consisted of about 5 people working for 5 years to fill 3 laboratories with equipment. The outcome of this massive effort was a comparison of one optical frequency with one particular microwave frequency. If one needed to make a measurement of some other optical frequency then this herculean task would need repeating.

The development of a relatively simple method, which is applicable to measuring optical frequencies all over the optical and infra-red spectrum, became the subject of intense interest from the early 1990s. This direction was motivated from the increasingly clear realisation that the best clocks of the future were going to be based on optical rather than microwave frequency transitions in atoms and ions [2]. It was not until 1997 that one research group, led by Ted Hänsch at the MPQ (Max-Planck-Institut für Quantenoptik) outside Munich, finally hit upon the recipe for a superior method [3]. The culmination of this work was the award of the 2005 Nobel Prize for Physics to both Ted Hänsch and John Hall. Their tool, which we will refer to as an “optical frequency synthesiser”, is a device aimed at creating a one-to-one phase relationship between some arbitrary optical signal, and two lower frequency signals that are amenable to electronic processing. We choose to term this de-

vice a synthesiser because its function is exactly the job of a conventional synthesiser: the generation of a signal(s) that has a frequency with some well defined phase relationship to some reference signal or signals. Unfortunately, this can cause a little confusion because the name optical frequency synthesiser has also been used to refer to end-user instruments (based on the same technology) that deliver useable strength optical signals at arbitrary wavelengths [4]. This school of thought refers to Ted and John’s tool as an optical frequency comb (for reasons that will become apparent below). Nonetheless, we will make use of “optical frequency synthesiser” in this article because it describes the function of the tool as opposed to the means by which it is achieved. The variation in the terminology is probably indicative of the early stage of the field, but we will attempt to be clear about what we mean throughout this article.

Once we have available the tool that creates this intimate relationship between the phase of our optical signal and some lower frequency signal, then it is possible to develop a new generation of instruments that have all the flexibility that was previously confined to the lower frequency electronic signal domain. For example, in recent times the literature has seen reports of optical frequency counters [5–7], optical pulse generators [8], high power tunable optical synthesisers [4], and optical clocks [9, 10]. The performance of these new systems is absolutely remarkable. As an example, it is now possible to compare the frequency of an optical and microwave signal with a precision of a few parts in  $10^{15}$  in just one second [11], while frequency comparisons between two optical clocks can be performed with a precision of a part in  $10^{16}$  in 1 second. In other words, we can compare the frequency of two optical clocks operating in the green part of the spectrum ( $\sim 550$  THz) with a resolution of just 50 mHz in just 1 second.

In the sections below we will describe the method of operation of this optical synthesiser as well as some of the highlights of their use. In addition, we will give some details of the work that is being performed in Australia in this field.



## II. THE HEART OF THE OPTICAL SYNTHESISER: THE FREQUENCY COMB

The invention of mode-locked lasers that can generate a light pulse of a few femtoseconds in duration is really at the heart of this revolution: without this device it would not be possible to obtain the strong non-linearity and the phase coherence that are at the heart of the process. Let's examine the optical output of a typical mode-locked laser in the time-domain and then follow its consequences in the frequency-domain (see Fig. 1).

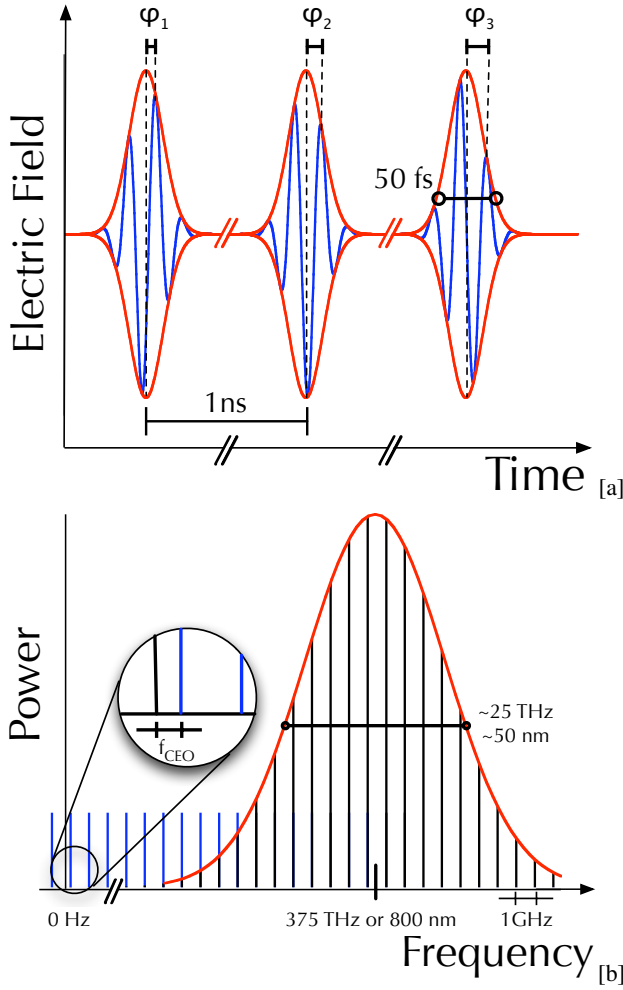


FIG. 1: A view of the (a) time and (b) frequency domain behaviour of laser pulses emitted from a mode-locked laser

A mode-locked laser gives a sequence of light output pulses of extremely short duration at regularly spaced intervals. We show the electric field amplitude of the output of a typical mode-locked laser as the blue trace in Fig. 1(a), with the envelope of the pulses shown as the red trace. Using the parameters of our laser as an example (GigaJet 20), the pulse duration is around 50 fs (about 20 cycles of the light field) and the pulse interval is 1 ns. Initially, let us assume that a mode-locked laser emits the pulse at strictly regular intervals and

thus that the pulse envelope is strictly periodic. Of course, in reality, various technical problems conspire to disrupt this periodicity. Let us now consider the appearance of these pulses in the frequency domain. If we consider a single archetypal pulse with a Gaussian pulse envelope in time, then the Fourier Transform of this pulse is also a Gaussian shaped feature in the frequency domain. The frequency width of the pulse is related to the reciprocal of the pulse duration while the centre frequency is equal to the carrier frequency. In the case of a typical Ti:S based mode-locked laser, the carrier frequency or average frequency of the pulses is around 375 THz, or 805 nm in wavelength. The frequency spectrum of a single pulse is shown as the smooth red curve (the envelope) on Fig. 1(b) where we have plotted the power as a function of frequency. In the case of our laser the spectrum extends over 30 nm centered at 805 nm. One can also think that this frequency width arises because the short duration of the pulse necessarily results in a poorly defined carrier frequency. This effect is analogous to the Heisenberg time-energy uncertainty that is familiar from Wave Mechanics. This observation makes it only more amazing that a pulse with an intrinsically poorly defined frequency is the basis for the most precise frequency comparisons ever.

A closer examination of the electric field emitted by a typical laser, as seen on Fig. 1(a), shows that even if the pulse envelope is emitted with perfect regularity, the electric field within the pulses may not be identical in each pulse. This phase slipping of the pulse carrier with respect to the envelope, indicated by the  $\varphi$  on the figure, arises from chromatic dispersion within the mode-locked laser. We will see the effect of this on the spectrum of the pulses in a moment.

So let us now consider the frequency domain properties of a long series of pulses, rather than that of just a single pulse. The periodic nature of the pulse sequence is reflected in a periodicity within the frequency domain: thus the spectrum is seen to be a comb of discrete equidistant frequency lines as shown on Fig. 1(b). The envelope of the power in these discrete modes has the same shape as the spectrum of a single pulse, while the spacing of the modes is exactly equal to the reciprocal of the inter-pulse duration, which in our case is 1 GHz. If we extrapolate this series of comb modes back to zero frequency (as shown by the blue lines on Fig. 1(b)) we see that the extrapolation does not (necessarily) co-incide with zero frequency. In other words, each of the comb lines is not exactly an harmonic of the repetition rate. The frequency offset of the comb from a pure harmonic series is the result of dispersion within the mode-locked laser. So here is the frequency domain equivalent of the slipping of the carrier phase with respect to the envelope that we can see in the time domain. To quantify this further, we can write the frequency of each individual comb mode as:

$$f_n = n f_r + f_{\text{CEO}} \quad (1)$$

where  $n$  is the harmonic mode number,  $f_r$  is the pulse repetition rate and  $f_{\text{CEO}}$  is called the carrier-envelope offset frequency. The offset frequency can be written as  $f_{\text{CEO}} = f_r \frac{\Delta\varphi}{2\pi}$  where  $\Delta\varphi = \varphi_{n+1} - \varphi_n$  is the phase change of the carrier with respect to the envelope between pulses (see Fig. 1(a)).

So what can we do with such an optical frequency comb?



The two frequencies  $f_r$  and  $f_{\text{CEO}}$  both fall in the radio-frequency or microwave frequency domain. In our case,  $f_r \sim 1$  GHz while  $|f_{\text{CEO}}|$  is less than 0.5 GHz (it may be negative or positive) - it is essentially the leftover bit of frequency after we have extrapolated the harmonic series to zero frequency (see inset in Fig. 1(b)). This means that both of these signals are easily comparable to other electronic signals or, perhaps more importantly, to the definition of the second through the Cs hyperfine transition which is exactly 9 192 631 770 Hz. Using Eq. 1 we can readily relate all the optical comb frequencies,  $f_n$  to these radio-frequency reference frequencies, and can hence accurately determine their absolute frequency. We will describe the process of comparing an optical frequency signal with a microwave signal later in Sect. V. Thus, the problem of measurement or control of the frequency of an optical signal reduces to the problem of determining  $f_r$ ,  $f_{\text{CEO}}$  and  $n$ : we will describe how to do this in Section IV. First let's take a quick tour of mode-locked lasers.

### III. QUICK INTRODUCTION TO MODE-LOCKED LASERS

One might ask about the physical significance of the two frequencies,  $f_r$  and  $f_{\text{CEO}}$ . It is important to understand this both from the point of view of fluctuations, as well as in developing a sensible means of control for these parameters. To gain some insight we will need a quick introduction into how a mode locked laser works. We do not have space for a proper description but a quick description of the salient facts may be interesting.

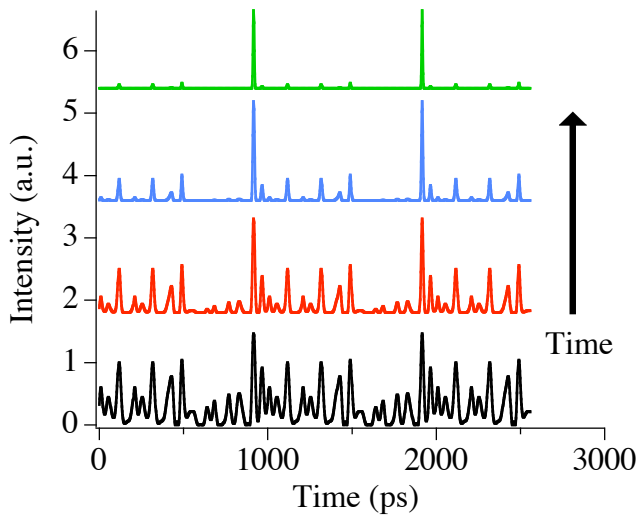


FIG. 2: A trace showing the simulated amplitude noise from a mode-locked laser at various times in acquisition of the mode-locked state. The curves have been separated vertically for clarity. The bottom trace shows a multimode laser. As the output evolves in the presence of the nonlinearity we see just a single pulse circulating in the cavity.

A mode-locked laser consists of a laser gain material and optics that will support oscillation across a very broad part

of the optical spectrum (more than tens of nm). When first started, the laser typically operates as a multimode source i.e. all available modes across the broad spectrum oscillate simultaneously but with a randomly chosen initial phase. In our case the gain spectrum of the laser is perhaps 20 nm wide while the available modes are spaced at 1 GHz intervals (the cavity length is 30 cm). Thus approximately 10,000 modes will commence oscillating simultaneously. This results in a very noisy signal circulating in the laser cavity (see bottom trace on Fig. 2). Both the amplitude and phase contain strong fluctuations, although the noisy trace very nearly repeats itself on a time scale corresponding to 1 round trip in the laser cavity: this occurs because the entire noisy signal makes a round-trip around the laser cavity in this time. In order to convert this noisy trace into a clean pulsed signal, every mode-locked laser contains some sort of nonlinear process. As one example of a suitable non-linearity, we could imagine an intensity dependent loss mechanism: one which more strongly attenuates the weak parts of the circulating beam as compared with the stronger parts of the circulating beam (a so-called saturable absorber). In this case the circulating intensity rapidly evolves so that higher intensity parts of the fluctuation grow, while the weaker parts are suppressed, leading eventually to a short pulse propagating around the laser cavity. This evolution can be followed in each successive trace shown on Fig. 2. The time interval between successive arrivals of the pulse at the output mirror will be  $L_e/c_g$  where  $L_e$  is the round-trip length of the laser cavity, and  $c_g$  is the mean group velocity of the pulse within the cavity. The repetition rate of the output pulses is clearly just the reciprocal of this time interval. Thus, any changes in the length of the laser cavity, or in the group velocity will change the repetition rate. Other nonlinear processes are also active in the mode-locked laser, which have competing effects on the temporal duration of the pulse. It is these that determine the ultimate duration of the pulses, as well as the width of the pulse output spectrum, but we will not consider those here.

The carrier wave of the pulse is essentially the average frequency of the comb. The carrier mode propagates around the cavity with the phase velocity of light for this frequency (which differs from the group velocity in general). The time for this carrier wave to make a round trip in the cavity will be  $L_e/c_{\text{ph}}$  where  $c_{\text{ph}}$  is the phase velocity for the carrier wave. It is the difference between the phase and group velocities that gives rise to the phase slip between the carrier and the envelope of the pulse, and hence to the offset frequency. The most common method to control the offset frequency is to vary the dispersion in the laser cavity by changing the pump power into the mode-locked laser. Changes in the pump power vary the temperature of the laser crystal, the population inversion in the crystal, and the circulating laser power. All these processes can change the cavity dispersion and hence the difference between the phase and group velocities.



#### IV. MEASURING THE COMB PARAMETERS

Determination of the repetition rate of the comb is relatively straightforward: let the pulse stream fall on a sufficiently fast photodiode (bandwidth  $> f_r$ ) and its electrical output will contain harmonics of the pulse repetition rate up to its cut-off frequency. In Fig.3 we display the output of a photodiode monitoring the repetition rate of one of our femto-second lasers. One can see harmonics up to and beyond 10 GHz.

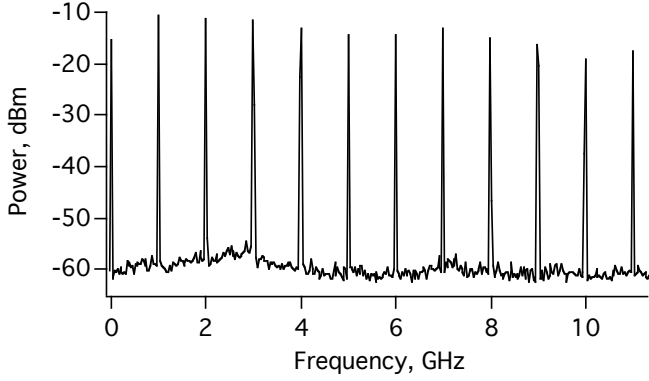


FIG. 3: The repetition frequency (1 GHz) and its harmonics generated by light from a femto-second laser falling on a high-speed photodetector.

Determining the offset frequency on the other hand is a more difficult proposition. Techniques for generating  $f_{\text{CEO}}$  have been written about extensively in the literature [12–18]. The most common approach, which we will refer to as the  $f:2f$  scheme, can be explained as follows. Let us choose a mode near the low frequency (red) end of the frequency comb, which from Eq. 1 has a frequency of  $f_n = nf_r + f_{\text{CEO}}$ . If the frequency comb spans at least one octave, then there will also be a comb member at  $f_{2n}$ , which naturally has a frequency of  $f_{2n} = 2nf_r + f_{\text{CEO}}$ . If we select the mode at the red end of the frequency comb and generate a new double-frequency signal using a nonlinear crystal e.g. through second harmonic generation, then the frequency of the second harmonic signal will be  $f_{\text{SHG}} = 2f_n = 2nf_r + 2f_{\text{CEO}}$ . Finally, heterodyning (mixing) this nonlinear signal with  $f_{2n}$  can produce an RF signal with a frequency equal to the offset frequency:  $f_{\text{CEO}} = 2f_n - f_{2n}$ . In practice several hundred adjacent comb members can be used in the heterodyning which enables increased  $f_{\text{CEO}}$  signal strength. This improvement in signal strength occurs because all modes are strictly coherent.

There are several means of enhancing the span of the frequency comb to be of the order of an octave in order to extract  $f_{\text{CEO}}$ . Some of the common methods involve: 1) Using microstructured or tapered fused silica fibers with their enhanced nonlinearity to spectrally broaden an ultrashort light pulse [19–22]. If the comb thereby spans an entire octave the  $f:2f$  scheme from above can be employed. 2) Constructing a laser that creates a very broad range of wavelengths (but not quite octave spanning) and using more complex nonlinear mixing techniques to obtain the offset frequency [23, 24],

or 3) Constructing a laser whose output spectral width is directly octave spanning [25] and to which the  $f:2f$  system can therefore be directly applied [26].

#### V. THE UWA OPTICAL SYNTHESIZER

The optical frequency synthesiser (OFSr) can be applied in a number of ways. Commonly, when frequency combs are used as spectroscopic tools, the comb is stabilised with respect to a low phase noise microwave synthesiser referenced to a Cs primary frequency standard [6, 27, 28], or an ensemble of Cs frequency standards (often with a hydrogen maser linking the microwave synthesiser and the Cs standard). The spectroscopic probe (usually a swept cavity stabilised laser) heterodynes with a second portion of the comb to produce a beat signal for frequency counting. Another means of frequency measurement is to lock the comb to an optical transition with a well known/previously measured frequency. Every other comb member is then known with equal precision to the 'known' frequency. For example, we can stabilise the beat frequency between a laser locked to an optical transition and the comb (and thus stabilise the comb), by using the correction signal to control  $f_r$ . A spectroscopic probe signal heterodyned with another portion of the comb provides a beat signal, which when counted gives the frequency of the probe in terms of the 'known' frequency. The advantage of this latter technique is that the measurement can proceed more quickly. The stability of the comb is  $\sim 10^{-15}/\sqrt{\tau}$  when locked to an optical transition, but falls to  $\sim 10^{-13}/\sqrt{\tau}$  when locked to a hydrogen maser and/or ensemble of Cs frequency standards. The OFSr can also be used as a synthesiser of very low phase noise microwave signals, lower in fact than all commercial microwave oscillators, at least for Fourier frequencies within 1 kHz of the carrier [11, 29].

At UWA we have been endeavouring to test the limits of frequency stability transfer from microwave to optical domains. In carrying out these tests we have available to us microwave sapphire oscillators which have been shown to reach  $3 \times 10^{-16}$  levels of fractional frequency instability [30]. The quest is to determine if such levels of instability can be transferred to the optical domain through the frequency comb. These investigations remain relevant while the definition of the second remains in the microwave domain and/or while commercial oscillators in the microwave domain are superior to their optical counterparts. The remainder of this section describes how the UWA group have undertaken this task along with some recent results.

The optical versus microwave frequency comparison is composed of three parts: 1) A cavity stabilised Nd:YAG laser at 1064 nm wavelength (referred to as the optical oscillator), 2) a femto-second laser based frequency comb acting as an OFSr linking the optical and microwave oscillators, and 3) a liquid helium cooled microwave sapphire oscillator (MSO) with carrier frequency 10.0 GHz. The layout of the oscillator comparison is described in Fig.4. The central graph is an example of the power spectrum generated by the microstructured fibre (MSF) and femto-second laser (on a linear scale).



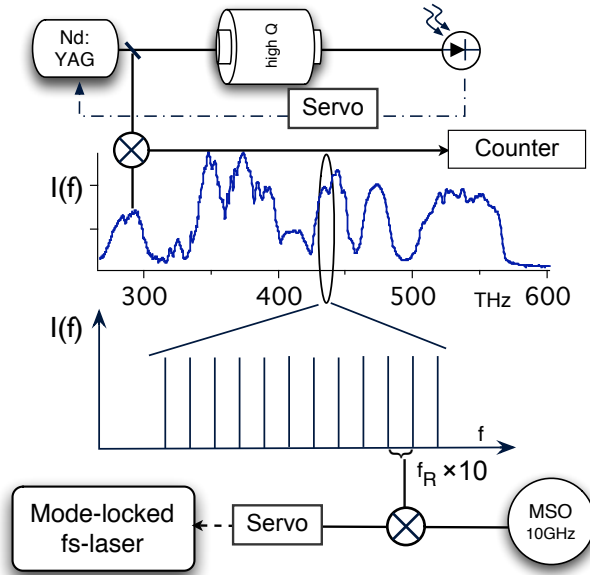


FIG. 4: Frequency stability comparison between an optical and microwave oscillator. The repetition frequency of a mode-locked laser is controlled by the output of a microwave sapphire oscillator (MSO). A Nd:YAG laser is locked to a high finesse optical cavity and a portion of its signal is combined with light from a MSF-broadened comb to produce a beat signal that has its frequency monitored by a frequency counter.

The frequency stability comparison between the optical and microwave oscillators occurs in the optical domain when  $\sim 1$  mW of the 1064 nm signal is combined with the IR portion of the optical comb (indicated by the mixer adjacent to the comb in Fig.4). Heterodyning between the 1064 nm signal and the nearest member of the comb produces an optical beat with sufficient signal-to-noise ( $\sim 30$  dB in 300 kHz) for frequency counting. The stability of this beat signal provides assessment of the frequency synthesis process.

#### A. Microwave and optical oscillators

The heart of the microwave oscillator is a cylindrical sapphire crystal resonator, with a height and diameter of 3 cm. It is excited in a whispering gallery  $E_{8,1,\delta}$  mode (or in alternate nomenclature  $WGH_{8,0,0}$ ) at 10.013 GHz ( $Q = 3 \times 10^8$ ), and acts as a frequency discriminating element of a loop oscillator circuit. The temperature of the resonator is controlled to 6 K, where its frequency becomes independent of temperature [30]. The oscillation frequency is stabilised with a Pound locking scheme, while unwanted amplitude modulation is actively suppressed by an additional control loop.

The optical signal is derived from a Nd:YAG laser that has been stabilised to a mode of a near room temperature, all-sapphire Fabry-Perot cavity (Finesse=5600). The laser signal is frequency stabilised to the cavity by using the Pound-Drever-Hall (PDH) scheme and beam pointing fluctuations are also minimised.

Both the optical and microwave oscillators have a double, so that independent frequency stability checks can be made. We have constructed two thermally stabilised optical resonators, to which the frequencies of two 1064 nm Nd:YAG lasers are locked to  $TE_{00}$  resonant modes of the separate resonators. The cavities are maintained slightly above room-temperature (301 K), thus avoiding the need for cryogenic fluids and their corresponding periodic disturbances. The resonators consist of sapphire super-mirrors clamped by stiff springs onto sapphire spacers. The use of sapphire confers excellent intrinsic length stability and vibration immunity as compared with ULE glass cavities (ULE is less sensitive to temperature variations). The cavities are housed in a vacuum chamber that contains two copper radiation shields, each held to a specific temperature. The outer shield experiences  $100 \mu\text{K}$  variations and the inner shield  $10 \mu\text{K}$  over 1 s measurement times. This two-stage approach has reduced the temperature variation of the sapphire cavity to approximately 20 nK for short time-scales.

#### B. Optical frequency synthesiser

The UWA optical frequency synthesiser is a femto-second laser and micro-structured fibre (MSF) based system using the  $f:2f$  non-linear interferometric scheme to detect the offset frequency [31]. A 35 cm, long microstructured fibre with a central core diameter of  $2.0 \mu\text{m}$  and zero-group velocity dispersion wavelength of 740 nm (NL-2.0-740, Crystal-fibre, Denmark) is used for octave-comb generation. At the input of the MSF the central air-hole silica structure is *collapsed* to form a single core fibre, onto which an angled fibre connector (FC/APC) is placed. The length of the collapsed region is a few millimeters (this fibre end treatment is carried out by Crystal-Fibre). The output end of the MSF is spliced to  $\sim 40$  cm of single mode large-mode-area (LMA) fibre (with quoted 1 dB loss). This LMA fibre provides single-mode behaviour across a large wavelength range, while enabling high power levels without nonlinear effects.

The collapsed solid core at the input ( $NA \sim 0.27$  at  $\lambda = 780$  nm) means that the incident (IR) light does not require the high levels of focusing needed to couple light into bare MSFs, and run the higher risk of fusing foreign material to the front facet of the fibre. In the event of foreign material accumulating on the face of the fibre, it is easily wiped clean and repositioned. The angled face connectors have been effective in reducing the level of optical feedback into the fs-laser and making mode-locking more robust.

Generating 12 kW peak-power pulses of light entering the MSF is a 30 cm length 6-element Ti:sapphire ring laser [32], pumped by 5.5-6.0 W of 532 nm  $TE_{00}$  light. This laser, when mode-locked, produces temporal pulse widths of  $\sim 50$  fs (outside the cavity) at a center-wavelength of 805 nm. No pulse compression is carried out between the laser and the micro-structured fibre. The femtosecond laser emits between 650 and 750 mW. Often the pump power is adjusted to tune  $f_{\text{CEO}}$  to a suitable frequency for division and servo operation.

Periodically-poled KTP is used to double the frequency of



the long-wavelength end of the broadened spectrum. The commercial 5 mm length PPKTP crystal ( $d_{\text{eff}} \sim 8 \text{ pm/V}$ ) [33] is phase-matched for 1064 nm light. The crystal produces approximately 2.4 mW of 532 nm radiation in a 2 nm bandwidth. Recombination of the two green signals occurs at a beam splitter, producing two signal ports: one is used for the detection of  $f_r$ , the other  $f_{\text{CEO}}$ . Photodetection with suitable optical filtering produces an  $f_{\text{CEO}}$  signal with a signal-to-noise ratio of  $\sim 40 \text{ dB}$  in 100 kHz of resolution bandwidth.

The  $f_{\text{CEO}}$ , once obtained from the  $f:2f$  non-linear interferometer, undergoes frequency division (by 10 or 20) and phase comparison with a synthesised rf signal in a digital phase detector before the correction signal is sent to an AOM in the pump laser beam path to form a closed servo loop.

To avoid the potential for multiplying noise from 1 GHz into the optical domain, a phase comparison between  $f_r$  and the MSO is carried out by combining the MSO signal with the 10th harmonic of the repetition frequency in a double balanced mixer. Sufficient  $10 \times f_r$  power was obtained from a high speed photodetector followed by an X-band amplifier. With low pass filtering, the difference frequency of  $\sim 10 \text{ MHz}$  is employed in a phase locked loop, whose output provides the correction signal for feeding back to the PZT element in the femto-second laser. A layout of the signal mixing and servo operation is shown in Fig. 5. The contribution of the commercial synthesiser instability is approximately at the  $1 \times 10^{-15}$  level.

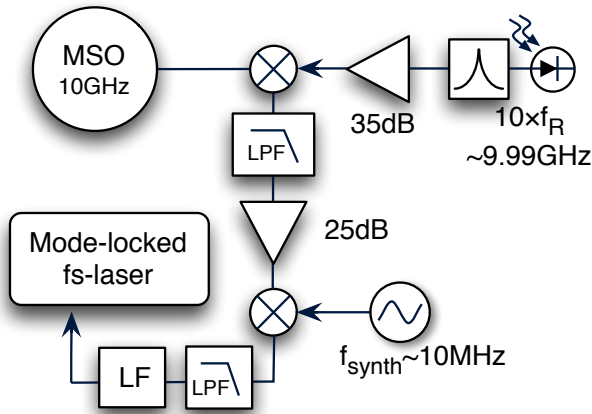


FIG. 5: Controlling of the repetition frequency of the mode-locked laser by making a phase comparison between  $10 \times f_r$  and the microwave sapphire oscillator (MSO) signal. LF = loop filter; LPF = low pass filter.

An example of the optical beat signal between 1 mW of 1064 nm radiation and the SC is shown in the inset of Fig. 6. This signal commands a sizable signal-to-noise ratio and is suitable for frequency counting. A measure of the frequency instability is shown in the main plot of Fig. 6. The frequency instability is presented in terms of the conventional measure, termed the Square Root Allan Variance (SRAV) [34], which can be thought of as the fractional frequency instability considered over various timescales (integration time). For comparison, a state-of-the-art commercial atomic beam clock (H-

maser) offers  $10^{-13}$  level frequency stability at 1 second integration time, while the best primary frequency standard ever built offers a stability of around  $4 \times 10^{-14} / \sqrt{\tau}$  where  $\tau$  is the integration time [35].

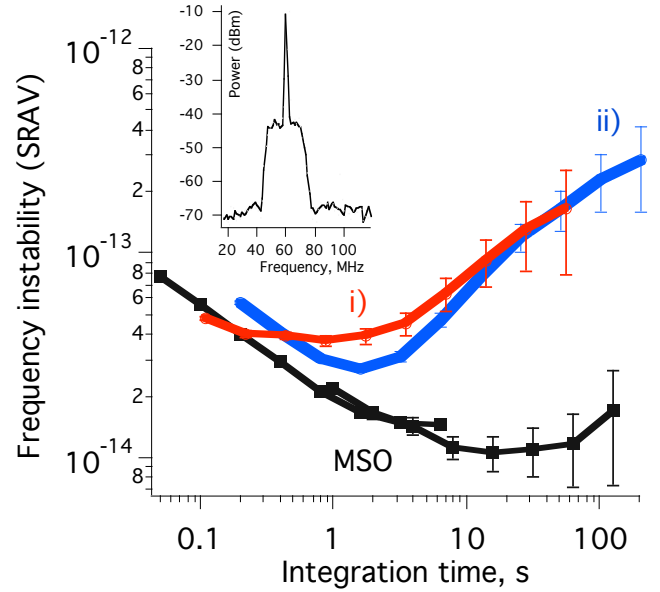


FIG. 6: A measurement of the frequency instability of an optical oscillator (cavity stabilised Nd:YAG laser) by comparing it with the ultra-high stability UWA microwave oscillators with the aid of the UWA optical synthesiser (Trace ii). Trace (i) shows the estimated instability of the optical oscillator by comparing it with another similar optical device. Trace MSO shows the estimated frequency instability of the MSO measured using two microwave MSOs. The inset shows an example of the RF spectrum of the beat signal (resolution bandwidth, 300 kHz). The pedestal is due to band-pass filtering.

For integration times up to a few seconds the present beat stability appears to be limited by the MSO, and not by the optical synthesiser. The MSO frequency stability (square root Allan variance (SRAV)) was measured by a comparison between two MSO's (two separate sapphire resonators). As they are almost identical the frequency instability contribution is assumed to be equal, and so the measured SRAV is divided by  $\sqrt{2}$ . For integration times longer than a few seconds, the measured instability between the optical and microwave sources appear to be dominated by frequency variations of the optical oscillator, stemming from residual temperature fluctuations of the optical cavity. The independently measured optical oscillator instability was estimated by comparing two similar devices. This result appears to be slightly worse than the microwave-optical comparison. We suspect that this occurred because the microwave-optical comparison was made with the better of the two optical oscillators, whereas the result shown here is representative of the worse of the two devices.

Closed loop phase spectral density measurements of the controlled repetition frequency of the femto-second laser show an improvement at 1 Hz of twelve orders of magnitude (units:  $\text{rad}^2/\text{Hz}$ ) over the free-running laser. Conversion to SRAV indicates that the frequency comb may impose a  $4 \times 10^{-15} / \sqrt{\tau}$  measurement limit in optical to microwave fre-



quency comparisons. The stabilised offset frequency will not impact on frequency comparisons until we are at a level of  $10^{-17}/\sqrt{\tau}$ .

The long term operation of frequency combs is an aspect that is being addressed with some effort. At present the UWA optical synthesisers can remain phase locked for a few hours, however, other solid-state frequency comb systems have been known to remain phase locked for more than a 24 hour period [36].

## VI. FIBRE-OPTIC BASED OPTICAL SYNTHESISERS

Advancing rapidly are stable frequency combs covering the telecommunications band (1.3-1.6  $\mu\text{m}$ ) and beyond. Commercial  $f:2f$  systems are already available centred on erbium-doped ( $\text{Er}^{3+}$ ) fibre laser design. These fibre based systems have some inherent advantages compared to their solid state cousins: they are generally more compact (and thus more portable), less expensive, can remain phase-locked for up to weeks at a time [37, 38], and are most often self starting. Their compactness arises because the laser pumping can be carried out with efficient laser diodes (at 0.98 or 1.48  $\mu\text{m}$ ) and there is little need for bulk optics. A report of frequency metrology with a turnkey all-fibre system has been recently reported [39].

Methods used to generate subpicosecond pulses in fibre lasers include: the nonlinear amplifying loop mirror (NALM) [40–42] nonlinear polarisation rotation (NPR), often referred to as polarisation additive pulse mode-locking (P-APM) [43–46], and semiconductor saturable absorbers [47–49]. A detailed description of each is out of place here and the reader is asked to refer to the literature for further details. In brief, however, the nonlinear amplifier loop mirror and nonlinear polarisation rotation achieve artificial saturable absorption and pulse shortening by combining the Kerr effect in a length of optical fibre and polarisation selection. Both are a form of additive pulse mode-locking [50, 51] (pulse shortening by a coherent addition of pulses). The NALM fibre laser is often used with polarisation maintaining fibre and most commonly forms a unidirectional figure-8 shaped ring cavity. The polarisation maintaining fibre reduces the laser's sensitivity to environmental perturbations. NPR lasers, on the other hand, are usually formed from a single loop of non-polarisation maintaining fibre.

Nonlinear polarisation rotation relies on intensity dependent rotation of an elliptical polarisation state through optical fibre. To get some understanding for this, one can treat the ellipse as a superposition of right- and left-hand circularly polarised components of different intensities. The two components experience different nonlinear phase shifts due to the intensity dependence of the refractive index in the fibre. Re-combination of the right- and left-handed polarisation states then corresponds to a rotated polarisation ellipse. In a more intense light pulse the two components (with a larger difference in intensities) will experience a greater phase shift with respect to each other and hence further rotation of the ellipse. The mechanism is represented by Fig.7. A linear polarised pulse is made elliptical using a quarter-wave plate (or polari-

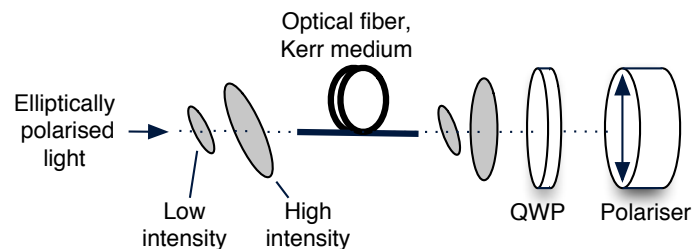


FIG. 7: Nonlinear polarisation rotation and selection of higher intensities

sation controller), after which the light passes through optical fibre and the polarisation ellipse rotates. The peak of the pulse rotates more than the lower intensity wings, thus the peak of the pulse can be made to pass through the final polariser, while attenuating the wings and thus achieving pulse shortening.

An advantage of P-APM fibre lasers is that the laser can be operated in two regimes: 1) in the soliton regime [52], where the net cavity dispersion,  $\beta_2$  is slightly negative, or 2) in the stretched pulse mode [53], where  $\beta_2$  is slightly positive. The stretched-pulse technique can deliver higher power pulses with shorter pulse widths [54, 55] because it is not constrained by limits imposed by soliton propagation [53, 54, 56]. For most frequency comb applications the stretched pulse mode has become the favoured option, since high peak powers are conducive to efficient comb broadening. With this in mind a short description of the stretched-pulse laser is described here. The fibre laser is balanced with positive and negative dispersive fibres, the positive  $\beta_2$  generally pertaining to the Er-fibre (See Fig. 8). The change in group velocity dispersion means that the pulse is temporally stretched and compressed in one cavity round trip. The changes in pulse width per pass can be an order of magnitude or more.

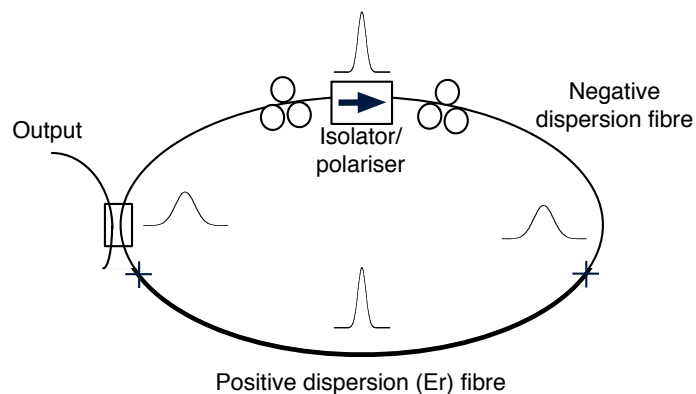


FIG. 8: Depiction of a stretched-pulse additive pulse mode-locked fibre laser

The output power and pulse energies of mode-locked fibre lasers depends on the laser design. Lasers in the soliton regime are restricted to output powers of a few mW and pulse energies  $\leq 50$  pJ (repetition frequencies vary from  $\sim 30$  to  $\sim 100$  MHz). Using the fibre lasers in the stretched pulse regime permits mean optical powers of  $\sim 10$  mW and pulse



energies of  $\sim 200$  pJ (single pulse propagation). There has been a report of output power much greater than this in the net-positive dispersion regime [57]. The authors report the occurrence of so called wave-breaking-free pulses that could be scaled up to high pulse energies. Their highest achieved output power reported was 675 mW with a corresponding pulse energy of 6.2 nJ. Their applicability to optical frequency synthesis is yet to be determined.

Rather than the air-silica microstructure fibre used with optical pulses to generate supercontinua, fibre-based systems use doped fused silica fibre (referred to as highly nonlinear fibre, HNLF). The dopants, typically germanium in the core and fluorine in the cladding, together with a core size reduction help increase the nonlinearity of the fibre [58]. The effective core areas are usually in the range of 10 to  $14 \mu\text{m}^2$  with nonlinear coefficients,  $\gamma$ , between 10 and  $20 \text{ W}^{-1}\text{km}^{-1}$ . The generation of an octave spanning comb centred around 1560 nm requires peak pulse powers of  $\sim 20$  kW (with corresponding pulse energies of  $\sim 2$  nJ). Early reports of octave-spanning SC generation across the 1 to  $2 \mu\text{m}$  region using fibre lasers are described in Refs [59–61]. Once the supercontinuum is generated a range of options is available to extract the offset frequency signal. Unique to fibre-systems (to-date) is an  $f:2f$  stage that does not require beam splitting into separate  $f$  and  $2f$  arms [39]. Using periodically poled lithium niobate (or any suitable quasi-phase matched crystal) for SHG of the long wavelength portion of the comb keeps the polarisations of the fundamental and SHG signal aligned. If the light polarisation across the supercontinuum varies then the setup is no longer optimal, but it can still perform better than *spatial*-interferometric methods. The task then is to ensure temporal overlap between the SHG pulse and the short wavelength portion of the comb. A means of doing this is by placing a carefully selected piece (a trial and error process!) of single mode fibre after the HNLF and using its anomalous dispersion to allow short wavelengths to catch up with long wavelengths.

The aspects in which fibre-laser based frequency combs fall down are with regard to  $f_{\text{CEO}}$  signal-to-noise,  $f_{\text{CEO}}$  frequency linewidth, and the servo bandwidth controlling  $f_{\text{CEO}}$ . Typically the  $f_{\text{CEO}}$  SNR is 10 dB weaker than those achieved with solid-state laser frequency combs. The weaker SNR is not an insurmountable problem, but the response time of the  $f_{\text{CEO}}$  to pump current changes appears to be a troubling issue. The low response bandwidth of the erbium fibre to pump changes partly limits the  $f_{\text{CEO}}$  control [62].

A new development in germanosilicate highly nonlinear fibres is the inclusion of a Bragg grating to enhance light generation at specific wavelengths [63]. This can be helpful in generating stronger  $f_{\text{CEO}}$  signals, or producing stronger beat signals when heterodyning between the comb and a cw signal. The gratings are inscribed by scanning a pulsed UV beam over a 2 or 3 cm section of the fibre (close to the input of the fibre) through a phase mask with a given period depending on the wavelength region of interest. The supercontinua exhibit a tenfold increase in signal level near the Bragg resonance wavelength. Even more recently Bragg gratings have been applied to air-silica micro-structured fibres for spectral enhancement [64]. Here the enhancement has not been as striking as

for HLNF fibres.

The first detection of the offset frequency in fibre laser systems occurred in 2002 [65], by means of an optical heterodyne with a mode-locked Ti:sapphire laser system. The first  $f_{\text{CEO}}$  detection using HNLF supercontinua occurred the following year [61], and shortly thereafter the offset frequency, and consequently the octave-spanning comb were stabilised [66]. Here, the repetition frequency is controlled through feedback to a fibre-stretcher with a bandwidth of  $\sim 5$  kHz, while  $f_{\text{CEO}}$  is controlled by feedback to the diode laser pump current. Unlike solid state systems  $f_{\text{CEO}}$  response to pump current modulation is relatively slow restricting the servo bandwidth to  $\sim 4.5$  kHz. These experiments demonstrated 0.2 mHz ( $2 \times 10^{-12}$ ) standard deviation for  $f_r$  and 60 mHz ( $3 \times 10^{-16}$ ) for  $f_{\text{CEO}}$ . The long term reliability of fibre-based frequency combs has been demonstrated by Adler *et al.* [38]. Here a continuous measure of the absolute frequency of a cavity stabilised diode laser was made over a time period of 88 hours.

Very recently the veracity of fibre combs has been tested by measuring the same optical frequency (at 194 THz) with separate fibre frequency combs [67]. With a measurement time of  $4 \times 10^4$  s ( $\sim 12$  hours) the measured frequencies agreed within  $6 \times 10^{-16}$ . The authors are confident that the limit was not imposed by the frequency comb technique, and expect future fibre-comb measurements to transfer accuracies with two orders of magnitude improvement. The future for fibre-laser based frequency combs looks particularly bright now that servo bandwidths on the control of the repetition frequency have been extended out to at least 200 kHz by using an intracavity electro-optic modulator [68].

## VII. PERFORMANCE AND APPLICATIONS OF OPTICAL SYNTHESISERS

The most impressive test of the quality of optical synthesis was made at NIST. They used four synthesisers and tested their ability to deliver the same answer in a frequency measurement of a common optical signal [10]. The disagreement between the devices was just a few parts in  $10^{17}$  over 1 second, averaging down to parts in  $10^{19}$  after 1000 seconds of averaging. It seems that the only limits seen so far are associated with various technical problems (Doppler Shifts arising from air fluctuations and thermal expansions of the optical tables on which the synthesisers sit).

The principal use of optical synthesisers to date has been to compare clocks in different frequency domains. For example, at NIST (National Institute of Standards and Technology, Boulder, CO), a comparison between two optical clocks, one based on a red transition (657 nm) in an ensemble of laser-cooled neutral Calcium atoms and a second based on an ultra-violet transition (282 nm) laser-cooled Mercury ion with a limit of just 7 parts in  $10^{15}$  over 1 second, improving to  $6 \times 10^{-16}$  at  $\sim 100$  s [9]. In separate work a synthesiser has been used to compare the microwave Cs clock transition at 9.2 GHz of the BNM-SYRTE fountain with an optical transition in cold Hydrogen atoms [69] with an accuracy of  $3 \times 10^{-14}$ . These tests are important for determining the per-



formance of new clocks and demonstrating the potential superiority of the new generation of optical clocks over the existing state-of-the-art devices in the microwave domain. However, perhaps of even more importance is the fact that these types of measurements are very sensitive tests of the existing conception of physics as well as in the search for new physics that goes beyond the existing standard model. For example, the precision measurements of the  $1S$ - $2S$  Hydrogen transition frequency and its associated Lamb Shift is the most sensitive test of Quantum Electrodynamics (QED) yet devised. If the validity of QED is assumed then these same and similar measurements of Deuterium can be used to generate precise measurements of the diameter of the proton and neutron. In terms of finding new physics one can look at recent measurements to search for drifts in the values of the fundamental constants by searching for frequency drifts between clocks built on different design principles. This is a complementary approach to the astrophysical tests that have, in one case, suggested that the constants are not, in fact, constant [70]. Once again, the comparison of the Hydrogen  $1S - 2S$  frequency and the Cs hyperfine transition can yield measurements of the time stability of the fine structure constant, as well as stability of the magnetic moments of various nuclei [69], and mass ratios of subatomic particles [71]. The sensitivity of the present measurements are nearly comparable to the astrophysical measurements despite being made only over a few years, rather than exploiting an effective measurement time of 10 billion years. This is another demonstration of the impressive performance of modern optical spectroscopy based on the frequency comb technology.

Optical synthesisers are at the forefront of a revolution in precision spectroscopy; around 200 papers a year are at present being published on techniques using these devices. Apart from those measurements mentioned earlier, there has been an explosion in the precision frequency measurement of numerous interesting spectral lines with accuracy below a few parts in  $10^{14}$ . The conventional method for making these measurements makes use of a highly stable cw laser that is locked to the transition of interest. This signal is then essentially counted by the optical synthesiser. However, in contrast to this approach, a couple of groups have made direct use of the optical frequency comb in the spectroscopic measurement. This was beautifully demonstrated in the case of one and two-photon transitions in Rubidium [72] as well as on the strong Cesium  $D_1$  or  $D_2$  lines [73]. These types of measurements will allow better scrutiny of the microscopic theories that predict the energy structure of atoms.

A recent application of optical synthesisers is the applica-

tion of the frequency comb for optical waveform synthesis. Essentially this process exploits the relationship between the offset frequency of the comb,  $f_{\text{CEO}}$ , and the evolution of the carrier-envelope phase. By a strong stabilisation of  $f_{\text{CEO}}$  we ensure that each pulse is an exact replica of the last. By locking  $f_{\text{CEO}}$  for two frequency combs that have different frequencies we ensure that the phase of each pulses from the two pulse trains evolves in the same way. We can thus coherently add those trains and thus synthesise an arbitrary optical waveform. The first steps in this direction have shown that it is possible to effectively emit a single coherent pulse from two synchronised laser sources [8, 74].

Using various techniques it has now become possible to produce coherent vacuum-UV and soft X-ray frequency combs [75, 76]. This is important both as a better understanding of atomic physics as well as testing present theories of physics (for example repeating the He experiments in [77]), as well as for spectroscopy of inner-shell electrons. One can also think of new outlandish devices such as coherent imaging methodologies based on X-rays.

## VIII. CONCLUSIONS AND FUTURE WORK

Remarkably exciting times are now upon us all as a result of all the new possibilities presented by the optical frequency comb technology. In the near future one expects to see optical frequency measurements in the sub- $10^{-16}$  level, and in fact if present rates of progress continue then one might provocatively predict a frequency measurement with an accuracy of  $10^{-18}$  by 2012 [78]. With this level of precision one would need to know the altitude of the experiment to within 1 cm just to correct for General Relativistic time dilation effects! The search for temporal instability of the fundamental constants using oscillators of this precision would become a real constraint on the astrophysical observations. Finally, new spectroscopic measurements may point to a new formulation of physics by finding exquisitely tiny violations to our present predictions of atomic structure. It has often been the case in Science that new understandings follow the application of new precision tools: perhaps we are poised at the beginning of just such an exiting time now.

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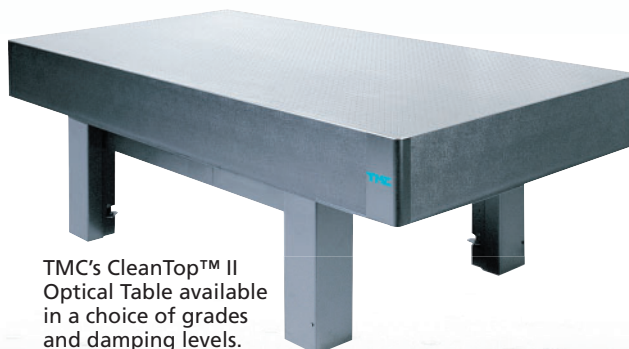
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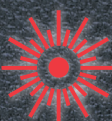
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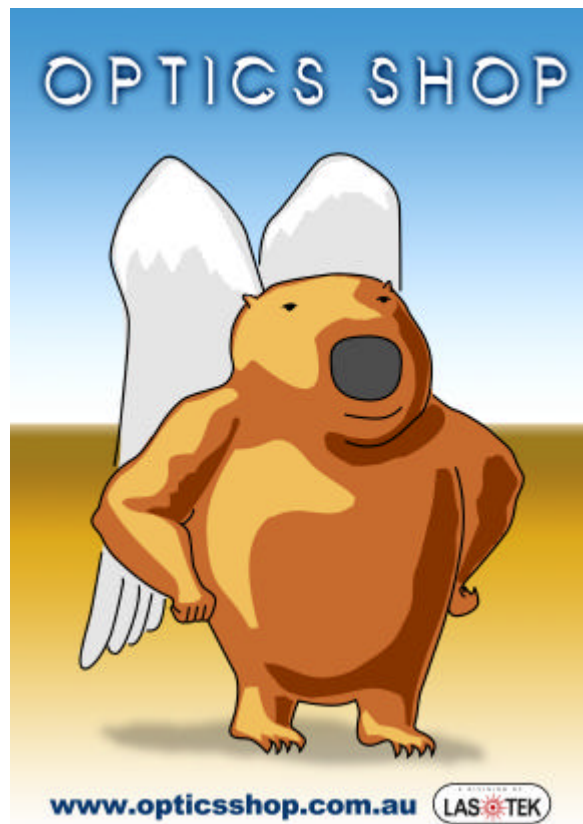


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## 20<sup>th</sup> Congress of the International Commission for Optics

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John Love

The 20th ICO Congress was hosted by the Changchun Institute of Optics, Fine Mechanics & Physics (CIOMP) in their magnificent new high-rise building opened in 2003 on the edge of the city of Changchun in the province of Jilin, some 800km northeast of Beijing. This city with a current population close to 7 million has a long and colourful history. For example, before and during World War II Changchun became the capital of the Japanese puppet state of Manchukuo and was home to Puyi, the last Emperor of China.

These days Changchun is a rapidly developing economic centre with many modern buildings - ironically some displaying Japanese architectural influence - wide sweeping streets and flourishing technology companies as well as being a centre for the Chinese car industry. Concurrent with these rapid developments, delegates flew into the old military-style domestic airport before the Congress and departed after the Congress from the impressive new Changchun international airport on its first day of full operation.

Congress guest Nobel Laureate Charles Townes, who gave a very perceptive opening Plenary address on "*The Development of the Science and Technology of Electromagnetic Waves*" also gave recognition to Changchun at the Congress Banquet as the "*City of Optics*" because of the highest concentration of optics researchers in China. For example, CIOMP houses some 700 researchers, 250 research students and 800 support staff.



*ICO-20 venue in the CIOMP building.*

The Congress attracted around 600 delegates from China and another 250 from 34 overseas countries who between them presented 1,000 of the 1,800 papers that had been originally submitted. The vast number and diversity of presentations required up to 12 parallel sessions per day over the 5 days of the meeting together with 2 large afternoon poster sessions.

In addition to Towne's presentation, 10 other Plenary speakers covered a broad range of topics. For example, Jianlin Cao from the Chinese Optical Society summarised "*The Current State and Progress of Optics in China*"; Tingye Li updated us with his views on "*Innovations, Economics & Applications: Revolution and Evolution in Optical Communications*"; James Wyant from the University of Arizona discussed "*Advances in Interferometric Surface Measurement*"; and Philip Stahl from NASA outlined the big questions about the universe and their link to "*NASA's Challenges in Optics for Future Space-based Science Missions*".

A special feature of the Congress was the award of the ICO 2003 Prize to Ben Eggleton, Director of CUDOS and an OSA Councillor for his outstanding work on optical fibres, waveguides and devices. The prize consists of a cash component of US\$2,000 and a glass medallion depicting an effigy of Ernst Abbe donated by the Carl Zeiss Foundation. Ben followed the presentation with his talk "*Towards Integrated Terabit per Second All-Optical*".



*Regenerators*” that presented a compelling summary of the latest strategic research and developments within CUDOS.



ICO-2003 Prize Medal



Ben Eggleton receives the ICO prize  
from René Dändliker & Secretary  
Maria Calvo

The AOS with the assistance of the Sydney Convention and Visitors Centre had made a formal and comprehensive bid to the ICO in 2004 to host the 21<sup>st</sup> ICO Congress in Sydney, Monday-Friday, 4-8 July 2008 at the Sydney Convention & Exhibition Centre at Darling Harbour. The Congress will incorporate the AOS Conference and, as a parallel event, the Opto-Electronics Communications Conference (OECC) incorporating ACOFT will be collocated at the same venue, Monday-Wednesday, 4-6 July 2008.

This proposal was discussed and endorsed by the ICO Bureau and subsequently supported by the ICO General Assembly meeting towards the end of the Congress. The Bureau is the peak committee responsible for overseeing all ICO activities, while the Assembly comprises members from the 51 territories and affiliated organisations such as IEEE LEOS, OSA, OWLS and SPIE that are involved in the ICO. A slide and video presentation promoting ICO 21 and Sydney was made to delegates as part of the Closing Ceremony of the Congress.

During the General Assembly meeting, John Love was elected a Vice-President of the ICO for the period 2005-2008 and subsequently was appointed ICO representative for the series of international meetings on Education & Training in Optics and Photonics (ETOP).





# Universal Michelson Interferometer

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## LEOI-20 Universal Michelson Interferometer

Uses a flat plane design which enables users easily place materials into the light path.

Experiment examples:

- Interference fringes
- Equal inclination interference
- Equal thickness interference
- White light interference
- Determination of wavelength
- Precise wavelengths comparison
- The refractive index of transparency slice
- The refractive index of air

## LEOI-21 Universal Michelson Interferometer & Fabry-Perot

Except having all features of LEOI-20, this model also enables users to do the experiments of Fabry-Perot Interferometer. Fabry-Perot Interferometer is used to observe the multiple-beam interference, measures fine structure of spectrum, i.e. wavelength disparity of yellow Sodium doublet lines.

Experiment examples:

- All the experiments on above LEOI-20
- The Fabry - Perot Interferometer
  - The multiple beam interference
  - Precise wavelengths comparison

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## Laser Mode Analyser Model LEOI-51

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### Introduction

Precision measurement and holography need a laser output with a fundamental transverse mode while laser ranging requires not only fundamental transverse mode but also single longitudinal mode. LEOI-51 Laser Mode Analyser allows users to quantitatively assess the mode characteristics of a laser. This can be done by performing a series of experiments and obtaining various parameters in which one can determine how the laser diode performs. Users can also perform the laser mode analysis on a computer as well as observe the mode spectrum with an oscilloscope connected.

### Experiment Examples

- Familiar with principle and operation of scanning confocal interferometer
  - Observation of longitudinal and transverse mode distribution
  - Observation of the modes of different lasers
  - Determine mode structure by calculating mode spacing of a laser
- The software will lead the user into different functions of the system. Users can perform analysis, display and printing of the laser modes.

### Specifications

He-Ne Laser	Cavity length: 246 mm Wavelength accuracy: 1 nm Centre wavelength: 632.8 nm
Scanning confocal interferometer	Cavity length: 20mm Finesse: >200 Free spectral range: 4 GHz Mode spacing error: < 20 MHz

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## Wide-angle transmission into photonic crystals

Presented at CLEO/QELS 2005 Baltimore, Maryland, USA 23–27 May 2005  
for the OSA New Focus/Bookham Student Prize competition.

Tom White

*Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS) and  
School of Physics, University of Sydney,  
NSW 2006, Australia  
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The 2005 Conference on Electro-Optics and the Quantum Electronics and Laser Science conference (CLEO/QELS) were held in conjunction with the Photonics Applications and Systems Technology conference (PhAST) from 23–27 May in Baltimore, USA. These colocated conferences continue to be one of the major international optics and photonics events of the year, attracting more than 5200 attendees and 320 exhibiting companies.

During the week, more than 1600 talks were presented across 12 parallel sessions, and in addition there were two plenary sessions covering topics as varied as commercial applications for optoelectronics, solid-state lighting, fermionic condensates and optical imaging of stem cells for medical research. While the contributed talks included many of the research highlights of the previous year, the most popular presentations were the more general tutorials and invited talks. For several of these presentations there was standing room only and even then the audience overflowed into the corridors.

One of the hot topics of the week was photonic crystal (PC) nanocavities, with a number of papers reporting both linear and nonlinear properties and applications of these structures. Kyoto University continues to lead the field in the fabrication of ultrahigh-Q PC cavities, reporting their latest experimental measurement of  $Q = 2.7 \times 10^5$  (Paper QWA2, Song et al., "Ultrahigh-Q nanocavity based on photonic-crystal double heterostructure"). Also from Japan was a postdeadline paper reporting all-optical switching in a PC nanocavity with a switching time of  $< 100$  ps and 10 fJ operating power (Postdeadline paper QPDA5, Tanabe et al., "Fast on-chip all-optical switches and memories using silicon photonic crystal with extremely low operating energy"). Other PC cavity papers covered topics including low-threshold lasers (QWA1, Strauf et al.), cavity quantum electrodynamics (QME5, Srinivasan et al.), organic semiconductor PCs (CMEE3, Kitamura et al.) and Raman amplification (CMU2, Yang et al.).

As one of the seven finalists for the OSA New Focus/Bookham Student Award, I was invited to present a paper to a judging panel during a special session of the conference. The title was "Wide-angle transmission into photonic crystals," in which I described some recent theoretical results on efficient coupling of light from free-space into the Bloch modes of a uniform photonic crystal. The remainder of this report is a summary of the work, which has since appeared in Applied Physics Letters [1]. The co-authors on this work are Ross McPhedran and Martijn de Sterke, also from CUDOS and the University of Sydney, and Lindsay Botten from CUDOS and the School of Mathematical Sciences, the University of Technology, Sydney.

### INTRODUCTION

Photonic crystals are expected to be one of the key technologies for developing all-optical devices and photonic integrated circuits. While they are best known for their ability to confine and guide light due to photonic bandgap effects, the unique dispersion properties of PCs are also being studied for a range of novel in-band applications. These properties include superprism behaviour, self-collimation effects, negative refraction and perfect lensing. To use these effects in practical devices it is essential to have an efficient method for coupling light into and out of the PC structure. This is necessary not only to minimise the insertion losses but also to prevent light from being scattered into other parts of the device and causing interference and cross-talk.

Several different approaches have been taken to improve the coupling at PC interfaces, including modifying the first few rows of cylinders to effectively apodise the interface [2, 3] and placing multi-layer gratings in front of the interface to pre-condition the incident fields for optimum coupling to the Bloch modes [4]. Here I consider transmission from a homogeneous dielectric into a uniform PC of high-index cylinders with no modifications to the interface. This class of PC exhibits very efficient coupling properties for a wide range of incident angles. I present one such PC that provides high-efficiency coupling to Bloch modes that exhibit strong self-collimation effects [5]. Both two-(2D) and three-dimensional (3D) simulation results are presented to demonstrate these properties.



## TRANSMISSION INTO ROD-TYPE PCS

Figure 1 shows the basic geometry considered here. The PC slab consists of Si rods with refractive index  $n_{\text{cyl}} = 3.4$  and radius  $r = 0.35d$ , arranged in a triangular lattice of period  $d$ . The core and cladding of the PC structure have refractive indices of  $n_{\text{slab}} = 1.46$  and  $n_{\text{clad}} = 1.458$  respectively. The core and the rods are of height  $h = 3d$ . In the 2D results presented below, the rods are taken to be infinite in length and embedded in a background of index  $n_{\text{slab}}$ .

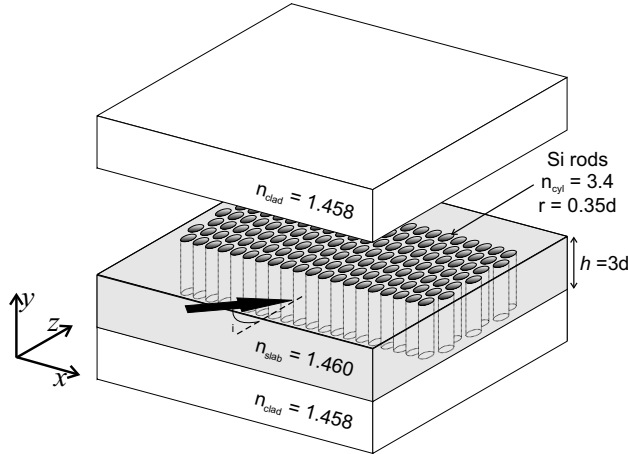


FIG. 1: Geometry of the PC slab with core and cladding index  $n_{\text{slab}} = 1.460$  and  $n_{\text{clad}} = 1.458$ . The upper cladding is lifted to show the interior structure of Si rods arranged in a triangular lattice with period  $d$ .

Consider first the coupling of light incident on the PC at an angle  $\theta_i$  as shown in Fig. 1. Figure 2 shows 2D plane wave reflectance spectra ( $R_\infty$ ) for light incident at  $\theta_i = 0^\circ$  (dotted curve) and  $\theta_i = 22.5^\circ$  (dashed-dotted curve), calculated using the Bloch mode scattering matrix method (BMM) [6]. In these calculations the PC is taken to be semi-infinite in extent, and hence it behaves as a perfect mirror ( $R_\infty = 1$ ) for bandgap frequencies, as can be seen at either end of the plotted spectral range. Observe that both spectra exhibit almost perfect coupling ( $R_\infty < 0.1\%$ ) at a normalised frequency of  $d/\lambda = 0.295$ , and  $R_\infty < 10\%$  over a bandwidth of approximately 15% of the centre frequency.

To demonstrate such efficient coupling in a realistic PC slab structure as in Fig. 1, a full 3D numerical calculation is required. Here the simulations are performed using a 3D Finite Difference Time Domain (FDTD) method, in which the boundary conditions are chosen to approximate an infinite cladding extending above and below the core. Figure 2 shows the 3D reflectance spectra for an elliptical Gaussian beam of width  $5d$  and height  $2.5d$  incident on 16 layers of PC at  $\theta_i = 0^\circ$  (solid curve) and  $\theta_i = 22.5^\circ$  (long

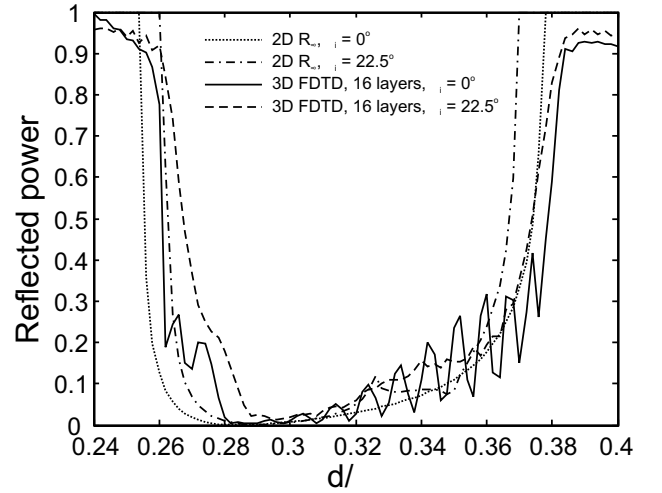


FIG. 2: 2D plane wave reflectance spectra (BMM method) for a semi-infinite PC and 3D FDTD reflectance spectra for a Gaussian beam incident on 16 layers of PC. Results are shown for  $\theta_i = 0^\circ$  and  $\theta_i = 22.5^\circ$ .

dashed curve). Note that the ripples in the 3D spectra are due to Fabry-Perot resonances between the front and rear interfaces of the PC – a feature not seen in the 2D calculations where there is no rear interface. The minimum reflectance for the 3D simulations is  $R \approx 1\%$ , which occurs at approximately the same frequency as in the 2D spectra. The difference in reflectance between the 2D and 3D results is attributed to the angular spread of the Gaussian beams in the 3D calculations.

The highly efficient coupling properties presented in Fig. 2 are far superior to results published for hole-type PCs, and are not limited to the specific PC parameters used in this example. From 2D simulations I have found that efficient, wide-angle coupling is a generic feature of rod-type PCs that occurs under two conditions: First, that incident light is mostly forward scattered by each cylinder and second, that when each layer of cylinders is considered as a grating, only a single grating order exists. These conditions can be satisfied in a wide range of rod-type PC geometries, thereby providing considerable flexibility for optimising other characteristics. As an example, the PC structure shown in Fig. 1 is designed to exhibit  $R < 1\%$  for  $0^\circ \leq \theta_i \leq 22.5^\circ$  and self-collimation properties at the same frequency. The reflectance spectra are shown in Fig. 2, and the self-collimation properties are demonstrated in the next section.

## SELF-COLLIMATION PROPERTIES

Self-collimation occurs when a beam incident on a uniform PC couples into a Bloch mode where the equi-



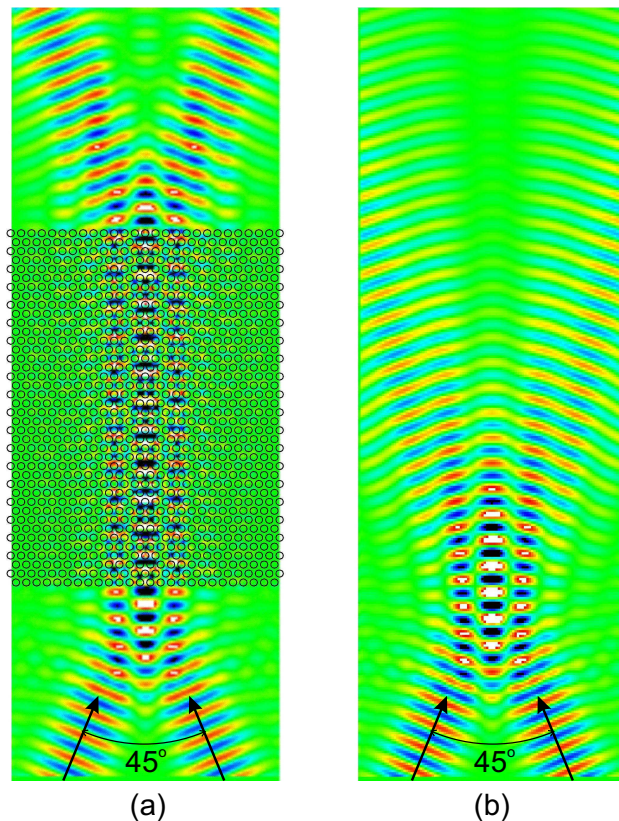


FIG. 3: (a) Electric field pattern for two Gaussian beams incident on a 40 layer PC at  $\theta_i = \pm 22.5^\circ$ . (b) Field pattern for the same two beams when the PC is removed (2D FDTD calculations).

frequency contour is locally straight [5]. When this occurs the wavevector components forming the beam all propagate through the PC in the same direction resulting in collimation. Moreover, if the equifrequency contour has straight sides, then multiple beams incident on the PC at different angles propagate parallel to each other while inside the PC. Photonic circuits based on auto-collimated beams have been proposed as an alternative to PC waveguide circuits as they have the potential for low cross-talk and easy reconfiguration [7].

Figure 3 illustrates an example of using self-collimation to combine two beams that are focussed onto the front face of a 40 layer PC with the same parameters as in Fig. 1. The electric field pattern in (a) clearly shows the collimation of the beams inside the PC when compared to (b) where the PC is re-

moved. Observe that the field pattern at the front face of the PC is transferred through the PC to the rear face with only minor distortion, and the beams continue to diffract once they exit the PC. A beam combiner with this geometry could be used as a platform for studying nonlinear interactions in photonic crystals.

In conclusion, I have found that highly efficient coupling to the Bloch modes of rod-type PCs is possible over a wide range of incident angles without any modification to the PC interface, in contrast to hole-type PCs. I have demonstrated that these properties can be combined with self-collimation behaviour to design highly-efficient in-band PC devices. Similar techniques could also be applied to the design of superprism structures, which require light to be coupled efficiently through two interfaces while maintaining a good beam shape.

#### ACKNOWLEDGEMENTS

I wish to thank the Australian Optical Society for providing funding to attend the CLEO/QELS conference as part of the 2004 AOS Postgraduate student prize.

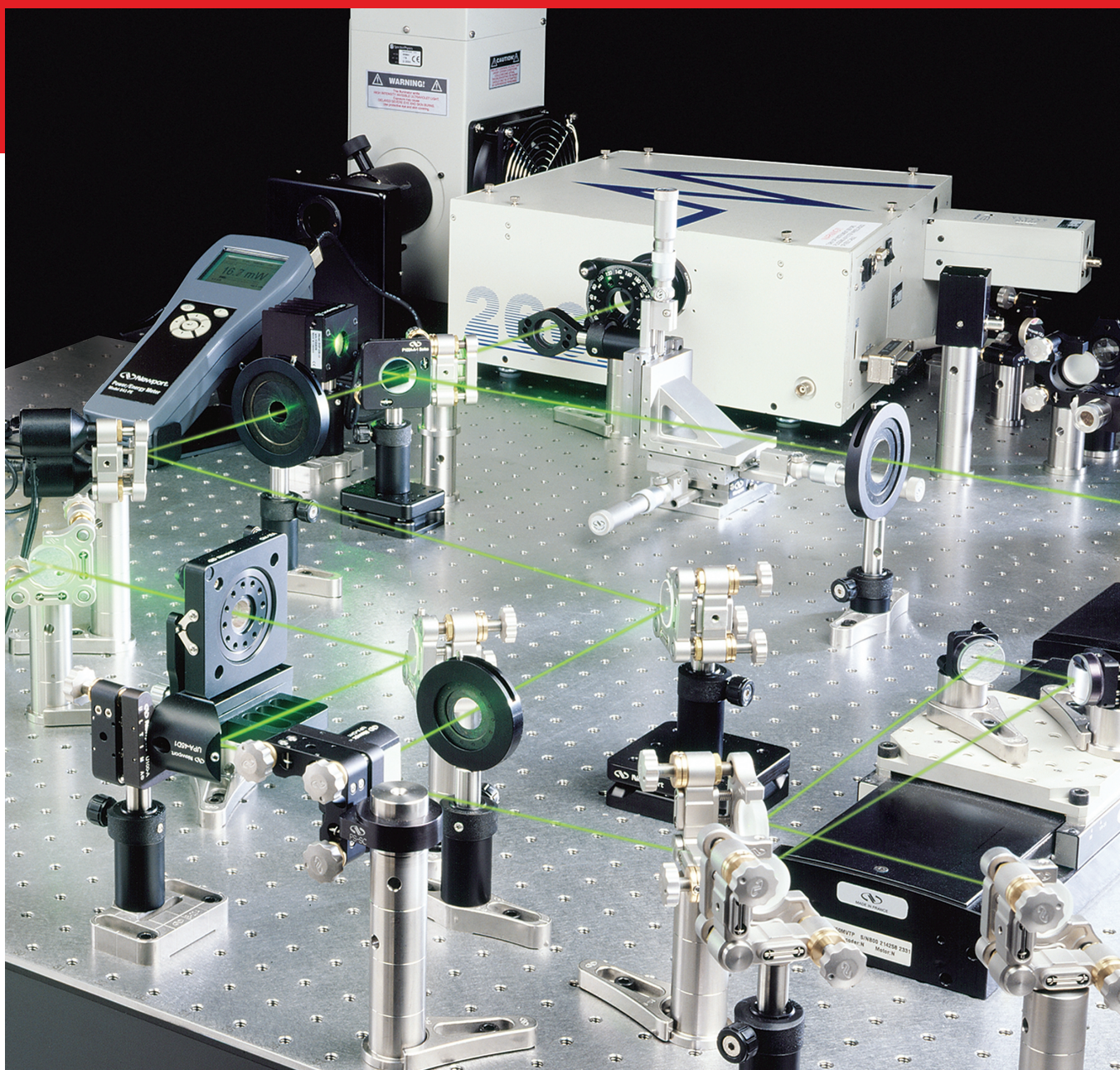
This work was produced with the assistance of the Australian Research Council under the ARC Centres of Excellence program.

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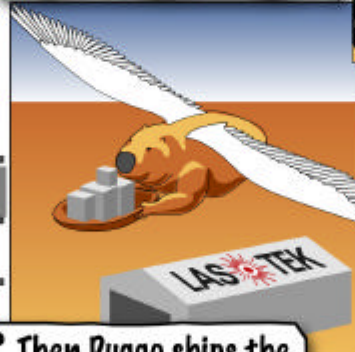
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The Australian Research Council Centre of Excellence for Quantum-Atom Optics (ACQAO) is one of Australia's contributions to the rapid development of quantum science that is happening around the world.

The Centre brings together scientists working in three cities, at the Australian National University (ANU) in Canberra, the University of Queensland (UQ) in Brisbane and the Swinburne University of Technology (SUT) in Melbourne, and links them with scientific partners in Europe and New Zealand.

Quantum science will play a major role in future technology and eventually our daily lives.

One area will be optics and wave effects for both light and atoms. Scientifically we are now able to investigate the quantum behaviour of larger objects, involving thousands and even millions of atoms, and see the transition from the microscopic world of a few particles to the macroscopic world of classical effects.

Technically we are now able to use the process of entanglement that was just a concept in the 1930s, and employ it in practical applications, such as communication systems.

We now have the technology for cooling atoms to unimaginably low temperatures and for creating Bose-Einstein condensates. Combining these, we are at the threshold of turning fundamental science into practical applications over the next two decades.

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The funding and support provided by the Australian Research Council, the three Universities ANU, UQ and SUT and the Queensland and Australian Capital Territory governments will allow us to tackle ambitious Outreach projects, to have an intensive exchange of people, to provide opportunities for young scientists and to build the required research facilities.



### ***Are atoms as ghostly as photons?***

The Einstein-Podolsky-Rosen (EPR) paradox comes about if we assume local realism: that is that certain properties of quantum particles are "real" before any measurements are made rather than having a ghostly, uncertain existence until actually observed.

So far, the paradox has only been tested experimentally with photons, and not with massive particles. For these, it may be more difficult to accept this quantum "ghostliness".

Physicists at the University of Queensland node of the Australian Research Council Centre of Excellence for Quantum-Atom Optics have now proposed a way to use another of Einstein's major contributions to 20th century physics, Bose-Einstein condensation, to test the paradox with atoms [see Phys. Rev. Lett. 95, 150405 (No. 15, 7 October 2005); "Einstein-Podolsky-Rosen correlations via dissociation of a molecular Bose-Einstein condensate."].

Karen Kheruntsyan, Murray Olsen and Peter Drummond have suggested that recent advances in the manipulation of atomic and molecular condensates can be adapted to perform a variant of the famous EPR gedanken experiment with correlated beams of atoms produced from a molecular BEC.

Related experiments with photons marked the emergence of quantum optics, the first field in which many of the fundamental properties of quantum mechanical theory were tested in laboratories.

The extension of these techniques to atomic and molecular physics will open a whole new field for fundamental tests with interacting massive particles.

This is of particular interest since these couple to the gravitational field, and hence can test quantum mechanics in a new way.





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## Digital camera performance: how to optimize settings<sup>1</sup>

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E-mail: [lionelbaker@ntlworld.com](mailto:lionelbaker@ntlworld.com)

### Abstract

Digital cameras are now available in a wide variety of designs. A simple test, based on the optimum print width obtainable with a camera, is used to determine the relative performance of different models. Optimum settings for the various controls provided by the manufacturer can also be found. Measured performance of six cameras is found to be approximately 75% of that expected from manufacturers' data.

### 1. Introduction

Digital cameras are now rapidly taking over the functions of their predecessors using roll film. Whether the application is related to professional photography, research, medicine, holidays or even mobile telephones the advantages of electronic imaging are now widely recognised. Small size, easy picture editing, image enhancing and emailing are just some of these. Designers have worked hard to provide the facilities of the film camera as well as embodying all the benefits of electronic imaging. Their success can be judged from soaring sales and the fact that some stores no longer offer film cameras.

There comes a time, however, usually after purchasing a second model or when comparing the performances of digital with film cameras, when image differences are seen but not explained in the handbooks. Help is not at hand, unfortunately, when camera reviewers describe resolution in terms of the number of pixels in the image sensor whereas in conventional photography we relate this to lens performance or grain size. Common terms such as 'zoom and focus are understood, but others such as 'sharpness', 'basic', 'normal' or 'fine' quality modes, which have a direct influence on the number of images that can be stored, are not. Confusion is further compounded by the unknown relationship between the number of physical pixels in the image sensor and additional pixels that may be generated by interpolation as required by the de-mosaicing process.

The prime function of a camera is to produce a picture that is usually viewed on a screen or as a print. The quality of this image depends on the performance of a long chain of elements and processes, including the lens, sensor, image processing, colour rendition, camera shake, display medium and the eye, under particular viewing conditions. It should also be borne in mind that the artistic quality of a photograph often depends more on composition than is the responsibility of the photographer than on camera resolution.

In spite of the obvious complexities of a thorough system analysis some success has been achieved in

comparing the performance of different cameras by the use of a simple test procedure, appropriate for use by the amateur, as described below.

### 2. Camera metrics

A selection of important papers [1,2] on the subject of image quality is available for detailed study. Standards in this field produced by ISO include:

ISO 12233: Photography-Electronic still picture cameras-Resolution measurement

ISO 14524: 1999: Photography-Electronic still picture cameras-Methods for measuring Opto-electronic Conversion Functions

ISO 15739: Photography-Electronic still picture imaging-Noise measurements

The researcher should study these references but there is a much simpler approach [3], if only the relative performance of cameras is sought. This is helped by the fact that electronic image sensors apply a process of 'equalization' maximising the contrast over spatial frequencies in the image that are detected above a threshold. This process provides considerable benefit by increasing the sharpness of edges - a fact that is welcomed even though resolution may be reduced compared with that usually available with a film camera. It also aids the determination of the spatial frequency bandwidth (SFB) of digital cameras. The SFB term is used here, in preference to resolution limit used in film photography, because it includes aliasing effects not seen when using film.

Our task is to define a metric related to overall camera quality. Since the process of measurement is defined as the 'ascertainment of extent in comparison with a reference' our first task is to define a suitable reference. In the context of photography we have chosen the average eye and define our metric as an Optimum Print



Width (OPW). This is the width of print, viewed at arm's length, where the resolution limit of the eye viewing the print is matched to the SFB of the camera. We are equating the cone size in the retina with the effective size of the pixels in the camera. This metric can be thought of as a measure of information content across the image. High quality cameras will have a large OPW. This parameter embodies the number of effective pixels, their size, lens aberrations and focusing errors as well as image processing. Even the quality of the viewer's eye and printer can be taken into account if required.

### 3. Method of test

In order to determine the SFB of our camera we need a test pattern with a variable spacing of lines as shown on the left in Fig. 1. This pattern has the great advantage of being invariant with magnification. Thus we do not need to know the focal length, zoom setting or magnification used - at least to a first order. A magnified image of this pattern, as shown on the right, will reveal an unresolved grey disk of diameter  $d$  at the centre. Some cameras show distorted lines within this area due to aliasing and these should be included when determining  $d$ . Only straight lines provide valid information. The grey disk might be thought of as a hole or sink removing information not required or not available in the final image.

Since the pattern has 36 bars and spaces the SFB of the camera producing this image will be given by  $36/\pi d$  and the number of cycles of limiting resolution across the complete image of width  $D$  will be  $36D/\pi d$ . This must equal the number of cycles across our print, assuming no cropping, which is  $5(OPW)$  where the resolution limit of the average eye is taken as 5 cycles/mm - all dimensions are in mm.

It follows from the above that

$$36D/\pi d = 5(OPW)$$

or

$$OPW = 2.3D/d.$$

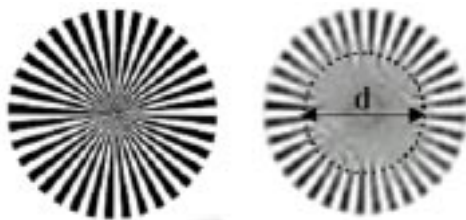


Fig. 1 Sector star pattern and its image on the right

The diameter of the grey disk viewed by a person with limiting resolution of 5 cycles/mm at a range of 500 mm is 2.3 mm.

The ratio  $D/d$  can best be obtained by loading the recorded image into a computer and using the length scale and zoom facilities available in Photoshop or equivalent software. Alternatively an enlarged print could be made but this will include the effect of the printer and paper. As a last resort some indication may be obtained just by using the camera display itself.

Depending on the size of the sector star pattern printed here it may be possible to use that, alternatively you may contact the author by e-mail and he will send a file with an image of the pattern and detailed instructions on how to carry out the test. It is preferable, for ease of measurement, to select a camera range such that  $d$  is about half the spread of the pattern.

We have assumed the limiting resolution of the eye is 5 cycles/mm at arm's length but the value for a particular person can be determined by judging  $d$  at a known distance and scaling the value to arm's length viewing. An individual with impaired vision will benefit from a larger OPW.

### 4. Test results

Images of sector star patterns obtained using different digital cameras have been published [3] and a selection of cameras tested since then with the number of megapixels ranging from 1.3 to 7 and OPW values varying between 89 mm and 270 mm gave values as indicated in the table below. Since we require a minimum of 2 pixels to detect a single cycle we need  $10(OPW)$  pixels across our image width viewed with an eye of limiting resolution of 5 cycles/mm. It follows that the expected value of the OPW should be the number of pixels across the sensor width divided by 10. In the table  $OPW_m$  is the measured value and  $OPW_h$  is the expected value based on the number of pixels across the sensor width as given in the handbook for that camera.

Megapixels	$OPW_m$	$OPW_h$
1.3	89	128
2	126	163
3	163	203
4	178	231
5	190	258
7	270	307

An immediate observation is that the  $OPW_h$  value calculated from the manufacturers data is substantially larger than can be expected in practice. This is most likely to be due to the fact that the number of pixels quoted in the handbook is much larger than is available



for image formation, as a CCD sensor requires separate red, green and blue pixels in order to provide a coloured image. This is not necessarily the case with a CMOS sensor where colour information can be accessed from within the depth of every pixel.

## 5. Conclusions

Rapid rise in the popularity of digital cameras combined with significant developments in the complex optical and electronic technologies involved have resulted in some confusion regarding image information content and spatial resolution. The total number of pixels, as a measure of image resolution widely adopted in the media, is confusing to the user firstly because a CCD sensor requires three pixels for each colour and secondly because a 2-dimensional comparative measure is less easily comprehended than a 1-dimensional picture width.

It is hoped that the simple metric described here, based on measuring the optimum print width (OPW) available for a particular camera, will help users to compare the performance of different models and to optimize the various controls provided by the manufacturer. Tests on six cameras suggest this measure of camera performance provides results around 75% of values calculated from handbook data.

An informal digital camera-testing group operated by e-mail [4] has been formed to help judge the support for an improved method for testing appropriate for the average camera user. The information obtained should also be of value to manufacturers when designing new models.

## References

1. Baker, L. R. (Ed) Selected Papers on Optical Transfer Function: Foundation and Theory, SPIE Milestone Series, Vol. MS 59, 1992 (SPIE, Bellingham, WA).
2. Baker, L. R. (Ed) Selected Papers on Optical Transfer Function: Measurement, SPIE Milestone Series, Vol. MS 60, 1992 (SPIE, Bellingham, WA).
3. L R Baker, "Digital cameras: spatial image quality matters", The Imaging Science Journal", Vol 53, pp38-45, RPS 2005.
4. [www.geocities.com/baker\\_lionel/DigicamTest](http://www.geocities.com/baker_lionel/DigicamTest)

## (Footnotes)

<sup>1</sup> This paper is based on a technique first proposed at an invited lecture organised by the Imaging Science Group of The Royal Photographic Society on 14 October 2003

## Lionel Baker

Following completion of a Research Fellowship at the Royal Aircraft Establishment in 1958 Dr Baker joined Sira and became a founding member of their Board of Directors in 1972. He presented the first paper on electronic wavefront sensing at an ICO conference on "Interference and Coherence" held in Sydney in 1964. Since retiring from Sira as Technical Director in 1990 he now operates as an International Consultant specialising in surface metrology and image quality and chairs a BSI committee on Photonics Standards. He is a Fellow of the Institute of Physics, the SPIE and the OSA.

## AOS Conference Calendar

### AOS conferences in 2006

ACOFT/AOS 2006, RMIT, July 2006 (2<sup>nd</sup> week)  
(3-days ACOFT + 1.5 day AOS with half day joint sessions.)

AIP Congress, Brisbane, December 2006

### AOS conferences in 2007

ACOFT/COIN 2007, Melbourne, probably in July.  
(Not an AOS conference, but AOS AGM will likely be held there!)

### AOS conferences in 2008

ICO Congress 2008 colocated with AOS conference, Sydney, July 2008

ACOFT/OECC 2008, Sydney, July 2008





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OCTOBER 2005



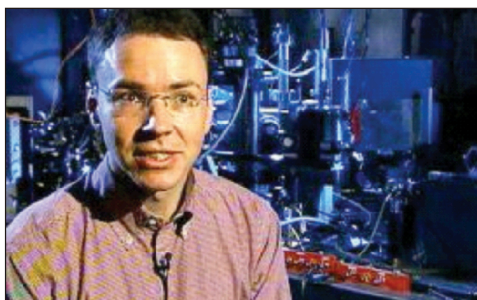
# NEWSLETTER



COMMISSION INTERNATIONALE D'OPTIQUE • INTERNATIONAL COMMISSION FOR OPTICS

## ICO Prize 2005 goes to Immanuel Bloch

**Bloch wins award for exploring quantum physics with optical microtraps formed by laser light.**



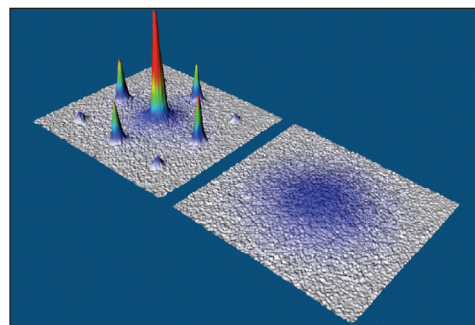
Immanuel Bloch, a professor of physics at the Johannes Gutenberg-University in Mainz, Germany, has won the ICO Prize 2005, celebrating the World Year of Physics.

In 1982 ICO established the ICO Prize, to be given annually to an individual who has made a noteworthy contribution to optics, published or submitted for publication before he or she has reached the age of 40. (Specifically, the prize-winner must not have reached the age of 40 before 31 December of the year for which the prize is awarded.)

The proposal of the ICO Prize Committee for this year, celebrating the World Year of Physics, was to award it to Dr Immanuel Bloch from the Johannes Gutenberg-University of Mainz, Germany. This proposal was unanimously approved by the ICO Bureau held in Changchun (China) last August. The award citation reads: "The ICO Prize for the year 2005 is given to Dr. Immanuel Bloch in recognition of his outstanding contributions in the areas of condensed matter physics, quantum optics, quantum information and atomic and molecular physics. These achievements were done as a researcher younger than 40 years old."

Bloch (aged 33) is full professor of physics at the Johannes Gutenberg-University of Mainz, Germany. His research interests include the investigation of ultra-cold bosonic and fermionic quantum gases, with special attention to applications in the field of condensed-matter physics, quantum optics, quantum information, and atomic and molecular physics.

His recent research has focused on exploring ultra-cold quantum gases in artificial periodic potentials formed by laser light, so-called optical lattices. Such optical lattices create a potential landscape of hundreds of thousands



Based on the first realization of Bose-Einstein condensation, by Nobel prize winners Wolfgang Ketterle and US physicists Eric Cornell and Carl Wieman, Immanuel Bloch has become the first to crack the Bose-Einstein condensation wave and regularly arrange several hundred of these special atoms into a glowing grid or optical lattice. In the future, this type of optical lattice could make up the basic elements of a new kind of matter state with applications in quantum computing.

of small optical tweezers like microtraps, in which the atomic gases can be trapped. Among Bloch's research highlights are the first experimental observation of a quantum phase transition from a superfluid to a Mott insulating state of matter; the observation of collapse and revivals of the macroscopic quantum field of a Bose-Einstein condensate (BEC); and the realization of collisional quantum gates for large-scale entanglement and quantum-information purposes.

Very recently his group was able to establish Hanbury Brown and Twiss-type noise-correlation techniques for the detection of strongly correlated many body quantum phases of ultra-cold atoms in periodic potentials (*Nature*, 2005).

Bloch studied physics at the University of Bonn, with a subsequent research visit to Stanford University. He received his PhD from the Ludwig-Maximilians-University in Munich for his work on atom lasers and phase-coherence properties of atomic BEC in the group of Theodor W Hänsch. Subsequently, he became junior group leader for ultra-cold quantum gases at the Max Planck Institute for Quantum Optics, Garching, and the Ludwig-Maximilians University in the same group.



In October 2003, at just 31 years of age, he was appointed to full professorship of physics (C4) at the Johannes Gutenberg-University in Mainz, Germany.

He has received several prizes for his research activities, among them the Otto Hahn Medal of the Max Planck Society (2002), the Rudolf-Kaiser Prize (2003) recognizing his work on ultra-cold quantum gases, and the 2005 Gottfried Wilhelm Leibniz Prize of the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), considered the most valuable prize in German research.

Bloch is expected to deliver an invited plenary lecture at the forthcoming ICO Topical Meeting in Optoinformatics, which will be

held in Saint Petersburg in September 2006, where the corresponding award ceremony will take place.

The ICO Prize Committee, chaired by Prof. Asher Friesem and comprising Profs. Henri H. Arsenault, Guofan Jin, Giancarlo Righini, Bahaa E. A. Saleh and Andrew M. Weiner, is now seeking nominations for the 2006 ICO Prize. Nominators are asked to follow the instructions given at the ICO website. Nominations should be sent by 15 April 2006 to Prof. A. Friesem, Chair of the Committee, Department of Physics of Complex Systems, The Weizmann Institute of Sciences, P.O. Box 26, Rehovot 7610, Israel. Fax: +972 89344109. E-mail: [friesem@wicc.weizmann.ac.il](mailto:friesem@wicc.weizmann.ac.il).

## ICO Congress in Changchun is biggest ICO event ever



Opening ceremony of ICO-20 at the hall of CIOMP. The ceremony was chaired by the president and vice-president of the Chinese Academy of Science, Yongxiang Lu and Jianlin Cao respectively, who warmly welcomed the congress delegates.



Discussion at the poster sessions.

ICO holds its General Congress every three years, consisting of a scientific meeting and the triennial General Assembly of the Commission. ICO-20 was held at the Changchun Institute for Optics and Fine Mechanics (CIOMP), Changchun, China, on 22–26 August 2005.

More than 660 delegates, from 34 countries all over the world, met for the scientific part of the event, which consisted of 11 parallel scientific sessions: Optical Devices and Instruments; Optical Communications; Biomedical Optics; Optical Information Processing; Lasers and Laser Technologies; Materials and Nanostructures; Display Devices and Systems; Remote Sensing and IR Devices and Systems; MEMS, MOEMS and NEMS; Illumination, Radiation and Colour Technologies; and Optical Design and Fabrication, together with corresponding poster sessions.

More than 1000 papers were submitted for presentation at ICO-20, and the Programme Committee selected around 830 of them. The congress started with three plenary sessions. Charles H. Townes, winner of the Nobel Prize for Physics in 1964, gave a lecture entitled “Development of the Science and Technology of Electromagnetic Waves”, in which he demonstrated that dynamism and enthusiasm are possible at the age of 90. Jianlin Cao’s lecture “The Current State and Progress of Optics in China” included statistics showing the emerging potential of optics and photonics in China (with currently 150 000 PhD students). Tingye Li, from AT&T Labs, presented “Innovations, Economics and Applications: Revolution and Evolution in Optics Communications”. James C. Wyant lectured on “Advances in Interferometric Surface Measurement”, while A. W. Lohman and J. Jahns spoke on “Diffraction Optical Processing of Temporal Signal” and H. Philip Stahl on “NASA’s Challenge in Optics for Future

Space-based Science Missions”. The award ceremony and third plenary session consisted of the presentation of awards and medals and four lectures, presented by ICO prize-winners Benjamin Eggleton (ICO Prize 2003), Ashok V. Krishnamoorthy (ICO Prize 2004), Milivoj Belic and Caesar Saloma (both Galileo Galilei Award 2004). Four hundred and eighty-three oral communications (including more than 80 invited papers) and 345 poster contributions were presented during the week.

In that same week, an exhibit on optics and optoelectronics industries was organized at the Changchun International Conference and Exhibition Center, an impressive modern building located in the new industrial area of Changchun. Under the lemma “Light of science leads to the future” more than 200 enterprises in optics manufacturing, telecommunications and related technologies were present in the hall. To give an idea of the dynamism of the exposition, local and national industries distributed in the order of 300 000 invitations. Moreover, the banquet of the ICO meeting took place in a magnificent park area where the most qualified tourist points were located, under an appealing Chinese atmosphere.

ICO gratefully acknowledges Guoguang Mu (general chair), Guofan Jin (Programme Committee chair), Arthur H. Guenther (International Advisory Committee chair), Jianlin Cao (International Organizing Committee chair), Ming Xuan (Local Organizing Committee chair) and their colleagues at the conference committee sessions for the considerable amount of work they did, which resulted in a very enjoyable and fruitful event.

As is traditional, the ICO General Assembly took place in two subsequent sessions, where the reports of the president, secretary, associate secretary and treasurer were presented. Moreover, the various committees of the ICO Bureau presented their corresponding triennial





Some members of the old and new ICO Bureau at the gate of CIOMP, where ICO-20 took place. From left to right, first row: A Wagué, M Gu, G Jin, A Guzmán, M Kujawinska, M L Calvo, I Yamaguchi and Y Kim. Second row: J Love, A Friberg, R Dändliker, H Arsenault, A A Friesem, G C Righini, G Von Bally, P Chavel, G Sincerbox, A Sawchuk and T Tshudi.

reports. Among the activities at the General Assembly were the election of the new Bureau for the next triennial term and the approval of admittance of new members, as well as the designation of the location for ICO-21. In the forthcoming sections of this newsletter, summaries of these aspects are reported.

As a satellite meeting of ICO-20, the 5th International Workshop on Adaptive Optics for Industry and Medicine (IWAOM) was held in Beijing from 28 August to 1 September, with Wenhan Jiang as chairman of the Programme Committee. Development of adaptive optics has reached the stage of extending the applications of optics from astronomy and laser propagation to many fields of industry and medicine. Many new advances have been achieved in recent years. Four successful work-

shops on AO for industry and medicine have already been held.

ICO felt it was very important to support this valuable event. Many topics were presented during the workshop, including AO for lasers and communication; medical applications; new wavefront correctors; new wavefront sensors; wavefront reconstruction and control algorithms and hardware; beam diagnosis; and innovative systems and theory.

To summarize, it is remarkable that this was the first time that an ICO General Congress was organized in a developing country, and the third time in an Asian country (after those in Japan and South Korea). The Congress was a great success, and the hospitality of the CIOMP, all the organizers and the city of Changchun was an added bonus.

## Two Territorial Committees become new members of ICO

During the last three years, three Territorial Committees – Ecuador, Greece and Moldova – have applied to become ICO members. Greece and Moldova were accepted unanimously as members by the ICO General Assembly in Changchun.

The presidents of the Greece and Moldova Territorial Committees are Prof. Nikos Vainos, from the Engineered Photonic Media Laboratory, the National Hellenic Research Foundation, Athens, and Prof. Andrei Andries from the Center of Optoelectronics, the Institute of Applied Physics, Academy of Sciences of Moldova, Chisinau.

Moreover, Ecuador, Tunisia and Morocco have been accepted as “associate members”. Recently, a new application for associate mem-

bership has been received from South Africa, through Prof. Philemon Mjwara from the National Laser Center of South Africa, Pretoria.

The Bureau has been authorized by the General Assembly to transform associate membership into full membership during the forthcoming triennium as soon as all the required conditions are fulfilled.

Moreover, each international society member designates its representative to the ICO Bureau. The LAM Network appointed Prof. Ahmadou Wagué of University Cheikh Anta Diop (Dakar, Senegal) and OWLS appointed Prof. Min Gu of the Center for Microphotonics, Faculty of Engineering and Industrial Sciences, Swinburne University of Technology (Australia), as their ICO vice-presidents.

## New ICO Bureau elected during the General Assembly

During the General Assembly, the new ICO Bureau was elected by the members. It consists of: **president** – A Friberg (Finland); **past-president** – R Dändliker (Switzerland); **secretary** – M L Calvo (Spain); **associate secretary** – G Von Bally (Germany); **treasurer** – A Sawchuk (USA); **IUPAP Executive Council delegate** – Y Petroff; **vice-presidents** – H H Arsenault (appointed by SPIE), S N Bagayev (Russia), A Guzmán (Colombia), G F Jin (China), M

Kujawinska (Poland), B Y Kim (South Korea, from industry), H Lefèvre (France, from industry), J Love (Australia), M Gu (appointed by OWLS), T Tshudi (appointed by EOS), A Wagué (appointed by the LAM Network), A M Weiner (appointed by IEEE/LEOS), I Yamaguchi (Japan); **senior adviser “ad personam”** – P Chavel (France). In addition the OSA representative now has to be designated by the OSA Board.

## News from ICTP: Gallieno Denardo wins Educator Award

The International Society for Optical Engineering (SPIE) established the Educator Award in 2003. The award is given to prestigious colleagues in recognition of outstanding contributions to optics education as SPIE instructors or educators in the field. The award

has an honorarium of \$2000. For 2005 the Educator Award has been given to Gallieno Denardo of the Abdus Salam International Centre for Theoretical Physics (ICTP), Italy. Denardo has been very active during the last two decades in promoting optics and photonics





Gallieno Denardo, ICTP faculty member and local organizer of the series of Winter Colleges in optics at ICTP, Trieste, Italy.

activities at the ICTP. Among these activities is the Winter College on Optics, usually held in January and February of each year, offering since 1995 various relevant topics and lectures to attendees from all over the world, and in particular from developing countries.

The Winter College is an activity sponsored as well by ICO, and international societies like SPIE, OSA and OWLS.

Since 2004 Denardo has been involved in new initiatives like the Trieste System Optical Sciences and Applications (TSOSA) advisory group. This is a new body created to help the ICTP promote optical sciences in the developing world. One of its priorities is the develop-

ment of mentoring activities for ensuring quality programmes for the exchange of students from developing countries, so that they can get specializations in reputed laboratories and research centres. ICO is also supporting this mentorship programme along with IAEA, EOS, OSA, OWLS, SPIE and UNESCO. It is expected that in forthcoming years proposals will be received from specific qualified centres to initiate this joint venture.

The Educator Award was won by Judith Donnelly in 2003 and James R Janesick in 2004. For more information see <http://oemagazine.com/fromTheMagazine/jun05/pdf/spieworld.pdf>.

## ICO-21 to be held in Sydney, Australia, in July 2008

One of the ICO General Assembly's responsibilities is deciding the location of the next ICO General Meeting and General Assembly. In Changchun we considered the bid received from the Australian Optical Society and presented by John Love, from the Research School of Physical Sciences and Engineering, Australian National University. The bid, supported by a high-quality presentation and

details of the forthcoming organization, was unanimously approved. Therefore, we will hold ICO-21 at the Sydney Convention Centre in Sydney, Australia, in July 2008. In due time more information will be provided. The call for bids for ICO-22, to be held in 2011, is now open to all our territorial committees. Bids should be sent to Ari Friberg ([ari.friberg@imit.kth.se](mailto:ari.friberg@imit.kth.se)).

## Contacts

International Commission for Optics (<http://www.ico-optics.org>).

### Bureau members (2002–2005)

**President** R Dändliker  
**Past-president** A H Guenther  
**Treasurer** G T Sincerbox  
**Secretary** M L Calvo,  
 Departamento de Óptica,  
 Universidad Complutense,  
 28040 Madrid, Spain. E-mail:  
[mlcalvo@fis.ucm.es](mailto:mlcalvo@fis.ucm.es).  
**Associate secretary** A T Friberg  
**Vice-presidents, elected**  
 A A Friesem, N Gaggioli,  
 G F Jim, B Y Kim,  
 M Kujawinska, G C Righini,  
 L Wang, I Yamaguchi  
**Vice-presidents, appointed**  
 H H Arsenault, G von Bally,  
 A A Sawchuk, T Tschudi,  
 A Wagué, A M Weiner  
**Senior adviser (ad personam)**  
 P Chavel  
**IUPAP Council representative**  
 Y Petroff



## Forthcoming events with ICO participation

### 2005

#### 5–7 October 2005

##### MUSCLE XIV (Multiple Scattering Lidar Experiment)

Quebec City, Canada. Contact: Dr Gilles Roy.  
 E-mail: [gilles.roy@drdc-rddc.gc.ca](mailto:gilles.roy@drdc-rddc.gc.ca).

#### 17–20 October 2005

##### International Topical Meeting on Optoinformatics

St Petersburg, Russia. Contact: Dr Ekaterina Yutanova. E-mail: [conf\\_optics@mail.ifmo.ru](mailto:conf_optics@mail.ifmo.ru).  
 Web: <http://ysa.ifmo.ru/tmo2005/>.

#### 24–26 October 2005

##### 9th International Conference on Education and Training in Optics and Photonics (ETOP)

Marseille, France. Contact: Serge Ungar. E-mail: [serge.ungar@popsud.fr](mailto:serge.ungar@popsud.fr). Web: [www.ETOP2005.org/](http://www.ETOP2005.org/).

#### 12–15 December 2005

##### International Conference on Optics and Optoelectronics (ICOL-2005)

Dehradun, India. Contact: J A R Krishna Moorthy. E-mail: [krish@irde.res.in](mailto:krish@irde.res.in). Web: [www.icol2005.com/](http://www.icol2005.com/).

### 2006

#### 30 January – 10 February 2006

##### Winter College on Quantum and Classical Aspects of Information Optics

ICTP, Trieste, Italy. Local organizer: G Denardo.  
 E-mail: [Smr173@ictp.it](mailto:Smr173@ictp.it).

#### 4–7 September 2006

##### ICO Topical Meeting on Optoinformatics 2006

Saint Petersburg, Russia. Contact: Dr Ekaterina Yutanova. E-mail: [Pavlov@soi.spb.ru](mailto:Pavlov@soi.spb.ru).

#### 26–29 October 2006

##### 7th International Young Scientists Conference "Optics and High Technology Material Science SPO 2006"

Kiev, Ukraine. Contact: Dr Viktor O Lysiuk.  
 E-mail: [lysiuk@univ.kiev.ua](mailto:lysiuk@univ.kiev.ua).

### 2008

#### 7–11 July 2008

##### 21st Congress of ICO

Sydney Exhibition & Convention Centre, Darling Harbour, Sydney, Australia. Contact: Prof. John Love. E-mail: [jdl124@rsphysse.anu.edu.au](mailto:jdl124@rsphysse.anu.edu.au).

Responsibility for the accuracy of this information rests with ICO. President: Professor René Dändliker, Institute of Microtechnology, University of Neuchâtel, CH-2000 Neuchâtel, Switzerland. Associate Secretary: Professor Ari T Friberg, Royal Institute of Technology, Optics, Electrum 229, SE-164 40 Kista, Sweden; e-mail: [ari.friberg@imit.kth.se](mailto:ari.friberg@imit.kth.se).



# Postgraduate and Honours Research with CUDOS

## Our Research Programs

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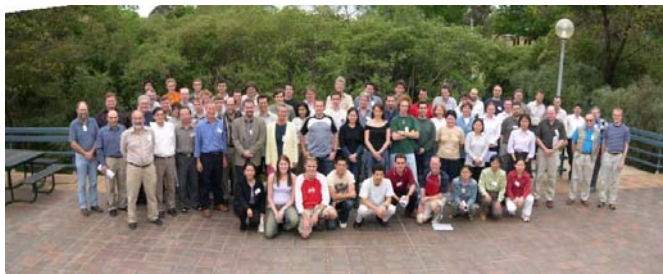
CUDOS has a range of exciting theoretical and experimental research projects for students at Undergraduate and Postgraduate level. We will provide you with strong mentoring support, experienced academic advisors and plenty of interaction with research staff and other students. We have state of the art facilities in our experimental laboratories at Sydney, ANU, Swinburne and Macquarie and strong theory research programs at Sydney, ANU and UTS.

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Professor Ben Eggleton, [egg@physics.usyd.edu.au](mailto:egg@physics.usyd.edu.au)
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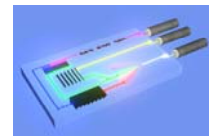
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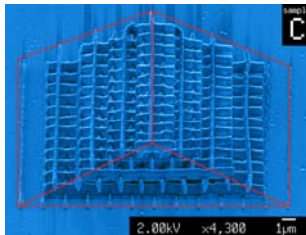
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## CUDOS Projects – towards the photonic chip!

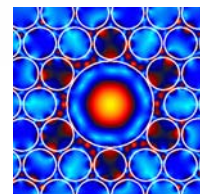
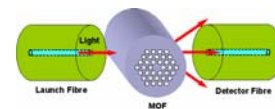
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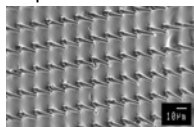
The aim of the **Microphotonics** project is to design, fabricate, characterize and model 3-D polymer-based photonic crystal structures. The demonstration of a photonic crystal superprism is of particular interest because of its startling optical properties.



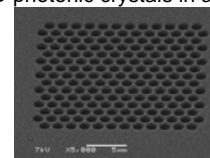
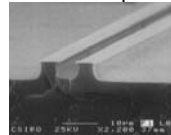
The **Micro-structured Optical Fibre (MOF)** project explores novel MOF designs for use in photonic device applications. MOFs are being explored for device applications and optical interconnects to provide efficient connections from standard single-mode fibers and planar waveguides.



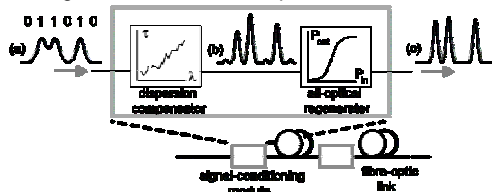
The **Laser Micro-Machining** project develops processes for laser-based micro-structuring of a range of linear, non-linear and high-gain optical materials, to produce photonic structures including waveguides in bulk glasses, 2-D photonic crystals and quasi phase matched crystals.



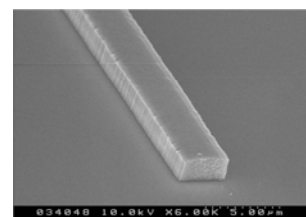
The aim of the **Photonic Integrated Waveguides and Circuits** project is to design, fabricate and characterise planar silicon optical waveguides and 2D photonic crystals in a range of different optical materials.



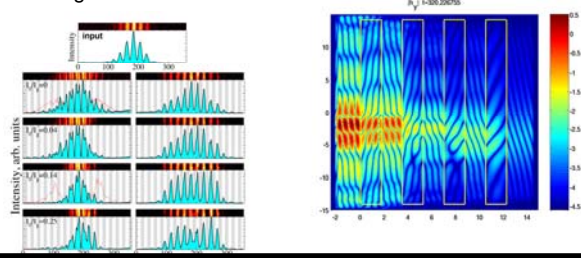
The **Optical devices and Applications** project develops all-optical signal processing functions including regeneration, wavelength conversion and amplification.



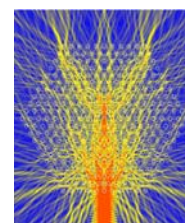
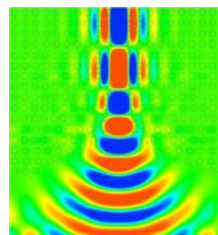
The aim of the **Non Linear Materials** project is to develop high nonlinearity chalcogenide glasses leading to novel nonlinear photonic devices including planar photonic crystals.



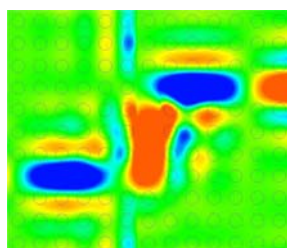
The **Non Linear Photonic Crystals** project studies the generation and propagation of nonlinear localized modes and all-optical switching in periodic photonic structures and waveguide circuits.



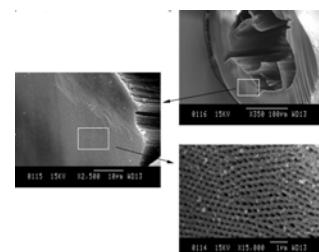
The **Computational Modelling** project provides computational modelling and visualisation techniques through generic modelling tools, new methods for modelling photonic structures and devices, and expertise in visualisation.



The **Photonic Circuits** project aims to find the best way to achieve tight guidance of light in optical circuits and to optimize photonic circuit features for Fresnel losses, radiation losses and impedance mismatches.



The aim of the **Radiation Dynamics** project is to explore radiation dynamics in microstructured photonic crystal materials. We aim to identify bandgap structures and use quantitative structural information to predict their optical properties.



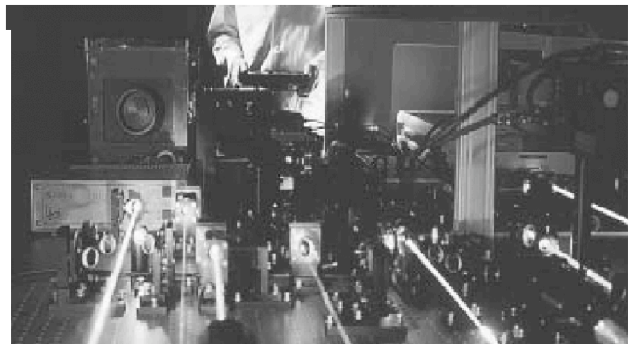


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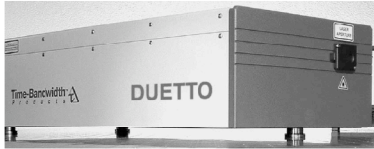
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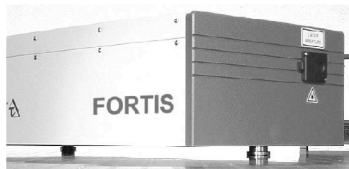
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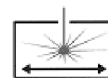


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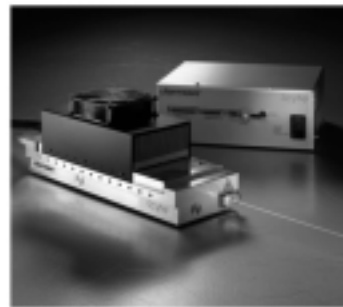
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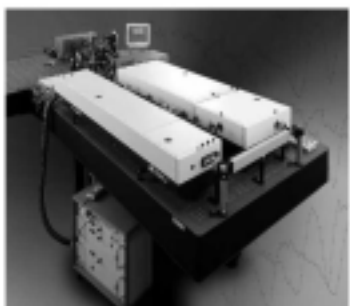
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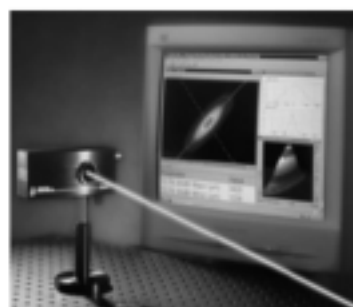
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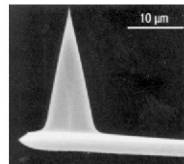


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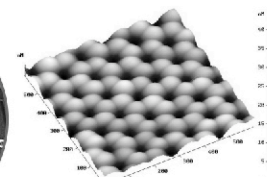
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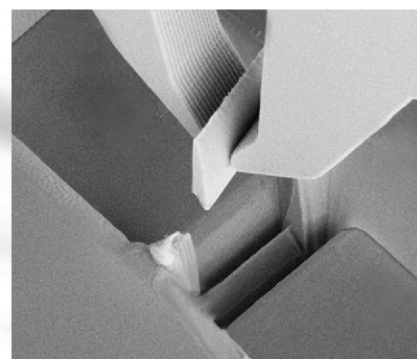
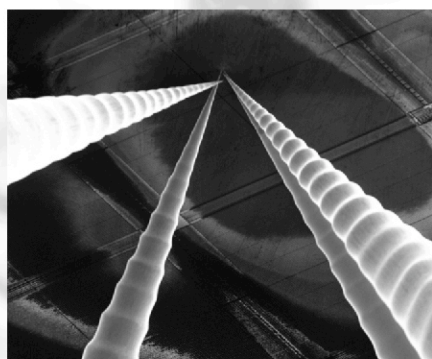
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AFM image of anodic porous  $\text{Al}_2\text{O}_3$  (600 x 600nm)



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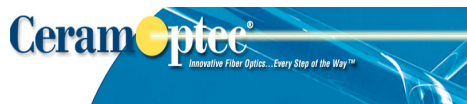
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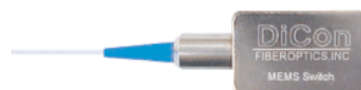
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<b>Fibre Optical Coupler &amp; Splitter</b> <ul style="list-style-type: none"> <li>- Fibre optic coupler 1x2, 2x2</li> <li>- Dual window coupler</li> <li>- 1x32 splitter/coupler for FTTH networks</li> <li>- Wideband tree coupler</li> <li>- Polarization maintaining coupler</li> <li>- 1x4, 1x8, 1x16, 2x16, 2x32 star or tree</li> <li>- 250um bare, 900um, 3mm cable version</li> <li>- packaging options</li> </ul>	<b>Filter/WDM/ CWDM/DWDM</b> <ul style="list-style-type: none"> <li>- Band pass filter</li> <li>- Fiber optic WDM 980/1550, 1310/1550</li> <li>- Multimode WDM</li> <li>- Amplified spontaneous emission filter</li> <li>- C band/L band WDM</li> <li>- CWDM/DWDM 4 channel/ 8 channel</li> <li>- Filter WDM 980/1550</li> <li>- Filter WDM 976/1064nm</li> <li>- Pump combiner</li> </ul>
<b>80um Reduced Cladding Components</b> <ul style="list-style-type: none"> <li>- SMF or PM fibre</li> <li>- Fibre coupled isolator</li> <li>- Filter WDM</li> <li>- PM collimator</li> <li>- RC fibre coupler</li> </ul>	<b>Fibre Optic Circulator</b> <ul style="list-style-type: none"> <li>- 3 port or 4 port</li> <li>- 1030, 1064, 1310, 1550nm</li> <li>- SMF or PM panda fiber</li> <li>- 250um, 900um, 3mm pigtail version</li> </ul>
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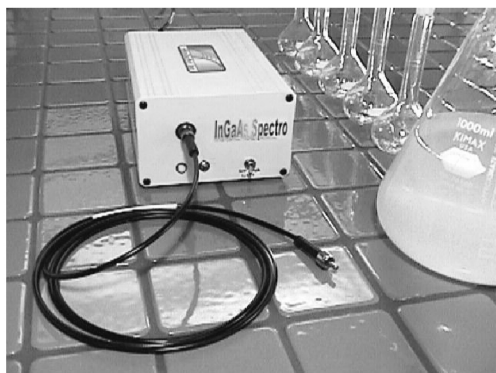
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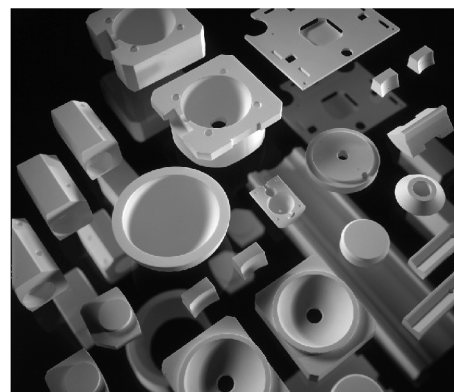
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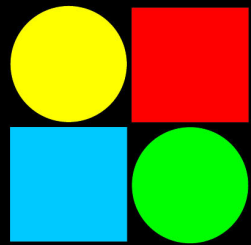












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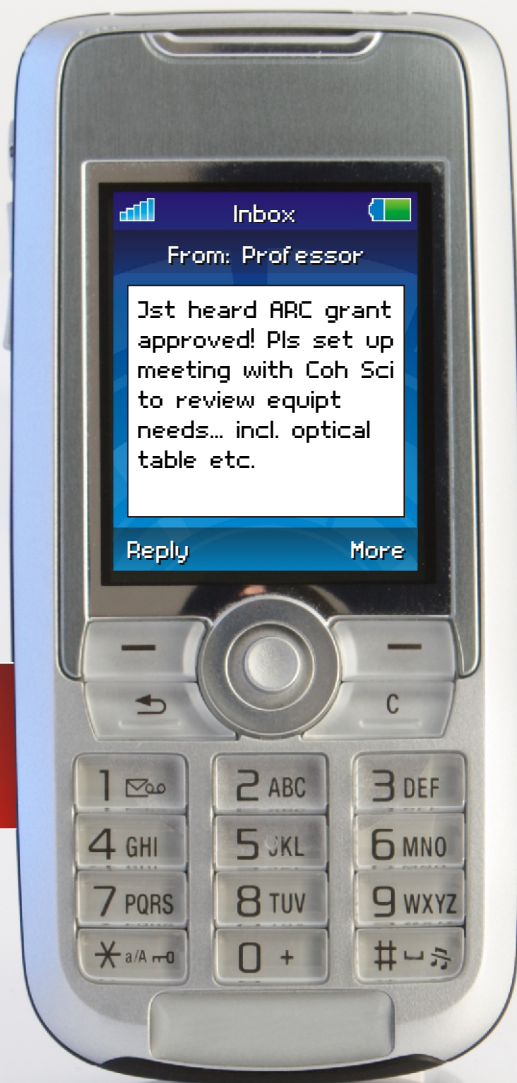
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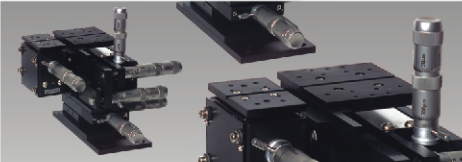
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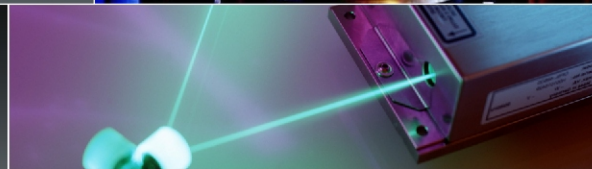
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