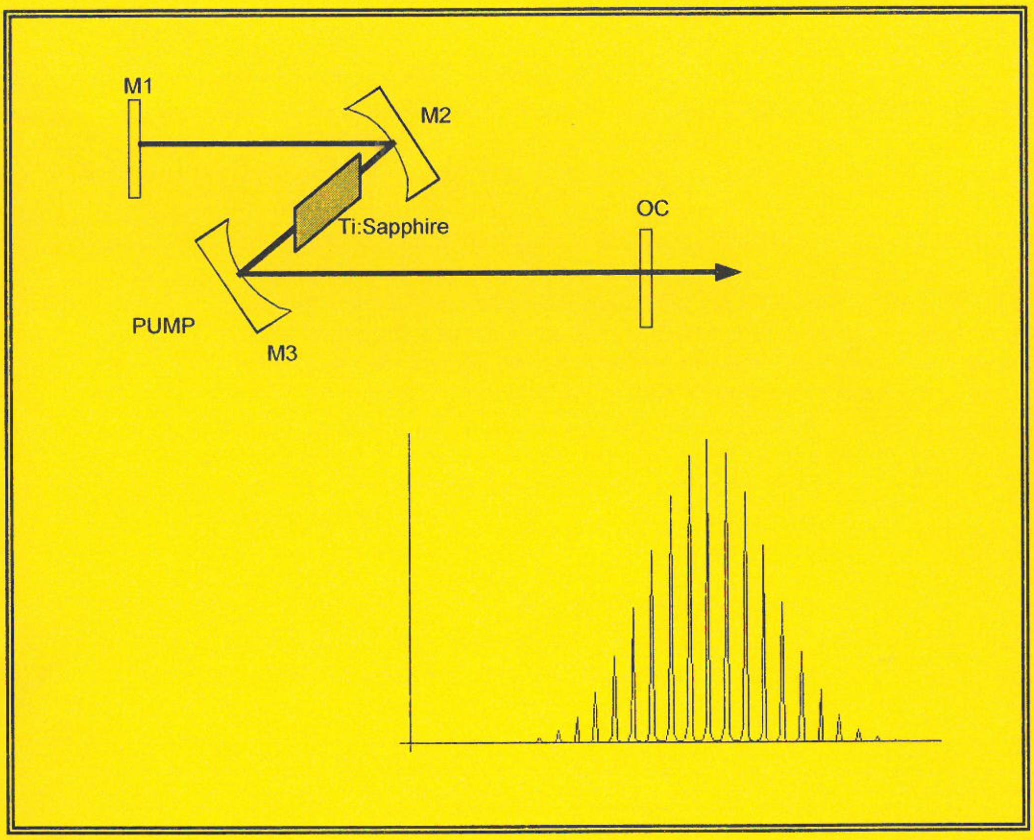
Australian Optical Society

NEWS



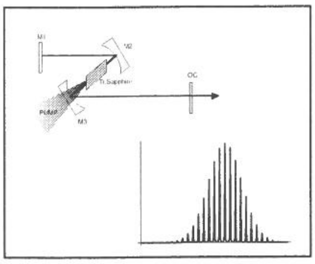
Volume 16 Issue 1
March 2002
Registered by Australia Post
Publication No: 233066 / 00021

MARCH 2002 VOLUME 16 NUMBER 1

AOS NEWS

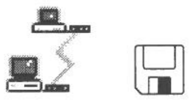
ARTICLES

DEPARTMENTS



COVER :
A simplified schematic of a mode-locked Ti:sapphire laser is shown, together with the frequency spectrum for a train of phase coherent output pulses. The article on page 23 discusses the application of such pulse trains, combined with microstructured optical fibres, to extremely precise measurements.

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



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

ADVERTISING:
Potential advertisers in *AOS News* are welcomed, and should contact the editor.

EDITOR
Wayne Rowlands
Swinburne University of Technology
PO Box 218
Hawthorn Vic. 3122
Tel: (03) 9214 8214
Fax: (03) 9214 5840
wrowlands@swin.edu.au

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

DEADLINE FOR NEXT ISSUE
27th May, 2002

Submission guidelines

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

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***
If you have been to conference recently, writing a short report would be greatly appreciated.

*∗ **News Item***
Any newsworthy stories in optics from Australia or abroad.

*∗ **Book Review***
If you have read an interesting (and relatively new) book in some field of optics please consider writing a review for the *AOS News*.

*∗ **Cartoon or drawing***
If you have some artistic bent why not consider submitting a cartoon!

How can you submit?

The easiest way is by email. Either send the document text in your mail, and attach diagrams and/or a word processor file. We accept nearly all file formats. (Famous last words!).

If you don't have email access, or cannot send diagrams or pictures via email, we can accept hard copies. (One copy only is required).

Australian Optical Society website

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

- News
- Membership
- Optics links
- Prizes/awards
- Conferences
- Jobs/Scholarships
- Affiliated societies
- ...and more

AUSTRALIAN OPTICAL SOCIETY

ABN 63 009 548 387

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

AOS EXECUTIVE

PRESIDENT
Keith Nugent
School of Physics
University of Melbourne
VIC 3010
Tel: (03) 8344 5446
Fax: (03) 9347 4783
k.nugent@physics.unimelb.edu.au

VICE-PRESIDENT
Barry Sanders
School of MPCE
Macquarie University
Sydney, NSW 2109
Tel: (02) 9850 8935
Fax: (02) 9850 8115
barry.sanders@mq.edu.au

ACTING SECRETARY
Duncan Butler
Ionising Radiation Standards
ARPANSA
Yallambie VIC 3085
Tel: (03) 9433 2274
Fax: (03) 9432 1835
Duncan.Butler@health.gov.au

HONORARY TREASURER
Stephen Collins
Optical Technology Research Lab
Victoria University
PO Box 14428, Melbourne City MC
Tel: (03) 9688 4283
Fax: (03) 9688 4698
stephen.collins@vu.edu.au

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

AOS COUNCILLORS

Chris Chantler
School of Physics
University of Melbourne
VIC 3010
Tel: (03) 8344 5437
Fax: (03) 9347 4783
chantler@physics.unimelb.edu.au

Chris Walsh
JDS Uniphase
4 Byfield St, North Ryde NSW 2113
Tel: (02) 9413 7156
Fax: (02) 9413 7200
Chris.Walsh@tip.csiro.au

John Love
Optical Sciences Centre
Research School of Physical Sciences and Engineering
The Australian National University
Canberra ACT 0200
Tel: (02) 6249 4691
Fax: (02) 6279 8588
jdl124@rsphyssc.anu.edu.au

Murray Hamilton
Department of Physics and Mathematical Physics
University of Adelaide
Adelaide SA 5005
Tel: (08) 8303 5322
Fax: (08) 8232 6541
mwh@physics.adelaide.edu.au

Peter Farrell
Altamar Networks
Level 1, 90-94 Tram Road
PO Box 644
Tel: (03) 9848 0600
Fax: (03) 9848 0650
pfarrell@altamar.com

Wayne Rowlands
Centre for Atom Optics & Ultrafast Spectroscopy
Swinburne University of Technology
PO Box 218, Hawthorn Vic 3122
Tel: (03) 9214 8142
Fax: (03) 9214 5840
wrowlands@swin.edu.au

Ken Baldwin
Laser Physics Centre
ANU RSPS Canberra ACT 0200
Tel. (02) 6125 4702
Fax. (02) 6125 0029
kenneth.baldwin@anu.edu.au

CORPORATE MEMBERS

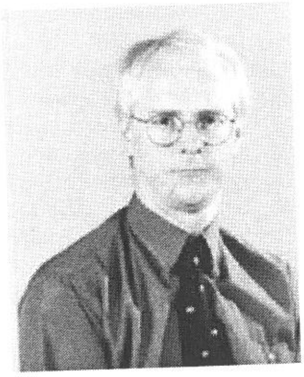
Coherent Scientific
Francis Lord Optics (Avtronics)
Hadland Photonics
IATIA
Laser Electronics (Operations)
Lastek
Optiscan
Photon Engineering
Raymax Applications
Warsash Scientific
X-Ray Technologies

AFFILIATES

OSA
(Optical Society of America)

SPIE
(International Society for Optical Engineering)

President's Report



I write this column with a great deal of sadness. Many of you will have heard that Professor Geoffrey Opat AO died suddenly and quite without warning on Thursday, March 7 at the age of 66. Geoff was the newest Life Member of the AOS and a former AOS President. He was an icon of the Melbourne science education community, a committed member of the Melbourne Jewish community and one of Australia's few public intellectuals, able to comment knowledgeably on all of the issues with which a leading scientist and educator should be concerned. Last, but not least, he was one of Australia's leading physicists with a deep love and knowledge of the subject. He was also a close friend and colleague of mine. I will miss his wisdom, humour and sound advice dearly. He his survived by his wife Diana, two sons, two daughters and 10 grandchildren.

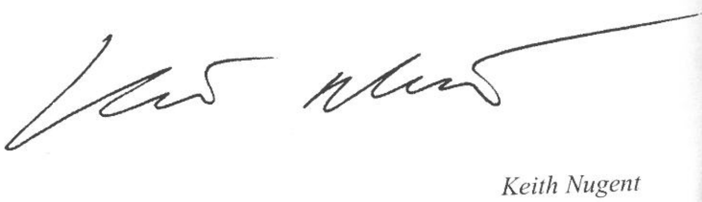
The School of Physics at the University of Melbourne is in a state of shock as I write this. This column would, in better circumstances, have rejoiced in Geoff's award of an Order of Australia in the 2002 Australia Day Honours. Geoff was delighted with this recognition. Perhaps he was even more delighted by the sincere joy this award brought to his many friends and colleagues.

I have included a poem written by one of the students in School of Physics, Tracy Mackin, when she learned of Geoff's passing. It captures Geoff beautifully. The next issue of AOS News will carry more on the celebration of the legacy of Geoffrey Opat.

And on February 17 this year, the AOS lost another eminent Life Member in Robert Hanbury-Brown. Although I did not know him personally, his scientific and cultural legacy is enormous. We all know of the contributions he has made with his development optical intensity interferometry, a technique now used far more widely than simply in astronomy. Indeed, I know that Geoff Opat suggested Robert Hanbury-Brown's name for a Nobel Prize for his developments in interferometry. Robert Hanbury-Brown was a truly international figure. He is survived by his wife Heather, one daughter and two sons.

Other new for the optics community was the announcement of the four ARC Priority Areas, one of which is "Photon Science and technology". Clearly the method and number of these areas was a matter of contention, however the recognition of the importance of optics related research to the national interest is welcome and appropriate. It now remains to be seen how these priority areas translate into real outcomes for researchers, although the ARC is already required to expend one third of its funds in these areas. This cannot help but make a real difference to those of us doing research in optics and cognate fields. Photon Science and technology is clearly a broad term, and is one with which we are unfamiliar. However it is clearly intended to have a wider scope than implied by the term "optics" and the term "photonics". Interestingly, I suspect that these priorities will have a national scope and so will soon be extending beyond the boundaries of the ARC. I urge all AOS members to make the most of this evolution in the governmental view of our discipline, and let's justify its confidence in what we do.

Finally, I remind members that the AIP Congress is to be held in Sydney in July. The AOS meeting is included as part of the congress. There is an excellent line-up of international speakers and this is a wonderful opportunity to meet with our colleagues in other disciplines. The AOS sessions, in particular, also look fascinating. I hope to see you there.



Keith Nugent
President of the Australian Optical Society
March 2002

Valediction to Geoffrey Opat

Young-old man,
Scientist frenetic with cocky's crest hair,
Random walking in corduroy pants, chalk-marked, across the podium
"I'm an electron..."

There are no fairies at the bottom of the garden

"By a miracle of chalk..."

But there was a spirit at the top of the building
Puck, ever-young, inquisitive and eager

"I did the calculation once, and it turned out that..."

Singer of songs

"Handel? You wouldn't start with Handel!"

Translator, faith-keeper,
Dominus, Patronus

See through his eyes the beauties of the world:
*   **that** the male voice sounds different to the female,*
*   **why** the female voice sounds different to the male.*

"You can see the difference in the vibrational modes,
the resonances...there was a study done..."

Questioner, comment maker,
Follower of tangents,
Drawer of parallels,
Silent sleeper, well-timed waker,
Teacher, student, gentleman scholar,
Lover of life's mystery,
Child of the universe.

Suddenness in his comings,
Quicksilver in his thinkings,
Leisure in his explorations,
Abrupt in his leave-taking,
Honoured in his passing.

Farewell and fruitful journey,
Spirit of the school -
*   the building echoes with*
*   your absence.*

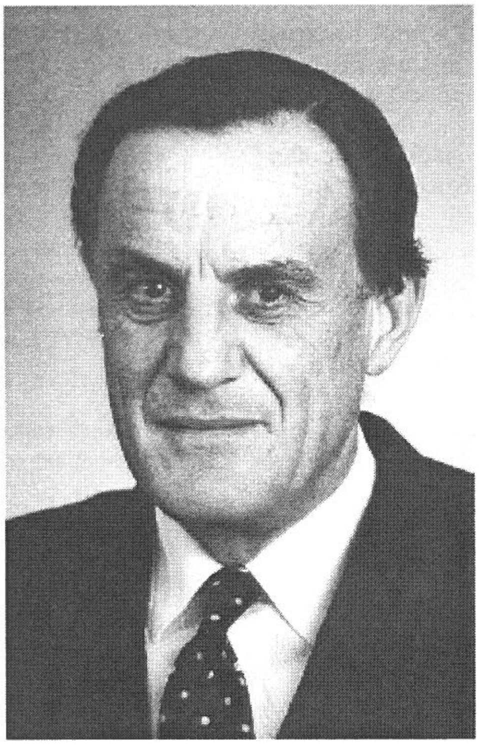
Tracy Mackin
March 7, 2002

Robert Hanbury Brown
Physicist and Astronomer
August 31 1916 – January 16 2002.

Robert Hanbury Brown, a Life Member of the Australian Optical Society, sadly passed away earlier this year. He was acknowledged as a well respected and revered figure in Australian science. The following obituary, written by Anthony Tucker, is reprinted with kind permission of The Guardian newspaper.

"One of Britain's outstanding scientists, he pioneered the development of radar and radio astronomy at Jodrell Bank"

The name of the physicist and astronomer Robert Hanbury Brown, who has died aged 85, is synonymous with the pioneering of radar and the development of radio astronomy. Among his many inventions, the most outstanding was, perhaps, the intensity interferometer, which he achieved despite assurances from mathematicians and physicists alike that it was impossible.



The world of science and technology has cause to be grateful that he forsook an early plan for a future as a classics scholar to become an engineer instead. He gave a stirring account of his life in his autobiography, Boffin: A Personal Story Of The Early Days Of Radar, Radio Astronomy And Quantum Optics (1991). It is a fascinating insight into the second world war quest for an effective radar, and of the early days at the Jodrell Bank radio observatory in Cheshire, as well as the highly entertaining story of a man who lived and breathed science, with all its excitement, interest and difficulty.

Sir Bernard Lovell once said that had Hanbury Brown not sought a research fellowship at Manchester University after the war, the Jodrell Bank radio telescope might never have been built. Characteristically, Hanbury Brown dismissed this notion with an embarrassed shake of the head. But his recruitment to Sir Bernard's pioneering team in 1949, and his subsequent emergence as professor of radio astronomy at Manchester in 1960, took a substantial load off Lovell during the period when he most needed time and energy to fight the battles for money and sound construction of the radio telescope.

Hanbury Brown, who took a BSc from London University in 1935 after attending Tonbridge school, was one of the very bright young engineers who were whisked away to work, under great secrecy, with Sir Robert Watson-Watt on radar development at the Air Ministry research station at Bawdsey (1936-42). Because of his knowledge and experience, in 1942 he was seconded, as assistant head of the combined research group, to the US naval research laboratory in Washington, to work - under equally high security - on the rapidly expanding US airborne radar programme.

When he emerged from government work in 1947, Hanbury Brown spent a period as an engineering consultant in partnership with Watson-Watt (1947-49). By then, he was one of Britain's most experienced electronic engineers but, because of secrecy, he had published nothing. It was thus not possible for him to apply formally for one of the few research fellowships then available. But Hanbury Brown's appeal to Manchester for a post was passed to Lovell, who remembered him from his own radar days. They met on Goostrey station on May 19 1949, ICI provided a fellowship, and the rest became scientific history.

During his period at Manchester, Hanbury Brown devised ways of minimising the background noise that plagued early radio astronomy, and subsequently designed an extremely elegant, but complex, intensity interferometer enabling radio telescopes to measure the diameters of distant radio sources. Then, it was thought that radio stars, like their visible equivalents, would be mere points in the sky.

It turned out that the powerful radio emissions then being detected in association with visible objects, such as the spiral nebula in Andromeda, covered vast regions, rather than points. Simpler techniques could be used to map them. Hanbury Brown's technique, which eliminates the effects of frequency variations, and which he had initially investigated at optical wavelengths (through mirror image superimposition, using a pair of old searchlight reflectors), turned out to have its greatest value in classical optical astronomy.

In 1963, with Jodrell Bank up and running, Hanbury Brown jumped at the offer of the chair of astronomy at Sydney University, for with it came an opportunity to build a large mirror intensity interferometer of his own design. This was set up at Narrabri, in the outback, some 250 miles northwest of Sydney, where the only conditions that could be described as good were those for night-sky viewing. Hanbury Brown intended to stay only a year or so, but, over two decades, he and his researchers compiled a catalogue of measurements of the southern sky whose precision is unequalled.

It is sometimes said that Hanbury Brown's decision to stay with his large mirror interferometer at Narrabri robbed him of a major career in radio astronomy, and even condemned him to a minor tributary of optical astronomy. But it was characteristic of his drive toward pure classical astronomy, and his creative enthusiasm for devising novel, often complex and unconventional equipment, which had to be made to work, that he opted for the new challenge. If he was trapped at all, it was by his own enthusiasm.

Narrabri was demanding, but he found the wide horizons of life in Australia, at the university - and especially as seen with his family from a house overlooking Sydney harbour - more satisfying than those of either the UK or the Americas. He would sometimes carry visitors to Narrabri back to his house at high speed in his dusty car, explaining the virtues of life as he dodged the traffic and frightened them out of their wits.

But this bursting enthusiasm was only one side of his personality. His sense of history and mystery in astronomy was poured into a beautiful short book, Man And The Stars (1978). His sense of family and his love of the sea were expressed at Sydney. Yet, strangely, many who knew him remember him for the care and skill he expressed when pruning roses. Sir Bernard Lovell recalls that, at one research station where he was often to be seen in a brown lab coat and busy with secateurs, Hanbury Brown was mistaken by visitors for the gardener.

It was not surprising that, in his mid-70s, he and his wife returned to England and to life in a Hampshire village. Highly critical of the modern emphases on mysticism in astronomy and high energy physics, Hanbury Brown settled down to writing about his own experiences in science and technology, such as his years with Watson-Watt.

Whatever he undertook, and whatever its scale or difficulty, Hanbury Brown carried it through superlatively well. To the end, he was a highly original engineer, a natural astronomer and a dreamer, who sometimes made the dream come true. One sadness is that the world will never know the full extent of his technical contributions to the success of airborne radar, although, without airborne radar, the second world war would certainly have been longer, and - like the Jodrell Bank proposals - the outcome might have been different.

He is survived by his wife Heather, and their twin sons and a daughter.

<This obituary has been updated since the author's death in 1998.>

Professor Rodney Davies writes: As one of the many young physicists at Jodrell Bank who came under Hanbury Brown's influence in the years leading up to the completion of the 250ft Lovell telescope, I am greatly indebted to him for inspiring a search for an understanding of the mysterious radio sky that we were challenged by at that time. He encouraged us to develop innovative receiver systems to map these faint radio objects, which always seemed at the limits of detection.

His particular invention, along with Richard Twiss, was the intensity interferometer, which clarified contemporary understanding of the dual nature of light (and radio waves). This led to a new way of measuring the diameter of the stars.

The fond respect in which he was held by the worldwide astronomical community was evident at last year's general assembly of the International Astronomical Union, of which he was a former president.

Anthony Tucker
Friday January 18, 2002
The Guardian

Quantum Information and Optics

Andrew G. White

Department of Physics and Centre for Quantum Computer Technology,
University of Queensland,
Brisbane, Queensland 4072, AUSTRALIA
http://www.physics.uq.edu.au/qt *andrew@physics.uq.edu.au*

This is the first of two articles that look at the new field of *quantum information* and it's relationship with optics. In this article we introduce the central concepts of quantum information, illustrating them with simple optical examples. In the next article we will look at making entangled photons, and some of their recent applications, including tests of nonlocality, quantum cryptography, and quantum computation.

Flicking through Physical Review the last couple of years you may have noticed a new section heading - *quantum information* (QI). And, like many colleagues of mine, you may have read an article or two in that section but were put off by the theory, or worse, the jargon, and not read on. If so, fear not because: a) you're not alone and b) many of the key ideas of quantum information are particularly accessible via optics, and so to readers of AOS News.

So what is quantum information? A standard definition[1] is "...the application of quantum mechanics to information theory...", which while succinct, isn't terribly informative. Perhaps better is the slogan "no information without representation", which highlights a key concept: all information storage and processing is achieved via some *actual* system, and the physics (and indeed chemistry, biology, etc.) of that system necessarily constrains the storage and processing.

If it were only a matter of constraints then our slogan is really not very exciting. However, if we treat the physical constraints as *fundamental*, and explore the consequences for information processing given these fundamental limits (particularly quantum mechanical limits) we come to a powerful realisation. It is possible to achieve information processes in quantum mechanical systems that are *impossible* with classical systems (and classical computational logic).

"Enough!" I hear you cry (or that may be someone else, in which case, thank you for your patience) "...what about optics?" In this and the next article we look at some of the basic concepts in quantum information, illustrating them with optical examples, and look at some recent optical QI experiments. On the way we'll answer important questions including: *what are qubits? what is entanglement? are there different kinds of entanglement? how is it characterised? why is it powerful? how is it measured?* and most importantly of all ... *why should I care?*

I. AN INTRODUCTION TO QUANTUM INFORMATION

1. What are qubits?

A qubit, or quantum bit, is *any* two level quantum system. Figure 1 shows some common examples: spin (electronic or nuclear); polarisation of light; energy levels in an atom, ion, quantum dot, nucleus, etc. In this article we will concentrate on using the polarisation of light as a qubit. Like classical bits, qubits can exist as a 0 or a 1; unlike classical bits, they can exist in superposition states. If we consider horizontal polarisation, $|H\rangle$, as our logical "0", and vertical polarisation, $|V\rangle$, as our logical "1", then it becomes clear that diagonal polarisation, $|D\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$, is the logical state $\frac{1}{\sqrt{2}}(0+1)$, and right-circular polarisation, $|R\rangle = \frac{1}{\sqrt{2}}(|H\rangle + i|V\rangle)$, is the logical state $\frac{1}{\sqrt{2}}(0+i1)$. Note that in quantum information the transformation $0 \rightarrow \frac{1}{\sqrt{2}}(0+1)$ is called the *Hadamard transform* - in polarisation optics we call a device that does this a *waveplate* (e.g., $|H\rangle \rightarrow \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$).

Qubits carry phase information. For example, diagonally- and right- circularly polarised light both are equal weight superpositions of horizontal and vertical light - they differ only in their relative phase.

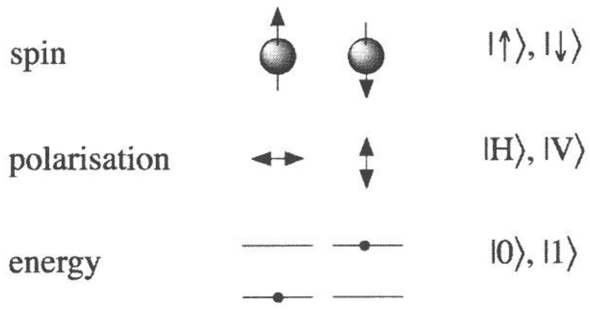


Fig. 1: Examples of qubits: a) spin b) polarisation c) energy levels.

[1] "Standard" in that I bandied it around the department and no-one disagreed.

Experimentally, if we send either a diagonal- or right-circular photon onto a polarising beamsplitter, it appears at the horizontal or vertical output ports with a probability of 50%, as shown in Figure 2a. This is no different to a 50/50 mixture of classical bits. However, as shown in Figure 2b, if we take the outputs of the beamsplitter and combine them onto a second polarising beamsplitter (with equal path lengths), we recover the original polarisation state and the qubit will always pass an analyser set at θ°. This kind of process is impossible with classical bits.

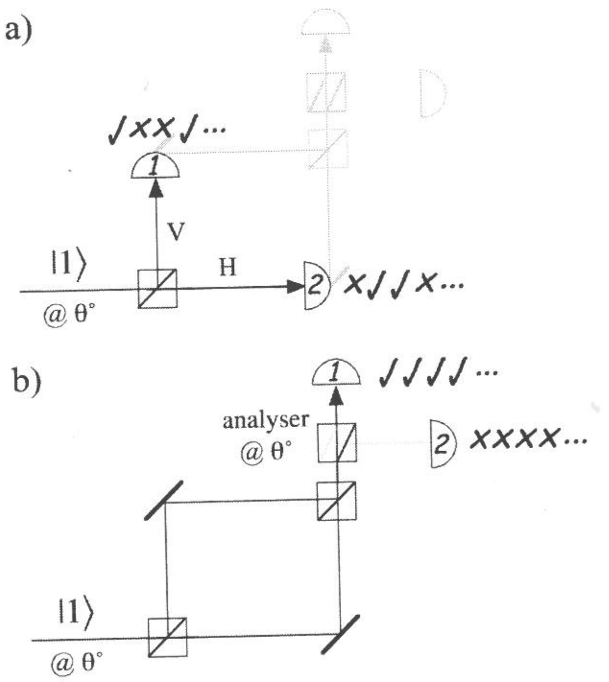


Fig. 2: Qubits carry phase information. a) a polarisation qubit, θ°, incident on a polarising beamsplitter. b) a polarisation qubit incident on a polarising interferometer. The qubit is passed unscathed by the interferometer.

2. What is entanglement?

So is the only difference between classical and quantum information the fact that in the latter we use qubits, and these can be superpositions? The answer is no, there is one other key difference: qubits can be correlated in a way that can not be mimicked using classical bits. This "super correlation" is known as *entanglement*[2] after Schrödinger [1]. So what is entanglement? Textbooks normally start with a mathematical definition, but we are going to eschew that for an optical example.

Let Alice and Bob be two individuals with too much time on their hands. There is an unknown source of light sending photons to both Alice and Bob, as shown in Figure 3. They wish to determine the polarisation properties of the light. Alice analyses only in the H/V basis, using some polariser (where 0° ≡ H, 90° ≡ V). In either basis, half the time she sees a photon, i.e $P_H = P_V = \frac{1}{2}$. Bob, meantime, is more of a free spirit, randomly analysing in many bases, θ (where 0° < θ < 180°, of course). Bob finds that the light appears totally unpolarised, consistent with Alice's observation.

In addition, both Alice and Bob keep a timing list, as follows: *Alice* "At 1 ns, I saw a photon at 0°; at 2 ns, I saw nothing; at 3 ns, I saw a photon at 0°..." *Bob* "At 1 ns, I saw nothing; at 2 ns, I saw a photon at 12°; at 3 ns, I saw a photon at 47°..."

After doing this for a while, Alice and Bob stop, and get together in the pub (why not?) to compare lists. In particular, they calculate the probability of Bob seeing a photon when Alice sees a photon - the *coincidence proabability*, P_{AB}. They make the interesting observation that whenever Alice saw a photon at 0°, Bob never saw a photon at 90°, i.e. $P_{HV} = 0$, and in fact, had a perfect probability of seeing a photon at 0°, $P_{HH} = 1$. The coincidence probability versus Bob's analyser setting looks like that given in Figure 4.

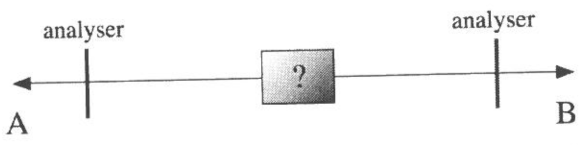


Fig. 3: An unknown source of light, analysed by Alice (A) and Bob (B).

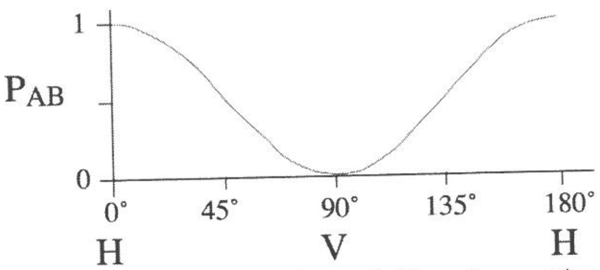


Fig. 4: Coincidence probability vs Bob's analyser setting. Alice is analysing in the H/V (0°/90°) basis.

So what is this source? One possibility is a random mixture of pairs of horizontally and vertically polarised photons. For example: at 1 ns, a pair of horizontally polarised photons might be sent to Alice and Bob; at 2 ns, another horizontal pair; at 3 ns a vertical pair, and so on. To check this possibility, Alice and Bob return the lab (fortified by fine ale) and repeat their measurements, with the only change being that now Alice analyses in the diagonal/anti-diagonal basis (45°/135°). Again, after a period of time, they stop measuring and repair to the pub. Now they observe that whenever Alice saw a photon at 45°, Bob never saw a photon at 135°, $P_{D\bar{D}} = 0$, and the coincidence probability versus Bob's analyser setting looks like that given in Figure 5.

[2] Although perhaps a better, and certainly more euphonious, translation from the German would be "entwinement".

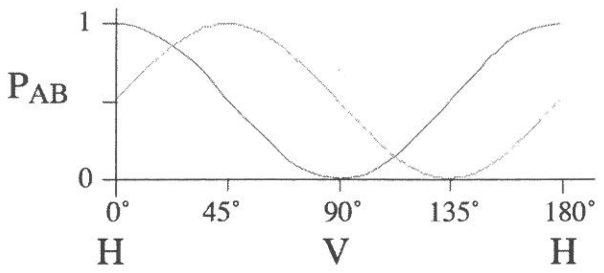


Fig. 5: Coincidence probability vs Bob's analyser setting. Alice is analysing in the $D/\overline{D}$ (45°/135°) basis.

This means the source cannot be a random mix of horizontal and vertical pairs. If it were, then Alice may see a diagonal photon, with $P_D = \frac{1}{2}$, and Bob may see an anti-diagonal photon, with $P_{\overline{D}} = \frac{1}{2}$, and the coincidence probability would be measured to be $P_{D\overline{D}} = \frac{1}{4}$, not $P_{D\overline{D}} = 0$. So what is the source? To further confound our heroes, they find that regardless of which basis Alice chooses for her measurements, Alice and Bob always find a perfect visibility coincidence fringe, i.e. they observe *perfect correlations (or anti-correlations) in every measurement basis*. This is entanglement.

In quantum information terms, Alice and Bob have a source of perfectly entangled qubits. How many bases do they need to measure in before they completely characterise the entanglement? Two? Infinity? ...

3. Characterising qubits and systems of qubits

In general, 3 parameters are required to completely characterise a qubit. The qubit can be represented graphically by using these parameters to plot its position on, or in, some characteristic sphere. For polarisation, this is the Poincaré sphere (for spin, the Bloch sphere). In the Poincaré sphere, as shown in Figure 6, the axes indicate measurement probabilities in some appropriate basis set, e.g. H, D, & R. The polarisation of any light source can be mapped onto the sphere by simply measuring the probabilities of the light passing through H, D, & R polarisers, respectively. Note that this requires 4 intensity/count rate measurements: I_H, I_D, & I_R plus, say, I_V, to give the total intensity/count rate ($I_0 = I_H + I_V$) and enable normalisation (e.g. $P_D = I_D / I_0$). These measurements are also known as the *Stokes parameters*, where $S_0 = I_0$ and $S_{1,2,3} = I_{H,D,R}$, and are related by $S_0^2 = S_1^2 + S_2^2 + S_3^2$ [2].

Completely polarised light will lie on the surface of the sphere. In quantum mechanical terms we say this is a *pure state*, and note that it is highly ordered. If the measured light lies at the centre of the sphere, i.e. has equal probability, $P = \frac{1}{2}$, of being found in any basis, the light is unpolarised. In quantum mechanical terms

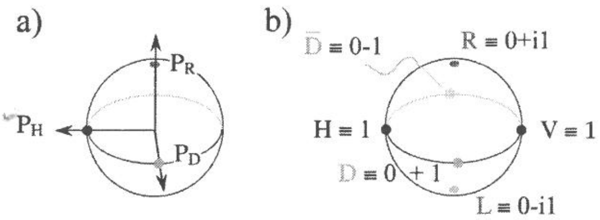


Fig. 6: Poincaré sphere. a) a set of measurement axes that define the sphere. b) positions of a range of polarisation (logical) states on the sphere.

we say the state is *mixed*, and it is highly disordered. If the state lies between the centre and the surface of the sphere, the light is partially polarised (partially pure). It is always possible to uniquely decompose a single qubit into a pure and a mixed component (or in polarisation terms, into completely polarised and unpolarised components.)

Alternatively, qubits can be represented by a characteristic matrix. For polarisation, this is the *coherency matrix*, or in quantum mechanical terms, the *density matrix*, $\hat{\rho}$. In such matrices, the diagonal elements are populations, and the off-diagonal elements are coherences. A range of typical matrices, and the states they represent, are shown below. The density matrix contains *all* the information about the qubit. For example: the purity, or degree of polarisation, of the qubit is $\mathcal{P} = \mathrm{Tr}\{\hat{\rho}^2\}$; the von Neumann entropy is $\mathcal{S} = -\mathrm{Tr}\{\hat{\rho}\log_2(\hat{\rho}^2)\}$; and the normalised linear entropy is $\mathcal{S}_L = 2(1-\mathcal{P})$.

qubit state		ρ (⟨H| ⟨V|)	ρ	purity
H-polarised light (0°)	|H⟩ |V⟩	$\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$	|H⟩⟨H|	1
D-polarised light (45°)	1/4.	$\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$	|H⟩⟨H|+|H⟩⟨V| +|V⟩⟨H|+|V⟩⟨V|	1
unpolarised light (-°)	1/2.	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	|H⟩⟨H|+|V⟩⟨V|	0

Fig. 7: Single qubit density matrices

What about a system of qubits? We've already consisted the simplest multi-qubit system in the previous section: two entangled qubits. It turns out that such a system cannot be completely characterised by isolated measurements on it's subsystem:, coincident measurements are required. In polarisation terms, it is no longer enough to measure the Stokes parameters of each beam: we need to measure the *bi-photon Stokes parameters* [3, 4]. These are 16 coincidence measurements, one possible set being the pairwise

combination of the traditional Stokes parameters, i.e. HH, HD, HR, HV; DH, DD, DR, DV; RH, RD, RR, RV; VH, VD, VR, VV. While it is somewhat difficult to draw a 15-dimensional sphere that represents the entangled state, it is relatively straightforward to combine these measurements into a 4×4 density matrix. Some experimentally measured density matrices, and the states they represent, are shown in Figure 8.

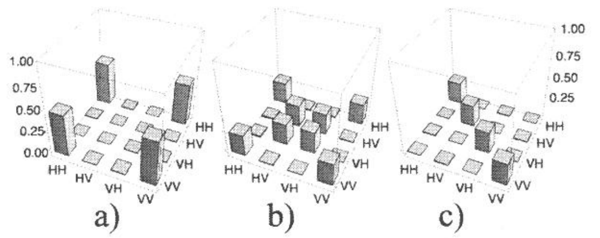


Fig. 8: Two qubit density matrices (measured). a) the maximally entangled state, $\frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle)$. b) a half-mixed, unentangled state. c) the fully mixed state.

4. Power of entanglement

Why is entanglement seen as a desirable characteristic in quantum information? A full answer to this is beyond the scope of this article but we can begin to get an insight by considering the number of parameters required to characterise a system of qubits.

As we've seen, a single qubit can be described by 3 parameters. If we have N qubits, but the qubits are not entangled, then each qubit can be described by 3 parameters and the total number of parameters required to describe the system is simply 3N (e.g. the polarisation of N separate laser beams).

However, if the N qubits are entangled, then the system is described by a density matrix of dimension, $d = 2^N$, which in turn requires $2^d - 1 = 4^N - 1$ parameters to describe (or $4^N - 1$ measurements). Clearly, there is an exponential blow-out in the number of parameters required to describe the system, as shown in the Table below. From an experimental point of view, this means that even a system of just 5 entangled qubits requires 1024 measurements (including the normalisation) - it rapidly becomes a laborious task to fully characterise the system.

Instead of asking how many parameters are required to describe the state, quantum computation inverts the problem and treats that number of parameters as computational degrees of freedom, with only one measurement made at the output of the device. So, in effect, the number of parameters are proportional to the computational power, and that number increases exponentially with the number of entangled qubits. Although this is a major over-simplification (e.g., it assumes mixture is computationally useful) it does capture the flavour of why quantum computation, and entanglement, is so powerful.

Table 1: Scaling with number of qubits, N. $\hat{\rho}$ is the density matrix that describes a N-qubit system.

# of qubits, N	dimension of $\hat{\rho}$, 2^N	# of parameters, $4^N - 1$
1	2	3
2	4	15
3	8	63
4	16	255
5	32	1023
⋮	⋮	⋮

5. Characterising entanglement

Let us return to just two entangled qubits. There are a wide range of entangled states - however just 4 states suffice to form a basis that span the space of possible states. These are the *Bell states*: in polarisation terms, $|\phi^{\pm}\rangle = |HH\rangle \pm |VV\rangle$ and $|\psi^{\pm}\rangle = |HV\rangle \pm |VH\rangle$. (Note that the normalisations have been omitted here, as they often are in quantum information articles, but they are very important!) For all 4 Bell states, the correlations are perfect, but they look different in different bases. For example, $P_{HH} = 1$ for the $|\phi\rangle$ states, whereas $P_{HH} = 0$ for the $|\psi\rangle$ states. More subtly, $P_{DD} = 1$ for $|\phi^{+}\rangle$, but $P_{DD} = 0$ for $|\phi^{-}\rangle$, and so on.

With 16 measurements (given by the bi-photon Stokes parameters) we can reconstruct the density matrix and completely characterise the state of two qubits. We can then analyse this in a number of ways. Perhaps the simplest is to look at the overlap, or fidelity, between the measured density matrix and some ideal density matrix, as shown in Figure 9.

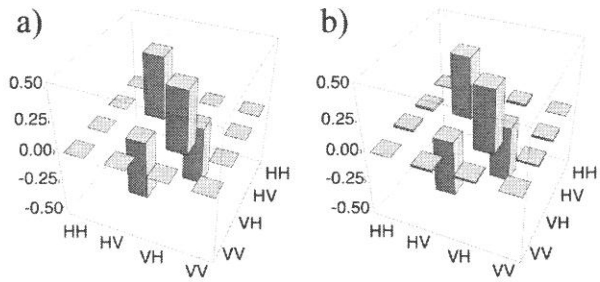


Fig. 9: a) density matrix of an ideal maximally entangled state b) tomographically reconstructed density matrix (the imaginary components are on the order of a few percent, and are not shown). The Fidelity between these matrices is 0.97 ± 0.03 - the measured state is quite entangled.

A more quantitative approach is to analyse both the degree of order and the degree of correlation in the measured density matrix. Earlier we discussed several measures for the degree of order (purity, von Neumann entropy, linear entropy). The degree of correlation can be extracted by calculating either the *entropy of entanglement*, or the *tangle* [5]. Measured entangled states can then be compared to one another by plotting their position on the tangle-entropy plane. Until recently, it has only been possible to produce either highly-entangled, highly-ordered states (circled area, top left, Figure 10), in optical, atomic and ionic systems; or unentangled, highly-disordered states (circled area, bottom right, Figure 10) in liquid-phase NMR systems. It was something of an open question as to what states, if any, were possible outside of these regimes. However, using optical qubits it is possible to controllably vary both the amount of entanglement and order (specifically, vary the degree of polarisation), as Figure 11 shows an entire range of states, covering the T-S plane, have now been made experimentally.

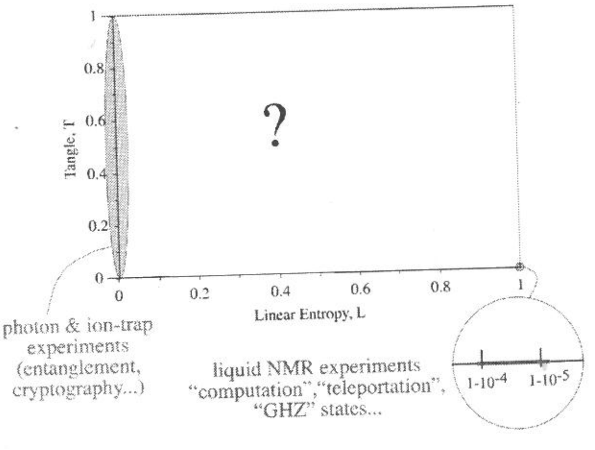


Fig. 10: Location of previous QI experiments on the tangle-entropy plane. The question mark indicates uncertainty over what states, if any, could be produced and characterised outside of these regimes.

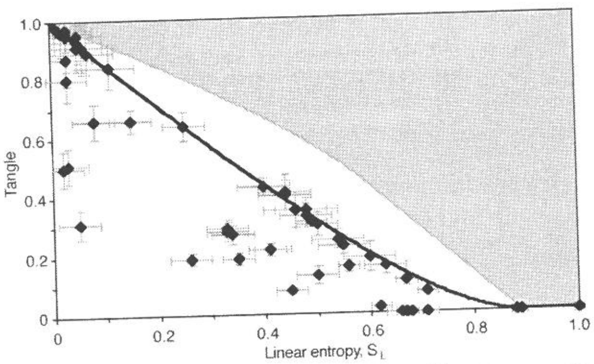


Fig. 11: Location of recent optical 2-qubit states on the tangle-entropy plane. The data points are calculated tangle and linear entropy from a range of measured density matrices. The black curve indicates the *Werner* states: these are states that are a combination of maximally mixed and non-maximally entangled components. The grey region indicates physically impossible combinations of T and S_L

II. QUANTUM INFORMATION IN AUSTRALIA

If you've read this far, please accept my most hearty congratulations! In the next article we get onto the good stuff: making entangled photons and some of their experimental applications in recent years (from tests of nonlocality to quantum computation). Before I leave you, however, let me finish with an update on quantum information research in Australia.

Quantum information can be divided into two major categories: systems of discrete variables (such as polarisation and spin); and systems of continuous variables (such as frequency and quadrature). Both discrete and continuous systems can be realised in optics: this article has concentrated on the former as our research group at UQ concentrates on discrete systems. There is excellent experimental and theoretical work on continuous variable systems done by the group of Dr Ping Koy Lam and Prof. Hans Bachor at ANU: entanglement, cryptography, teleportation and so on can all be realised. It would require yet another entire article (!) to describe these systems in detail - I encourage interested readers to contact the ANU group directly.

Outside of optics, there are major research efforts in quantum information in Australia, perhaps the largest being the Centre for Quantum Computer Technology. This is an Australian multi-university effort (with nodes at the Universities of New South Wales, Melbourne, and Queensland, and a major collaboration with Los Alamos National Laboratory in the USA) undertaking research on the fundamental physics and technology of building, at the atomic level, a solid state quantum computer in silicon together with other high potential implementations, including optics. The Centre encompasses major research infrastructure at each of the three nodes, including an extensive semiconductor nanofabrication facility, crystal growth, ion implantation, surface analysis, laser physics, high magnetic fields/low temperatures, and has substantial theoretical support.

Of course, all of these groups are very interested in hearing from motivated undergraduate students wishing to pursue PhD's, or motivated PhD's wishing to pursue postdocs. If you fall into one of these categories, I am sure they would love to hear from you!

III. ACKNOWLEDGMENTS

This article would not have occurred without the heroic efforts (read: threats and encouragement) of the editor, Wayne Rowlands. It is based on a presentation given at the inaugural meeting of the Centre for Quantum Computer Technology at the Blue Mountains, December 1999.

References

[1] E. Schrödinger, *Naturwissenschaften* **23**, 812 (1935).

[2] G. G. Stokes, *Trans. Camb. Phil. Soc.* **9**, 399 (1852).

[3] A. G. White, D. F. V. James, P. H. Eberhard, and P. G. Kwiat, *Physical Review Letters* **83**, 3103 (1999).

[4] D. F. V. James, P. G. Kwiat, W. J. Munro, and A. G. White, *Physical Review A* **64**, 052312 (2001).

[5] W. K. Wootters, *Physical Review Letters* **80**, 2245 (1998); V. Coffman, J. Kundu, W. K. Wootters, *Physical Review A*, **61** 052306 (2000)

AOS News Vol 16 Number 1, 2002

Conference Report – ACOLS 2001

Judith Dawes and Martijn de Sterke

ACOLS Past and Present

Along with many other delegates, in December we attended the very successful Australasian Conference on Optics Lasers and Spectroscopy (ACOLS), held in Brisbane. The weather was hot (the lecture theatres were blessedly air-conditioned) and the campus of the University of Queensland was beautiful with many tropical flowers and an intense greenness everywhere.

Over the four days of the conference, there was an excellent set of 8 plenary speakers who offered talks on topics from rotational spectroscopy to atom interferometry to optical devices and lasers to astronomy. Particular highlights included the Frew lecture by Prof M. Kasevich from Yale University, and the Coherent Scientific Lecture by Prof H. Mabuchi from CalTech. Two of the plenary speakers were the Presidents of OSA and SPIE. There were also many interesting keynote and contributed papers reporting recent research in atom optics, quantum optics, lasers and applications, spectroscopy, imaging, instrumentation, photonics, biophysics and optometry. One well-attended keynote address discussed trends in research funding, in which the recently announced ARC Priority Area of Photon Science and Technology was foreshadowed. Short courses in infrared fibre optics and ultrafast laser pulse measurement were offered at the end of the conference. There were plenty of chances to meet socially and for business, and the technical exhibits hall, next to the poster hall, was especially busy in the tea breaks.

ACOLS 2001 Program Committee Chair, Bill McGillvray, graciously accepting his "Golden Goddess" award. Unfortunately, we could find no corresponding picture of conference organiser Halina Rubensztein-Dunlop with her "Golden God".

OSA and SPIE jointly sponsored two prizes covering travel to overseas conferences for the best student papers at the conference. The prizes were awarded by Prof A. Johnson and Prof J Harrington, representing OSA and SPIE respectively, to Warwick Bowen of the Australian National University and Winfried Hensinger of the University of Queensland. One of us (Judith) was on the judging committee and can attest to the high quality of student work being presented in talks and posters. Students gave enthusiastic and knowledgeable descriptions of their work and many showed great flair in presentation. The decision on the winners was difficult, and the committee wanted to award many more prizes. Of the 232 presentations in total, students gave 77 papers, of which about half were talks. The future of optics research in Australia and New Zealand is in good hands!

During a tea break, some of us discussed the changes in ACOLS over the past ten years. Although we missed the first ACOLS, we have supported subsequent conferences, and we have been considering how the conference has evolved. In a little over ten years, the numbers of presentations at the conference have been reasonably stable, with 236 presentations in Canberra in 1991 for example. While we don't have attendance figures for the various conferences, judging from lists of paper contributors, this number has increased by about 40% to about 340 contributors, though not all contributing authors attend. When the International Quantum Electronics Conference was held in Sydney in 1996, it subsumed ACOLS and the numbers were slightly greater as a result.

Of course, the mix of research areas has evolved. Fashions in optics come and go, and there are certainly some "hot topics" currently. There are also some notable absences compared with the earlier conferences. We constructed a table listing the general session topics (and counted the numbers of talks for each topic area) from the 1991 Canberra conference, the 1993 Melbourne conference and the 2001 conference (see Table 1). We note in advance that any possible trends may be skewed by the differing ongoing research interests at the universities in the host cities.

There are, nonetheless, some interesting trends in this table, which readers and future ACOLS hosts may wish to consider. For instance, there has been a gradual (one paper in 1993 was titled "The untimely death of

Table 1. Comparison of contributions at ACOLS meetings

1991 Canberra	**1993 Melbourne**	**2001 Brisbane**
Molecular spectroscopy 20	Molecular spectroscopy 22	Lasers and applications 22
Lasers 15	New faces 14	Quantum optics 15
New faces 14	Lasers and applications 13	Photonic devices 14
Quantum optics 10	Optics techniques 10	Spectroscopy 14
Nonlinear optics 8	Nonlinear optics 9	Instrumentation 12
Optical instruments 8	Quantum optics 8	Quantum communication & computing 10
Inorganic spectroscopy 7	Atom optics 6	Atom optics BEC 10
Photonics 7	Fibre optics and sensors 5	Imaging 9
Atomic spectroscopy 5	Atomic cooling 5	Laser trapping 6
Optics 5	Imaging 4	Lithography 4
Applied spectroscopy 4	Applied spectroscopy 4	Research funds 2
Ultrafast 4	X ray optics 3	
Posters 129	Posters 165	Posters 114
Total 236	**Total 268**	**Total 232**

decline in numbers of chemical spectroscopy papers microwave absorption spectroscopy"!), and an associated decline in chemists among the attendees. There are also fewer instrumentation papers and their emphasis has changed towards microscopy and away from interferometry. On the growth side, quantum optics has remained strong and atom optics and Bose Einstein Condensation have emerged during the 1990's. Lasers and their applications has remained a strong area throughout. Nonlinear optics in 2001 seems to be subsumed into Lasers and Photonic devices. The area of photonic devices (and optical fibres) is of course also covered by ACOFT, the Australian Conference on Optical Fibre Technology, which will be held jointly with the next AOS meeting as part of the AIP congress in Sydney in July.

The conference was expertly organized by the Organising Committee, chaired by Halina Rubensztein-Dunlop; a strong program was put together by the Program Committee chaired by Bill MacGillivray. Thanks very much to them and the Committee members, as well as to all others who helped make ACOLS 2001 a great success!

Judith Dawes,
Department of Physics,
Macquarie University

Martijn de Sterke,
School of Physics,
University of Sydney

For those with an eye for figures...

Do you know how many AOS conferences there have been? Until recently you may have come up with the wrong number. The diligence of AOS Councillor Ken Baldwin brought our attention to the following anomaly in the numbering of past AOS conferences:

ACOLS 98	Including 12th AOS Conference
AOS/ACOFT 99	No AOS number specified!
AOS/AIP 2000	Including 13th AOS Conference
ACOLS 2001	Including 14th AOS Conference

Thus, despite the un-numbered meeting of 1999, this year will bring us the 16th AOS conference, incorporated as part of the Australian Institute of Physics' Biennial Congress in Sydney.

See page 32 of this issue for more details about attending the 15th Biennial Congress of the AIP (incorporating the 15th or 16th AOS Conference).

FEDERATION OF AUSTRALIAN SCIENTIFIC AND TECHNOLOGICAL SOCIETIES

Science and Technology for the Social, Environmental and Economic Benefit of Australia

Professor Chris Fell
President

Mr Toss Gascoigne
Executive Director

PO Box 218, DEAKIN WEST, ACT 2600
Phone: (02) 6257 2891, Mobile: 0408 704 442

Dr Brendan Nelson
National Press Club, May 8

FASTS' Forum
"Science and maths education: across the Spectrum"

Are we equipping young people with the right skills for the workforce or for the next generation of scientists and innovators?

Are we equipping young people with the skills to become well-informed citizens?

What role is there for Vocational Education and Training?

Leaders from industry and education will to put forward their solutions to education issues in the morning session, before the keynote address.

"We believe that the whole education sector is hungry for action, and will listen with great interest to the Minister's address at the National Press Club.

"Minister Nelson has signalled quite clearly in public statements that he intends to be an education innovator. (Professor Chris Fell, President FASTS)

9 am to 3.30 pm at the National Press Club, Canberra on 8 May.

Register NOW for the Forum at the FASTS' web site: www.fasts.org

SPIE The International Society for Optical Engineering

SPIE was formed in 1955 as the Society for Photo-optical Instrumentation Engineers, and has been dedicated to providing the best possible service to the optical engineering community. SPIE is an international technical society dedicated to promoting the engineering and scientific applications of optical, photonic, imaging and optoelectronic technologies through its education and communications programs, meetings and publications.

SPIE offers...

International Networking

Today SPIE is the largest international professional engineering society serving the practicing engineer and scientist in the field of optics and photonics. The Society serves the global technical and business communities, with over 14,000 individual, 320 corporate, and 3,000 technical group members in more than 75 countries worldwide. Advance professionally through networking and visibility among your peers. Learn from others and gain access to the voices, ideas, and the energy of a global community.

Meetings

Among the many services the Society offers are the sponsorship, planning, and execution of technical conferences, product exhibitions, and symposia. SPIE's technical meetings and symposia are internationally-acclaimed gatherings of engineers and scientists working in optics, optoelectronics, and many related fields. They take place in large and small venues, from specialised topics to cross-disciplinary information exchanges, complete with extensive programs including short courses, workshops, and other special activities.

Publications

A major activity of SPIE is the publication and distribution of archival professional journals, full-manuscript conference proceedings, newsletters, and optics-related texts and monographs. SPIE publications deliver timely, high-quality technical information to the optics, imaging, and photonics communities worldwide. Membership includes a subscription to *OE Reports*, a monthly newspaper that provides news and commentary on cutting-edge technology.

...and More

In addition, SPIE provides numerous services to its members, including on-line electronic databases, electronic bulletin board and networking services, and employment assistance. To further serve the public good, the Society sponsors a number of awards, scholarships, and educational grants every year, and publishes a comprehensive catalogue of educational resources in the optics field, *Optics Education*.

To join SPIE: Complete the online membership form at *www.spie.org/membership_form.html*, print and fax it to SPIE along with a copy of your AOS dues receipt. (Be sure to indicate that you are eligible for the US$20 discount as an AOS member). Any queries can be directed to Mr Paul Giusts at *membership@spie.org*

SPIE International Headquarters
Tel: +1 360 676 3290 *Fax*: +1 360 647 1445 *email:* spie@spie.org *web*: http://spie.org
PO Box 10, Bellingham WA 98227-0010 USA

Accurate Optical Frequency Measurement and Synthesis

Andre Luiten

Frequency Standards and Metrology Group,
Physics Department, University of Western Australia,
Nedlands 6907 WA, Australia

In recent times a remarkable breakthrough has occurred in the field of optical frequency measurement and synthesis. For the first time it is now possible to generate arbitrary waveform light pulses, perform accurate optical frequency synthesis and accurately measure the frequency of optical frequency signals. These long dreamed of possibilities have been delivered because of the existence of two innovative technologies: ultra-fast pulsed lasers that generate pulses only a few optical cycles in duration, and specially tailored optical fibre that can broaden the output spectrum of these light pulses across the entire optical spectrum. In a seemingly improbable feat, this combination of the extremely fast and extremely broad has proven to enable reliable measurements with a higher precision than any other technique. This article outlines the mechanisms inherent to the operation of the pulsed laser, as well as the tailored optical fibre, and then presents the techniques that enable the promised frequency synthesis and measurement.

1. Introduction

Scientists and engineers working in the optical part of the electromagnetic spectrum (10^{14}-10^{15} Hz) have long dreamed of coherent instrumentation that can perform similar operations to that readily available to researchers working with the audio, radio-frequency and microwave parts of the spectrum (0 Hz -10^{11} Hz). For example, until very recently it has not been possible to observe the time evolution of the electric field of an optical signal on the equivalent of an optical oscilloscope, or to synthesize a lightwave with an accurately defined frequency (colour). We now stand at the threshold of an era in which this type of coherent measurement and generation will become readily available in the optical domain. For example, within a few years it is likely that one will be able to purchase accurate frequency counters, spectrum analysers, frequency synthesisers and arbitrary waveform pulse generators in the optical domain. The basis of this breakthrough is the development of a relatively simple apparatus that can create a one-to-one phase relationship between a microwave frequency signal and an optical frequency signal: the so-called *femto-comb*.

In this article I will describe the principles of the *femto-comb* scheme as well as outline the operation of its constituent parts. For a more detailed description the reader should refer to the references attached to this article together with some recent review articles [1-3]. The two key enabling technologies for this new technique are the development of lasers that can generate pulses of light only a few optical cycles in length (a few tens of femtoseconds in duration), and the use of special microstructured optical fibre that can transform these short pulses of light into a broad rainbow of optical radiation that is more than an octave wide. Surprisingly, this stream of extremely short pulses of light, each of which spans the optical spectrum, can allow generation or measurement of the frequency of an arbitrary light signal with greater precision than any other technique.

2. Background

Let us consider the process of making a frequency measurement of some arbitrary frequency signal. If the measurement is to be accurate then the frequency of the signal to be measured must be, either directly or indirectly, compared to the definition of the second. The second in the *Systeme Internationale* (SI) is defined as the duration of 9,192,631,770 cycles of the microwave radiation corresponding to the frequency splitting of two hyperfine levels in the ground state of a free Cesium-133 atom. For a signal lying in the radio-frequency, microwave or audio domains there are well developed and precise electronic techniques for making this type of frequency comparison. However, for optical signals, which have a period of only a couple of femtoseconds long (a femtosecond equals 10^{-15} s), this frequency comparison has always proved to be extremely difficult. This is essentially because the period of an optical signal is too short for it to be directly counted by any electronic means. Before suggesting a solution to this optical frequency counting problem lets us turn our attention to another coherent operation that may be of interest: optical frequency synthesis. In this operation one wishes to generate a signal that has a well-defined frequency relationship with some reference signal. If the synthesized signal is to be accurate then the reference signal should be related in a known way with the Cs microwave frequency, and in addition, the synthesis process itself needs to be accurate. The ideal way to ensure this accuracy is to require that the phase of the output signal of the synthesiser is always related in a known way to the phase of the reference signal. Of course, if the phases of the output and reference signals are held in a fixed relationship then it guarantees that the frequency of the two signals (which is just the time derivative of the phase) is also related.

If one can create this type of phase relationship between an optical signal and, for example a microwave signal, then not only have we created an optical frequency synthesizer, but an immediate solution to the frequency counting problem mentioned

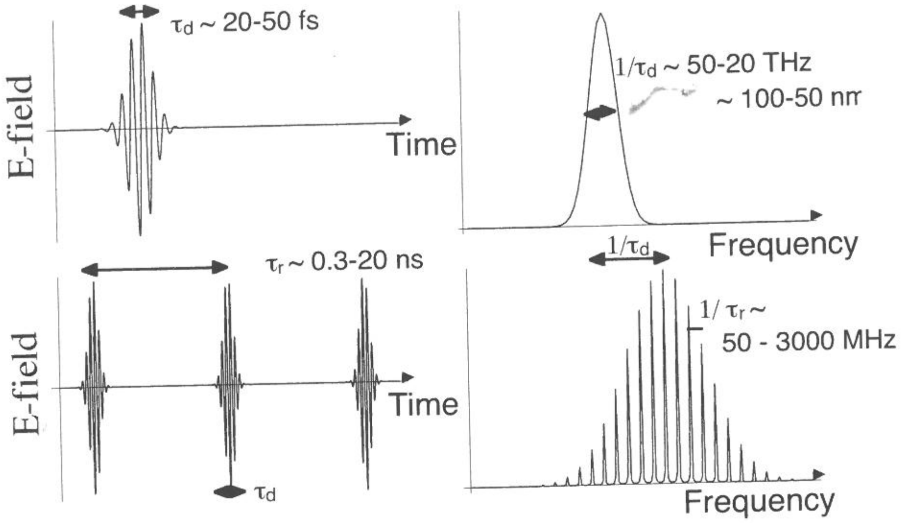


Fig. 1: A figurative view of the time evolution of the electric field vector (first column) and frequency spectrum (second column) of a single short light pulse (top row) and multiple phase coherent light pulses (second row). Typical values for pulse duration (τ_d) and pulse repetition rate (τ_r) have been shown on the plots.

earlier comes to mind. Instead of directly measuring the optical signal properties we could examine the microwave signal and since there is a simple relationship between the phases of the two signals we can infer the instantaneous phase of the optical signal. Any coherent measurement that can be performed on a microwave signal can now be translated into the optical domain. The remaining problem, of course, is how to create this phase relationship between two signals that differ by at least five orders of magnitude in frequency. Before describing the modern and simple solution to this problem I will describe the two intrinsic technologies that are at the basis of the technique.

3. Femtosecond-pulse Mode-locked Lasers

In 1991 the serendipitous discovery of Kerr-lens mode-locking in Wilson Sibbett's laboratory at the University of St. Andrews [4] led to a reliable and simple method for producing pulses of laser radiation in the near infrared with a duration of just a few tens of femtoseconds: in other words each light pulse contains just a few cycles of the light wave. This remarkable advance has been the enabling technology for a whole raft of new types of measurements in an exceptionally wide range of fields. These new types of measurement have only been made possible because light pulses with such extremely short duration have several special ensuing properties:

- in such a short interval light may only propagate a few microns and thus its energy is well located and confined in the propagation direction,
- this confinement in the propagation direction means that the peak intensity of the pulse can be extremely high (up to hundreds of GW/cm^2 i.e. 10 million times more intense than the sun's flux at the surface of the sun),
- the reciprocal relationship between time and frequency requires that a short pulse of light must consist of a broad spectrum of wavelengths. The shortest pulses yet generated (of the order of 5 fs [5]) contain radiation across many hundreds of nanometres range in wavelength (colour) – see Figure 1.

In one example of a new application enabled by this technology the pulses were used to illuminate and examine very rapid processes analogously to a 'stroboscopic' or stopaction camera. The 1999 Nobel Prize in Chemistry was awarded to Professor Ahmed H. Zewail of Caltech who demonstrated that with the aid of a femtosecond pulsed laser one can see how atoms in a molecule move during a chemical reaction, leading to a new area of physical chemistry; called "femtochemistry".

The particular property of femtosecond lasers that makes them useful in a frequency measurement and synthesis application is that the laser not only delivers a short pulse but produces a continuous stream of pulses with a very stable inter-pulse time interval. If we look again at figure 1 we see that a single extremely short pulse is necessarily composed of a relative broad spectrum of radiation wavelengths. The broad spectrum arises essentially because in a pulse of only a few tens of optical cycles the central wavelength of the pulse can only be ascertained with a relatively poor resolution. This is the precise manifestation of the Heisenberg Uncertainty Principle when applied to energy and time. In contrast, if we examine the spectrum of a stable stream of short pulses we find a discrete comb of optical spectral lines (see figure 1). The envelope of this spectral comb has a span related to the reciprocal of the pulse duration, while the separation of the "teeth" of the comb is equal to the pulse repetition rate. In 1979 Theo Hänsch had suggested a revolutionary use of these types of frequency combs: one could use such a comb as a "frequency ruler" to measure the frequency (or colour) of an arbitrary frequency signal. His concept was finally implemented experimentally 20 years later by his group at the Max Planck Institut für Quantenoptik (MPQ) when technology had caught up with his idea

[6]. To understand the properties of this *femto-comb* in more detail we need to understand the mode-locking processes that give rise to the *femto-comb*.

3.1 Mode-Locking

A highly simplified view of the optical arrangement of a solid-state mode-locked laser is shown in Figure 2. A solid-state laser crystal that is capable of optical amplification over a very broad range of the optical spectrum is centred between the two broad-band and high-reflectivity curved mirrors. The laser cavity is closed with two flat mirrors, one of which has the same high reflectivity optical coating as the curved mirrors, while the other has a reflectivity in the range of 90-99.5% to provide an output coupler for the laser. The laser crystal is pumped by an external laser with many watts of green (Titanium doped sapphire laser[7]) or red (Chromium doped $LiSrAlF_6$ laser[8, 9]) light. The pumped laser crystal is capable of providing optical gain over many hundreds of nanometres of the optical spectrum, and when strongly pumped the crystal's gain can exceed the cavity losses across 50 to 100 nm of the spectrum. In this situation one expects that the laser will oscillate in millions of longitudinal modes simultaneously. The onset of mode-locking, which is the key to conversion of this disordered multi-mode output into an ordered stream of femtosecond optical pulses, can be understood in many ways, although in this paper we will only consider the "time domain" argument for how this is achieved

Let us refer to Figure 3(a) showing us the spectrum appearing at the output of the laser prior to initiation of mode-locking. The spectrum exhibits the typical multi-mode behaviour of a broad-bandwidth laser: a forest of nearly equally spaced modes, with each mode having a relatively similar amplitude but with an independent and random initial phase. In mathematical form the instantaneous electric field amplitude of each mode can be written as: $A_m \cos(2\pi \nu_m t + \phi_m)$ where A_m is the amplitude of the mth mode, ν_m is the frequency of the mth mode and ϕ_m is the initial phase of the mode. The frequency of the mth mode in the spectrum will satisfy the boundary conditions of the cavity and will be given as $\nu_m = m\, c(\nu_m)/2L$ where the speed of light (the phase velocity), c, is shown with an explicit frequency dependence. The phase velocity for a mode in the laser cavity differs from the free space value because of the refractive index of the transmissive components in the cavity. In addition it is in general frequency dependent because of dispersive effects in those components. Typically one takes additional steps to minimise the magnitude of these dispersive effects, either by inserting compensating prisms into the laser cavity, or using special dispersion compensating mirrors . Thus, prior to mode-locking, the spectrum of laser modes is nearly but not quite uniform.

The output power of a multi-mode laser appears as a rapidly time varying and apparently noisy signal resulting from the super-position of all of these constituent modes. However, it is important to note that the amplitude (A_m) and phase (ϕ_m) of each of the constituent modes only changes relatively slowly (on the time scale of the cavity photon lifetime, ~100-1000 ns) and so although the output signal appears to fluctuate wildly (on the timescale of reciprocal of the spectral width of the output of the laser, ~10-100 fs), the output power is very nearly perfectly periodic after one cycle around the laser cavity ($2L/c(\nu) \sim 0.3$-10 ns). In addition to the broad gain bandwidth there is one other feature that a laser must possess if it is going to generate femtosecond pulses. The cavity must contain some form of saturable optical loss i.e. a loss that

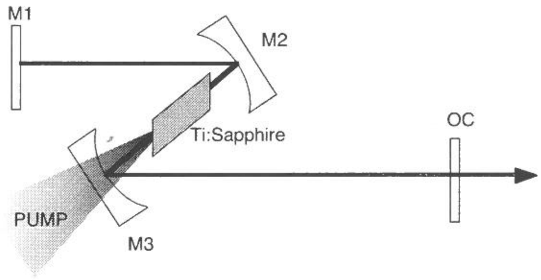


Fig. 2: A simplified overview of a mode-locked laser based on a Ti:sapphire laser crystal. Mirrors M1-M3 have a broad-band high-reflectivity coating. The output coupler (OC) has a somewhat lower reflectivity to couple a small fraction of the circulating light power out of the laser. Typically the laser crystal is pumped by a high power pump laser through one of the concave mirrors.

decreases as the intensity of radiation impinging upon it increases. In modern lasers this is provided by a semiconducting layer in the cavity mirrors that increases the mirrors reflectivity as the power incident on the mirror increases. When mode-locking was first observed this power dependent loss arose from a fortuitous combination of a power dependent focussing effect in the laser crystal (the Kerr effect [10]), and an aperture somewhere else in the laser cavity. An increase in power in the crystal resulted in more power passing through the aperture and thus less loss in one round trip around the laser cavity.

So considering Figure 3(b) let us follow the effect of a power dependent loss upon the circulating power in the laser cavity. The peaks in the fluctuating curve experience less loss on a round trip in the cavity as compared with the valleys, and thus the circulating power evolves so that the peaks grow larger at the expense of the valleys. The eventual result (Fig. 3c) is that all of the output power of the laser is concentrated into one short burst (with a pulse duration of the order of the reciprocal of the spectral width of the laser). This pulse travels around the laser cavity arriving at the output coupler once per cycle giving rise to a pulse of radiation exiting the laser. The time interval between these exiting pulses will be $\sim 2L/v_g$ where v_g is the group velocity of the pulse ($v_g = \partial\omega/\partial k$ where k is the propagation vector and ω is the angular frequency of the pulse [11]). If we consider the spectrum of this strictly periodic pulse stream at the exit of the laser it will be a wide comb of signals that are exactly separated by $v_g/(2L)$. The envelope of the amplitudes is related to the pulse shape and has a half width approximately equal to the reciprocal of the pulse duration. In this respect the mode-locked spectrum appears similar to the initial multi-mode spectrum, however, now all of the phases of the individual modes are held in a strict relationship to ensure that all of the modes come to constructive interference at only one 'single point' in the cavity, or at a 'single point' in time. One sees that the onset of mode-locking has imposed a perfect uniformity on the spectrum as well as ensuring that the relative phase of each mode is held to a fixed value. This is in significant contrast to the initial multimode mode of operation when the comb was not perfectly uniform and the phase of each mode was independent and random.

This simple argument was tested by a careful experimental study at the MPQ group in 1999 and showed that the *femto-comb* uniformity was better than a few parts in 10^{17} [6]. In other words, the spacing of the modes was the same to within a few milliHertz across the entire optical spectrum! This group also tested the proposition that the pulse repetition rate was equal to the frequency spacing of the comb and found that this was true to an experimental level of six parts in 10^{16} [6].

By more careful consideration of the mode-locking process one can write the frequency of the mth order mode in the *femto-comb* as:

$$\nu_m = m\, v_g/(2L) + (c - v_g)/\lambda_0 \ldots = m\, f_{rep} + f_0 \qquad (1)$$

where λ_0 is the central wavelength of the comb, f_{rep} is the pulse repetition rate of the laser and f_0 is termed the offset frequency of the comb. It characterises the frequency offset of the entire comb from falling upon the exact harmonics of the repetition rate and arises from the difference in the group velocity of the pulse and phase velocity of each mode in the spectrum[12]. We note that if one were able to accurately determine f_{rep} and f_0 for the comb, then a determination of the mode order (m) for a particular mode would immediately determine the absolute optical frequency of that mode. The repetition rate can be easily measured by letting the pulse stream fall on a high-speed photodiode and monitoring the output voltage pulses with a radio-frequency counter. Unfortunately, until recently, there was no equally obvious and simple method to measure the offset frequency of the comb with high accuracy. In the next section of this article we will present the key that unlocked this possibility.

4. Microstructured Fibre

In the late 1990s both Bell Laboratories [13] and the University of Bath [14] developed special optical fibre that was designed to have minimal group velocity dispersion in the region of the spectrum around 800nm. The structural group velocity dispersion arising from a

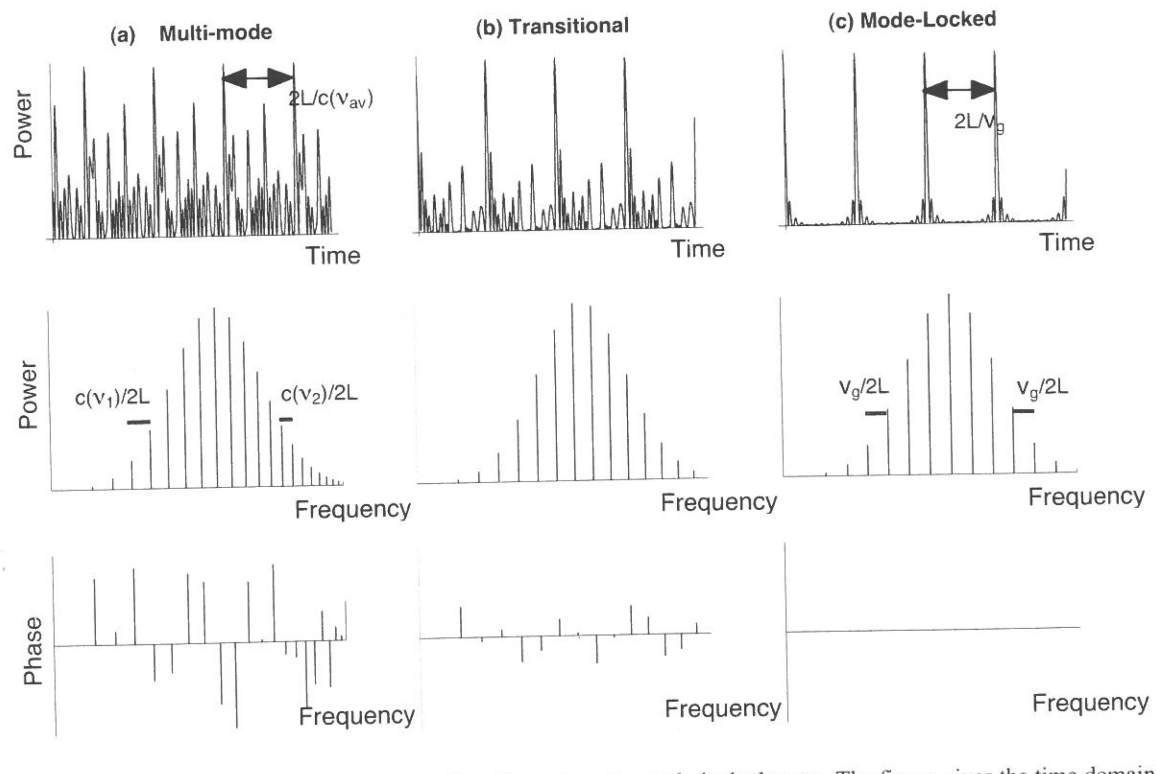


Fig. 3: A representation of the evolution of a broadband laser into the mode-locked state. The figure gives the time domain view of the laser output power in the first row, the optical frequency spectrum of the laser in the second row, and the initial phase of each optical mode in the third row. The initially noisy output power evolves into a periodic pulsed output while the mode spectrum becomes strictly uniform. See text for further details.

periodic microstructure (a photonic crystal) around the silica fibre core was used to compensate the intrinsic material dispersion allowing the fibre to exhibit some highly unusual propagation properties [13]. Of particular interest to frequency metrology was the remarkable observation that when femtosecond pulses were launched into a short length of this type of fibre, the output pulses from the fibre were observed to consist of a broad continuum of radiation [15]. This continuum radiation ranged from around 400nm in the blue part of the spectrum to beyond 1600nm in the optical telecommunication bands. This was despite the initiating 850nm pulse having a spectral width of only 50-100nm. The low dispersion of the fibre prevents a spreading of the pulse energy along the fibre and thus encourages strong non-linear interactions because of the maintenance of high pulse intensity over long distances. It is believed that a combination of non-linear processes, probably dominated by four-wave mixing and self-phase modulation, leads to the spectral broadening of the pulse [16]. An important question is whether the special phase relationship that exists between the spectral members of the input comb is preserved in the incredible conditions (Intensity >200 GW/cm^2) that prevail in the core of the microstructured fibre.

Measurements by several groups have shown that the phase coherence of the comb is indeed preserved during transmission through the fibre [16] and is transferred to the new broadened comb i.e. the newly generated modes in the output spectrum of the fibre can still be modelled with Eq. (1). We now address the importance of this broadened comb to frequency metrology.

5. Femto-Comb

As stated earlier the frequency of each mode of the comb seen at the output of the fibre can be expressed as $\nu_m = m\ f_{rep} + f_0$. If one were able to determine f_{rep} and f_0 for the comb, then a determination of m for any particular mode would immediately determine the absolute frequency of that laser mode. The repetition rate can be easily measured since one just needs to measure a radio-frequency rate of pules exiting the laser (this falls between 80 MHz for a traditional two metre long Ti:sapphire laser up to around 3 GHz for the shortest cavity modern lasers). The real difficulty is measurement of the comb offset frequency.

Let us imagine that we can isolate one of the modes near the low frequency (red) wing of the *femto-comb* having a frequency, $\nu_{m1} = m1\ f_{rep} + f_0$, and pass this signal through a non-linear crystal so as to generate the second harmonic of the signal. The second harmonic has a frequency of $2\nu_{m1} = 2\ m1\ f_{rep} + 2f_0$. Let us isolate a second member of the comb at the high frequency (blue) end of the *femto-comb* that has a mode number, m2, that is twice that of m1. Its frequency is $\nu_{m2} = m2\ f_{rep} + f_0 = 2\ m1 f_{rep} + f_0$. If we combine the second harmonic and blue wing signals on a photodiode it will generate an interference signal (a beat note) that oscillates at the difference frequency. In this case this is at $2\nu_{m1} - \nu_{m2} = f_0$ i.e. exactly the offset frequency of the comb! In fact, one can verify that instead of a just comparing a single doubled red mode with one blue mode it is possible to double the entire red end of the comb and compare it with the blue end of the comb. All the beat notes are generated at the same frequency and are phase-coherent so that the efficiency of the process can be very high.

We have now outlined a method to extract both f_{rep} and f_0 for the *femto-comb*. To determine the exact frequency of the mth mode it merely remains to determine the mode order ie. the value of m. Modern interferometric techniques can easily determine the wavelength of a signal to an accuracy of a few hundred megahertz. If one chooses a mode spacing for the comb that is larger than the wavemeter's accuracy then a simple interferometric measurement will unambiguously determine the value of m.

6. Applying and Stabilising the Comb

To use the *femto-comb* as an optical frequency measurement tool we combine the unknown signal with the *femto-comb* on a photodiode. The lowest frequency output signal (beatnote) from the photodiode will be the difference frequency between the unknown signal and the nearest member of the *femto-comb*. Identification of the mode order of this closest member of the *femto-comb* (m), together with the known values of f_{rep} and f_0 immediately enable determination of the frequency of the unknown signal. Of course, in practice the values of f_{rep} and f_0 fluctuate because of fluctuations in the length of the mode-locked laser cavity (vibrations and temperature fluctuations) and because of fluctuations in the dispersion in components of the cavity (driven by pump laser power fluctuations). Although in recent times a technique for using even an unstabilised *femto-comb* for frequency measurements has been developed [17], it is probably most useful to attempt at least some level of stabilisation. Of course, if one is making use of one of the comb modes as a synthesised optical source then this type of stabilisation is essential.

Stabilisation of the comb has been achieved in a number of laboratories, in particular the work at MPQ [18], Joint Institute of Laboratory Astrophysics (JILA) [19] and the National Institute of Standards and Technology (NIST) [2] have been very successful. To stabilise both of the *femto-comb* parameters (f_{rep} and f_0), one needs a technique to control the two parameters independently. By examining Eq. (1) one can see that modification of the length of the laser cavity will result in a change of the repetition rate of the laser alone, while a change in the group velocity (the dispersion) of the laser cavity changes both the repetition rate as well as the offset frequency. A feed-forward system can be designed to modify the dispersion and length together in such a way to control solely the offset frequency. The length of the laser can be changed by directly moving one of the cavity mirrors using a piezo-electric actuator, while the cavity dispersion can be modified by changing the pump power or by rotating a mirror in the dispersion compensation section of a long cavity mode-locked laser [12]. In preliminary measurements the NIST group has stabilised one mode of the *femto-comb* to an electric-quadrupole transition at 1.064 PHz (282 nm) of a single laser-cooled and trapped Mercury Ion. The comb offset frequency was separately stabilised to a highly stable radio-frequency signal source. The overall frequency stability of the comb was measured by comparing another comb mode against an independent 657 nm Ca optical frequency standard. The experiment showed that the modes of the comb had a frequency instability at the level of 7 parts in 10^{15} over a 1 second timescale [2]. Such a stable comb could provide the ability to measure the frequency of a signal anywhere in the optical spectrum with a resolution of a just a few hertz with a 1 second measurement. The work at JILA has resulted in the construction of a comb stabilised to a transition in molecular iodine (I_2). The reported stability of this comb was 5 parts in 10^{14} limited by the stability of the optical clock. Unfortunately (or fortunately depending upon your viewpoint) it is impossible to fully characterise the stability of these combs with respect to conventional microwave clocks since the short-term stability of these combs is far higher than the short-term stability of conventional microwave clocks! One really needs to use a better performance microwave oscillator (such as the one constructed by our group at UWA [20]) or alternatively build two optical clocks. The combination of an optical frequency standard with a stabilised *femto-comb* provides the world's first true example of an optical clock.

Despite the very early stage of this type of work, *femto-combs* have already been applied to a great number of optical frequency measurements of fundamental significance. For example, a *femto-comb* has been used as a crucial element in determining an improved value of the fine structure constant [21] as well as in improved measurement of the Hydrogen 1*S*-2*S* transition frequency [22, 23]. The Hydrogen 1*S*-2*S* measurement will eventually feed into an improved measurement of the Rydberg constant. The *femto-combs* have also been used as highly accurate optical frequency counters to improve the spectroscopy of Cesium [21], Iodine [24], Rubidium [24], Calcium [25], Methane [26], as well as ions of Strontium[27], Mercury [2], Ytterbium[27], and Indium [28]. In addition, application of the comb to optical synthesis [16], optical clockwork [2, 29], and pulse/waveform synthesizers [19] have all been demonstrated.

7. Conclusion

There is no doubt that these exciting developments will have a marked effect on the types of experiments possible in the optical domain, as well as on the technology available to the researcher in the near future. Already one company is selling a complete stabilised *femto-comb* for just three times the price of the pumped mode-locked laser alone. Perhaps the importance of this work can be best demonstrated by the fact that almost every metrology laboratory in the world has commenced constructing a *femto-comb*. In a more local development, a collaboration between the Frequency Standards and Metrology laboratory at the University of Western Australia (UWA), David Sampson's Electronic Engineering group at UWA, Peter Hannaford's group at Swinburne University of Technology and Deb Kane's group at Macquarie University is presently constructing a portable version of a stabilised *femto-comb* so that we can provide this type of technology to Australian researchers and industry. The expected fractional optical frequency accuracy for the portable chain is around 10^{-12} for a 1 second measurement, and around 10^{-13} for a 10^4 second measurement. In other words this system can determine the optical frequency of an 850 mn signal to a level of 400 Hz within 1 second. We expect that this will be available within two years and are happy to receive requests to provide the facility to any interested parties. For further information on our work please visit our web-site at http://www.fsm.pd.uwa.edu.au/.

8. Acknowledgements

I must thank Jun Ye of the Joint Institute of Laboratory Astrophysics (JILA), Thomas Udem of the Max Planck Institut für Quantenoptik (MPQ), and Leo Hollberg of the National Institute of Standards and Technology (NIST) who have all provided me with their latest publications and pre-publication articles. The international frequency standards and metrology community has always welcomed our group warmly and for that we are very grateful. Finally, I must thank the students of my laboratory in particular the frequency chain tamers, John McFerran and Richard Kovacich, who have kept us in the game despite the relatively poor resources available to Australian science.

References

1. J. L. Hall and J. Ye, Optics and Photonics News , Sept., 44-50 (2001).
2. S. A. Diddams, T. Udem, J. C. Bergquist, *et al.*, Science **293**, 825-828 (2001).
3. A. N. Luiten, *Frequency Measurement and Control: Advanced Techniques and Future Trends* (Springer-Verlag, Berlin, 2001).
4. D. E. Spence, P. N. Kean, and W. Sibbett, Optics Letters **16**, 42-44 (1991).
5. R. Ell, U. Morgner, F. X. Kärtner, *et al.*, Optics Letters **26**, 373-375 (2001).
6. T. Udem, J. Reichert, R. Holzwarth, *et al.*, Optics Letters **24**, 881-883 (1999).
7. D. E. Spence, J. M. Dudley, K. Lamb, *et al.*, Optics Letters **19**, 481-483 (1994).

8. G. J. Valentine, J.-M. Hopkins, P. Loza-Alvarez, *et al.*, Optics Letters **22**, 1639-1641 (1997).
9. M. J. P. Dymott and A. I. Ferguson, Optics Letters **20**, 1157-1159 (1995).
10. G. Cerullo, S. De Silvestri, and V. Magni, Optics Letters **19**, 1040-1042 (1994).
11. A. Siegman, *Lasers* (University Science Books, Sausalito, CA, USA, 1986).
12. J. Reichert, R. Holzwarth, T. Udem, *et al.*, Optics Communications **172**, 59-68 (1999).
13. J. K. Ranka, R. S. Windeler, and A. J. Stentz, Optics Letters **25**, 796-798 (2000).
14. J. C. Knight, J. Broeng, T. A. Birks, *et al.*, Science **282**, 1476-1478 (1998).
15. J. K. Ranka and R. S. Windeler, Optics and Photonics News **11**, 20-25 (2000).
16. R. Holzwarth, T. Udem, T. W. Hänsch, *et al.*, Physical Review Letters **85**, 2264-2267 (2000).
17. H. Telle, B. Lipphardt, and J. Stenger, Applied Physics B **in press** (2001).
18. T. Udem, R. Holzwarth, and T. W. Hänsch, Nature **in preparation** (2002).
19. R. K. Shelton, L.-S. Ma, H. C. Kapteyn, *et al.*, Science **293**, 1286-1289 (2001).
20. S. Chang, A. G. Mann, and A. N. Luiten, Electronics Letters **36**, 480-481 (2000).
21. T. Udem, J. Reichert, R. Holzwarth, *et al.*, Physical Review Letters **82**, 3568-3571 (1999).
22. J. Reichert, M. Niering, R. Holzwarth, *et al.*, Physical Review Letters **84**, 3232-3235 (2000).
23. M. Niering, R. Holzworth, J. Reichert, *et al.*, Physical Review Letters **84**, 5496-5499 (2000).
24. S. A. Diddams, D. J. Jones, J. Ye, *et al.*, Physical Review Letters **84**, 5102-5105 (2000).
25. T. Udem, S. A. Diddams, K. R. Vogel, *et al.*, Physical Review Letters **86**, 4996-4999 (2001).
26. P. V. Pokasov, R. Holzwarth, T. Udem, *et al.*, in *Proceedings of the Sixth Symposium on Frequency Standards and Metrology*, edited by P. Gill (World Scientific, St Andrews, Scotland, 2002), to be published.
27. S. N. Lea, H. S. Margolis, G. Huang, *et al.*, in *Proceedings of the Sixth Symposium on Frequency Standards and Metrology*, edited by P. Gill (World Scientific, St Andrews, Scotland, 2002), to be published.
28. J. von Zanthier, J. Abel, T. Becker, *et al.*, Optics Communications **166**, 57-63 (1999).
29. J. Ye, L. S. Ma, and J. L. Hall, Physical Review Letters **in press** (2002).

AOS Technical Optics Award

Call for nominations for *2002*

This award recognises those who have made a significant achievement in technical optics, not necessarily in a manner manifested by an extensive academic record or a traditional academic reputation. The work for which the award is made must have been carried out principally in Australia.

Applications are encouraged from, but not restricted to, young optical workers.

The winner will receive a prize consisting of $300 cash, one year's free membership of AOS, and an invitation to attend the AOS conference and make an oral presentation of his or her work.

Nominations are now invited from (or on behalf of) suitable candidates for the 2001/2002 award, which will be presented at the next AOS Conference.

Details of the applicant's or nominee's activities and achievements should be sent to the Acting Secretary:

Dr Duncan Butler
Ionising Radiation Standards
ARPANSA
Yallambie VIC 3085
Fax: (03) 9432 1835

to be received by **4th May 2002**

15th Biennial Congress 2002

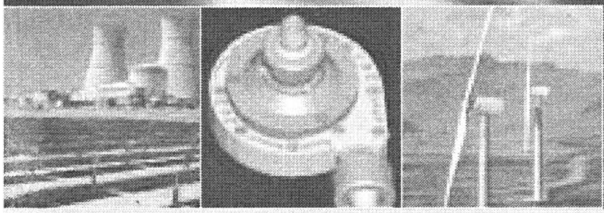
AUSTRALIAN INSTITUTE OF PHYSICS

physics and industry working together

INCORPORATING ACOFT & AOS

Sydney Convention & Exhibition Centre, Darling Harbour
Monday, 8 July to Thursday, 11 July 2002

www.aip.org.au/Congress2002



INVITATION FROM THE ORGANISING COMMITTEE

The Congress Organising Committee invites you to participate in the 15th Biennial Australian Institute of Physics Congress, **AIP2002**, to be held at Sydney Convention & Exhibition Centre, Darling Harbour, Sydney from Monday, 8 July to Thursday 11 July 2002.

AIP2002 will be the largest physics conference in Australia in 2002. Only once every two years do we get a chance to meet such a gathering of the best and brightest physicists in Australia and from overseas - **don't miss out!**

We look forward to welcoming you to this important event.

CONGRESS PROGRAM OVERVIEW

The Congress will commence with the Official Opening of the Program on Monday, 8 July. The Welcoming Reception is also on Monday, 8 July at the Sydney Convention & Exhibition Centre. The Congress concludes on Thursday 11 July.

Congress AIP2002 will be the largest physics conference in Australia in 2002.

It incorporates the following Physics Conferences:

- AINSE / Nuclear and Particle Physics **(AINSE/NUPP)**
- Astronomy Group **(AG)**
- Atomic and Molecular Physics and Quantum Chemistry **(AMPQC)**
- Australasian Society for General Relativity and Gravitation **(ASGRG)**
- Australian Conference on Fibre Optic Technology **(ACOFT)**
- Australian Optical Society **(AOS)**
- Condensed Matter Physics **(CMP)**
- Industry Forum **(IF)**
- Medical Physics **(MP)**
- Physics Education Group **(PEG)**
- Science Teachers Association of New South Wales **(STANSW)**
- Vacuum Society of Australian Congress **(VSA)**
- Women in Physics **(WIP)**

Keynote speakers:

* Mark Sceats (ACOFT) - is Chief Executive Officer of the Australian Photonics Cooperative Research Centre. The centre has over 200 staff and sponsorships from 5 Universities, TAFE, DSTO and 24 companies and which has spun off 8 companies. He holds 4 patents on photonic devices.

* Bertram Batlogg (CMP) - is a Distinguished Professor at ETH, Zürich. In his recent work on organic conductors he has discovered the electrically powered organic laser, the fractional quantum Hall effect in organic semiconductors and superconductivity in organic crystals.

* Richard Maughan (MP) - is a Professor of Medical Physics, he played a major role in establishing the fast neutron therapy accelerator facility at the Karmanos Cancer Institute and is currently working on developing a proton therapy program at the University of Pennsylvania.

* Sheila Tobias (PEG) - is from Arizona, trained in the liberal arts, now focuses on why bright, ambitious college students choose not to study the physical sciences. She is working on professionalizing the science master's degree to attract more management students to science.

Registration – *online registration is now open*

Fees	Before 16/05/02	After 16/05/02
AOS/AIP member	$600	$700
Non-member	$650	$750
Student/Teacher	$400	$450
Industry (2 days)	$400	$400

Accommodation/Travel/Social Program

Detailed information is available on the conference website.

www.aip.org.au/Congress2002

AOS Speakers

- **Savely Karshenboim** – is one of the leading theorists in Quantum Electro-Dynamics, heading part of the Russian and European schools. Has given numerous excellent invited plenary talks at the International Conference on Atomic Physics, and at the conference on Precision physics of simple atoms. Savely was born 1960 and graduated from Saint-Petersburg State University (SPbU) in 1983. He got his Russian Ph.D. degree in Physics in 1992 from SpbU and Habilitation in 1998. He is a Leading Researcher at D.I. Mendeleev Institute for Metrology and has published more than 70 papers in refereed journals and a number of contributions to conference proceedings. He was an editor of the book Hydrogen atom: Precision physics of simple atoms published by Springer-Verlag in 2001. He is a member of CODATA task group on fundamental constants and was a co-chairman of PSAS'2000 conference and co-chairman of PSAS'2002. His scientific interests are related to precision study of simple atoms: theory, interpretation of experiments, applications.

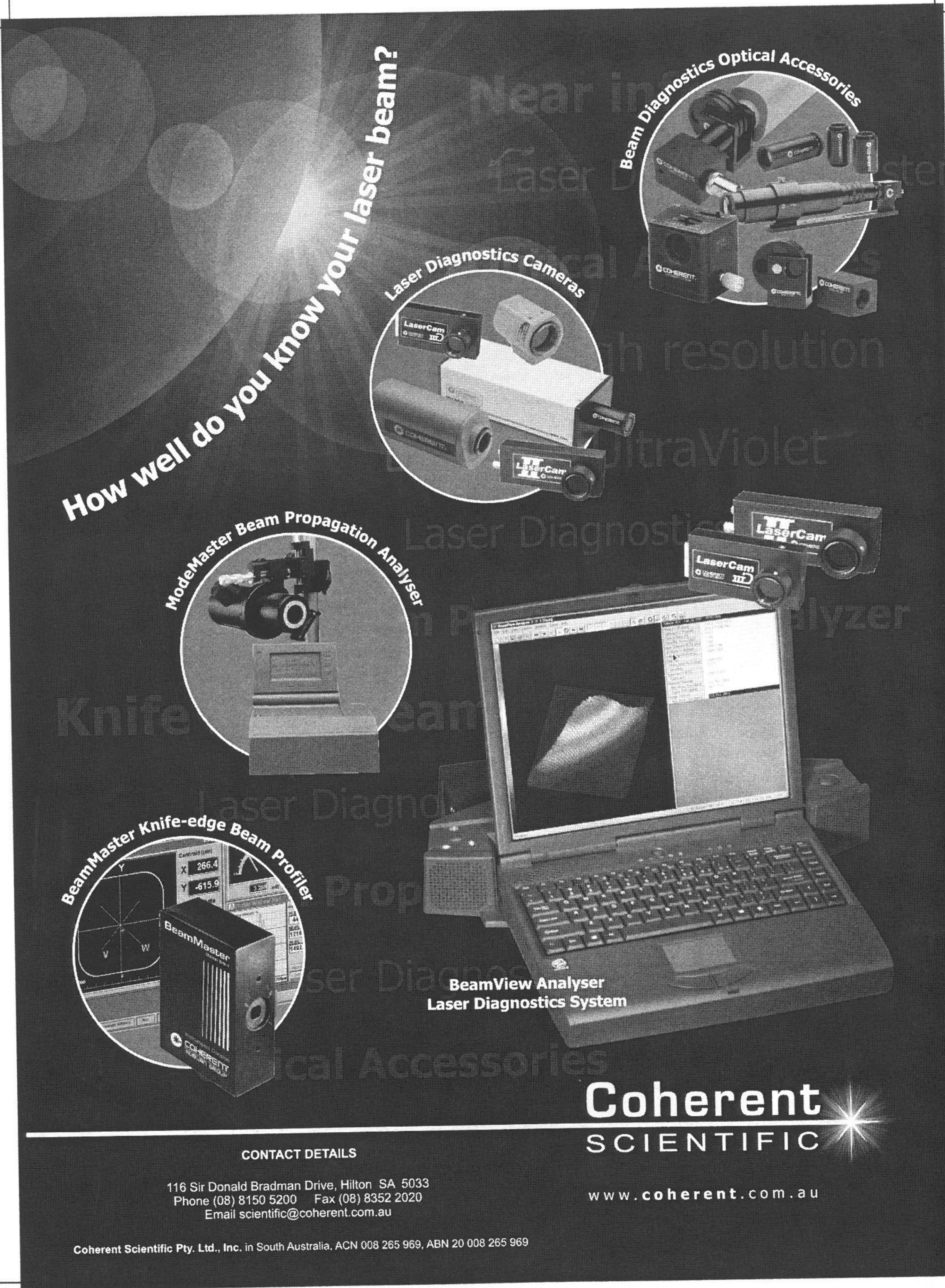
- **John Gillaspy** - has received NIST's highest honour (the Bronze Medal) for his Electron Beam Ion Trap work, and is the Plasma Group leader in the Atomic Physics Division at NIST. He is an excellent speaker, and has been given a Nobel Symposium for his UV and EBIT work. He has produced seminal works on UV & visible laser resonance experiments including Phys.Rev.Letts and Science publications with Nobel Laureate Bill Phillips. Under his leadership, the NIST EBIT has produced quantum dots and made dramatic progress in near-UV and X-ray physics.

- **Gerhard Rempe** is the Director at the Max-Planck-Institute for Quantum Optics, and Professor at the Technical University of Munich (since 1999). He has been awarded the Millikan-Prize-Fellow, California Institute of Technology, Pasadena, USA (1990) amongst many other honours. His experiments and expertise on atom interferometry, atom trapping and Bose Einstein Condensates have made numerous seminal Nature and Physical Review Letters papers in recent years. His work towards cavity Quantum Electro-Dynamics has direct impact for the possibility of Quantum information transmission and storage.

- **Prof. G. Michael Morris** - President-Elect, Optical Society of America; Chief Executive Officer, Corning Rochester Photonics Corporation, Rochester, New York. Michael Morris received his B.S. degree with Special Distinction in Engineering Physics in 1975 from the University of Oklahoma, and his M.S. and Ph. D. degrees in Electrical Engineering from the California Institute of Technology in 1976 and 1979, respectively. From 1979 to 1982, Morris was a Scientist in Optics at The Institute of Optics, University of Rochester. From 1982-2001, Morris was a Professor of Optics at The Institute of Optics, and is currently an Adjunct Professor of Optics.

  In 1989, Morris co-founded Rochester Photonics Corporation (RPC) that specialized in design, prototyping, and manufacturing of diffractive- and micro-optics components and subsystems. In February 1999, RPC was acquired by Corning Incorporated, and now functions as a wholly-owned subsidiary of Corning Incorporated. Morris is currently serving as Corning Rochester Photoncs' Chief Executive Officer.

  Morris' research has spanned a wide variety of topics in statistical optics, optical information processing, automatic pattern recognition, and diffractive- and micro-optics. Morris' current research interests centers on the design and fabrication of telecommunication that utilize diffractive- and micro-optical elements. He is a Fellow of the Optical Society of America and SPIE, and is currently President-Elect of the Optical Society of America. He is also the recipient of the 1997 Rochester Chamber of Commerce Civic Award for Science and Technology, and is an Honorary Member of the OSA, Rochester Section.


How well do you know your laser beam?
Beam Diagnostics Optical Accessories
Laser Diagnostics Cameras
ModeMaster Beam Propagation Analyser
BeamMaster Knife-edge Beam Profiler
BeamView Analyser
Laser Diagnostics System
Coherent
SCIENTIFIC
CONTACT DETAILS
116 Sir Donald Bradman Drive, Hilton SA 5033
Phone (08) 8150 5200 Fax (08) 8352 2020
Email scientific@coherent.com.au
www.coherent.com.au
Coherent Scientific Pty. Ltd., Inc. in South Australia, ACN 008 265 969, ABN 20 008 265 969

Report from FASTS

Chris Fell

President, Federation of Australian Scientific and Technological Societies

IN SUMMARY

1. RESEARCH PRIORITY SETTING
2. FASTS' OCCASIONAL PAPER 4
3. "SCIENCE MEETS PARLIAMENT" DAY 2002
4. WORKING WITH DEPARTMENTS
5. THE PRIME MINISTER'S SCIENCE, ENGINEERING AND INNOVATION COUNCIL
6. THE FASTS' POLICY DOCUMENT
7. MEETINGS WITH MINISTERS AND SHADOW MINISTERS

1. RESEARCH PRIORITY SETTING

I have written to the Minister to express our concerns about the recently-announced research priority areas, and met two weeks ago with Science Minister Peter McGauran to discuss ways that FASTS and the working science community could contribute to the development of national priority areas.

While FASTS has consistently supported the identification of national goals, as well as some degree of prioritisation of the research effort towards meeting those goals, we do have reservations about the system as it was announced. Our concerns fall into five areas:

a. process - lack of consultation
b. target - too much at the basic research end
c. quantum - too large a slice
d. plurality - preserving a pluralistic system
e. coordination - a whole-of-government approach needed to priorities

In our view, Bill Clinton's science adviser Dr Neal Lane had it right when he addressed the National Press Club in October 2000. When asked how Australia should prioritise its research, he responded:

"How do you know what to invest in? I don't have a complicated solution to that. I said earlier that especially in basic research, we have found that we get the most out if it by investing in the very best people and the very best ideas...

"And there will be some very high priority national challenges that a nation wants to get at in a given period of time - national security or perhaps for all of us in the area of the environment ... Then we think it's important for the Federal Government to try to bring together the scientific communities and all the different agencies that are involved...

"And it's a little bit more directed research, and that's fine, so we spend some of our increases each year on that kind of multi-disciplinary research that's focussed on larger national needs; but then, within that, you still can't do better than betting on the very best people with the very best ideas."

The essential difference between the Government's initial approach and that recommended by Dr Lane is the process of consultation. The Government is now moving towards a more consultative process, and FASTS will assist in that process of consultation.

2. FASTS' OCCASIONAL PAPER 4

We have just launched our fourth paper in the FASTS' "Occasional Paper" series. It was prepared by the Australian Society of Parasitology and is named "An Investment in Human and Animal Health: Parasitology in Australia".

I thought that you might be interested in seeing the paper and hearing how FASTS and the ASP worked together to launch it into the public arena. It does provide a model for how your Society could work towards a paper on similar lines, with the aim of bringing an issue to the attention of policy-makers and the general public.

The paper was prepared by members of the ASP. The text was approved by the Executive of FASTS and formatted to meet the style of our publications. (We have since prepared guidelines on Occasional Papers, and they are available from our office.) The FASTS' office then worked with the Society to organise the launch at Parliament House in Canberra. This involved room bookings, catering, security arrangements, drafting and distribution of media releases, and correspondence with the Minister. FASTS also arranged for the printing of the paper and putting it on our website in pdf format.

The costs were shared by the ASP and FASTS. FASTS contributed our time and expertise in making arrangements for the launch, and met some printing costs.

The launch received significant media coverage: the 7.30 Report, ABC 7 pm News; articles in the SMH and the Canberra Times; interviews on commercial and ABC radio. It raised a general issue as well as the specific concerns of parasitologists: that the national investment in science and technology is inadequate.

The Parasitology paper had its genesis nearly three years ago, following a priority-setting exercise at a national ASP conference led by Toss Gascoigne of our office. It was a significant effort by ASP and involved many of its members, but the result is a clear statement of policy and directions for parasitology which will fuel the Society and the discipline for some time.

If your Society is interested in the possibility of publishing a paper in the FASTS' series, please contact our office. A copy of the Paper will be sent to you; and in the meantime it is available as a pdf file on the FASTS' web site: www.fasts.org.

3. "SCIENCE MEETS PARLIAMENT" DAY 2002

This event will be held on Tuesday-Wednesday November 12-13. At this stage the morning of Tuesday 12 November will be free if you wished to organise supplementary meetings. We are hoping to incorporate a new aspect, a Science-Industry dinner on the evening of Wednesday 13, and will announce a full program as soon as possible.

This unique event offers a special opportunity for working scientists from across Australia to make the case for science and technology directly to their representatives in Parliament. While the funding initiativesannounced in "Backing Australia's Ability" in January last year were a welcome step, Australia is still out of step with other comparable countries in terms of our national investment in S&T.

We are dealing this year with a new Ministerial team, new Members of Parliament, and new Shadow Ministers, and it is important to continue to build links with Parliamentarians.

SmP Day also offers a valuable opportunity to convene other meetings, and some Societies may be able to schedule regular Council of Executive meetings to coincide with the event in Canberra.

4. WORKING WITH DEPARTMENTS

I led a team of FASTS' Executive members in meeting with officers from the newly-formed Department of Education, Science and Training earlier this month. It was a productive discussion on our respective priorities over the next year, and an exploration of matters where we can contribute to each other's efforts.

We discussed matters such as the Prime Minister's Science Council; the Forum we propose holding at the National Press Club in mid-year; the division of responsibilities between the two Ministers with responsibility for science; triennium funding for the government-funded science agencies; the possibility of having another funding round for Major National Research Facilities; and the selection round for new CRCs in May.

5. THE PRIME MINISTER'S SCIENCE, ENGINEERING AND INNOVATION COUNCIL

The Standing Committee (the scientist members of PMSEIC) meets on March 8. These meetings set the agenda for the full Council meetings which the Prime Minister and most of his Cabinet colleagues attend. The agenda has yet to be approved by the Prime Minister, but the draft focuses on natural resource issues.

The full Committee chaired by the Prime Minister meets on May 17. This is becoming an increasingly important committee in terms of setting national agendas, and I will report on the non-confidential discussions in due course.

6. THE FASTS' POLICY DOCUMENT

We will be releasing a revised policy document later this year. The Policy Committee chaired by Ken Baldwin will be handling the drafting process, and all Member Societies will be invited to comment on draft documents. The new document will have more graphs and diagrams , and reflect changes in the science policy scene with the announcement of "Backing Australia's Ability" and the injection of the ALP's Knowledge Nation proposals.

7. MEETINGS WITH MINISTERS AND SHADOW MINISTERS

I have had three meetings with Science Minister Peter McGauran; and will meet Education, Science and Training Minister Brendan Nelson this week to complement our phone discussions and correspondence.

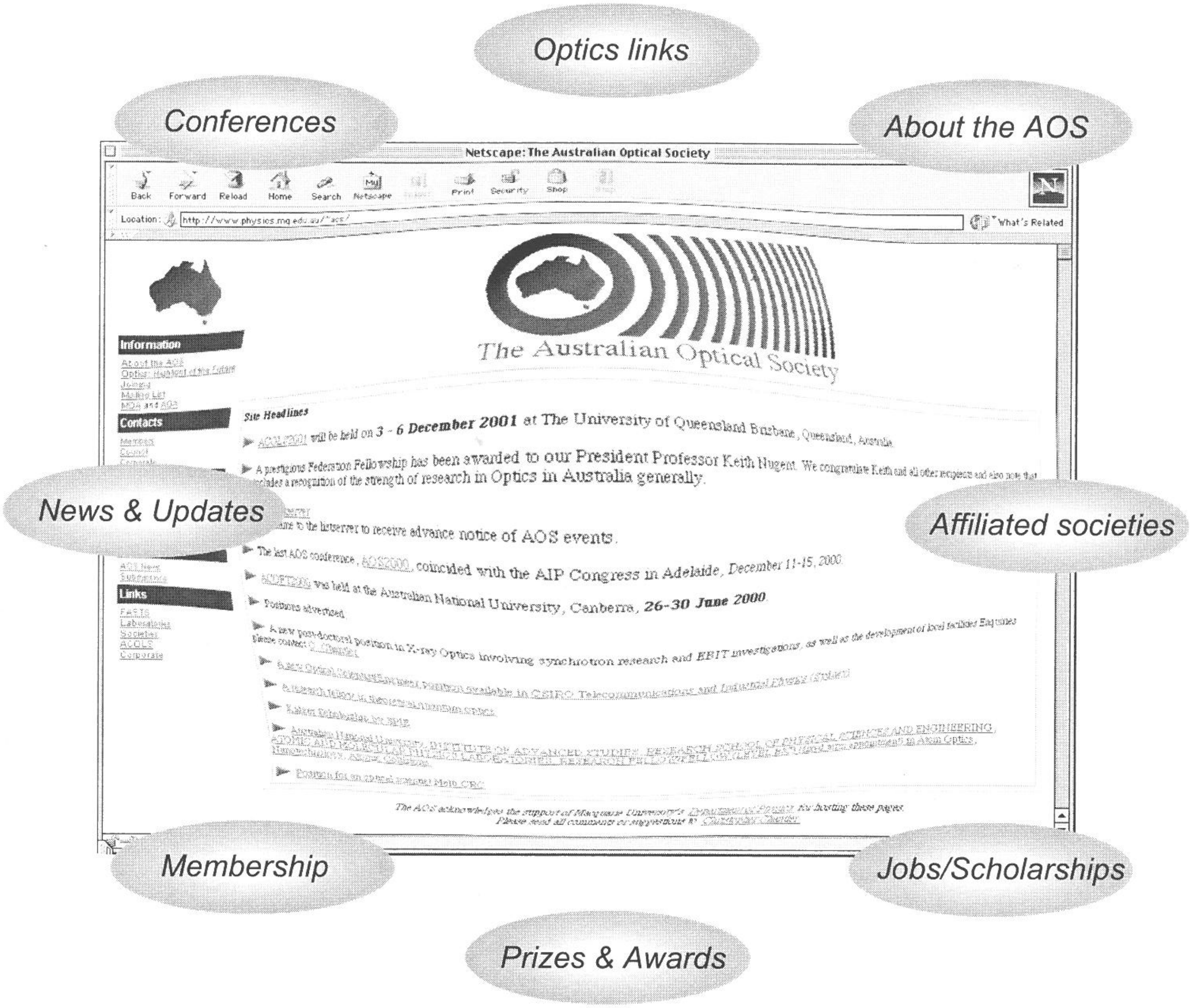
We have met with Shadow Science and Research Minister Senator Kim Carr; and have an appointment with Senator Natasha Stott Despoja as Science spokesperson for the Democrats early in March.

These formal meetings are complemented by more frequent informal contacts between our offices, and by phone conversations. Both Ministers and Shadow Ministers are in no doubt about the FASTS' positions on science and technology issues!

Chris Fell
President
25 February 2002

The Australian Optical Society Web Site

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



Keep up-to-date with what's happening in the AOS - add your name to the AOS listserver (see web page for details)

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

CONFERENCE ANNOUNCEMENT

ICOLS 03 : 13-18 July 2003

Venue

The conference will be held at the Novotel Palm Cove Resort, a beautiful, year-round coastal resort 20 km north of Cairns International Airport, between Cairns and Port Douglas, in Tropical North Queensland. Palm Cove is located where the mountain rainforests of the Atherton Tableland meet the palm fringed beaches of the Coral Sea near the Great Barrier Reef.

Format

Following the tradition of ICOLS conferences, the program will consist of single sessions of invited talks and posters covering the latest developments in Laser Spectroscopy and related topics. Scheduling will allow significant time for informal discussions. The number of participants will be limited to about 250-300.

Topics

* Atomic and molecular laser spectroscopy
* Precision spectroscopy and metrology
* New methods in laser cooling
* Bose condensation, degenerate Fermi gases, and atom lasers
* Cold collisions and cold molecules
* Atom optics and interferometry
* Cavity QED
* Quantum optics
* Nonlinear optics
* Quantum computation, information, and communication
* Laser sources
* Ultrafast spectroscopy and high field physics
* Spectroscopy in biology and medicine
* Novel applications of spectroscopy

Local Committee

Peter Hannaford (Co-Chair)
Hans Bachor (Co-Chair)
Ken Baldwin
Ping Koy Lam
Russell McLean
Andrei Sidorov

For more information: **email:** icols03@swin.edu.au **web:** www.swin.edu.au/lasers/icols03

EDITORIAL

This edition comes with an imperfect blend of grief and excitement. The passing of two iconic figures in Australian optics (both were Life Members of the AOS) has caused a deep sadness for many of us whose lives and careers they touched. I was fortunate enough to have interacted with both men, at extremely different levels of involvement (Robert Hanbury Brown was a lecturer at an International Science School I attended as a High School student, and Geoff Opat was my PhD supervisor and close collaborator). I am sure that their legacy of great science will continue to inspire future generations.

The excitement that I alluded to at the beginning of this editorial comes from the delightful science contained in the articles contributed to this issue. Drs White and Luiten both show remarkable new avenues that optical research has progressed down, and they have provided clear and accessible introductions to these exciting fields.

The other excitement is of course the upcoming AOS conference, incorporated as part of the AIP Congress in Sydney. After the success of last year's ACOLS meeting in Brisbane (refer to the conference review on page18 of this edition), our anticipation for this year's event is strongly encouraged by the list of interesting speakers and topics. I hope to see many of you in Sydney come July.

Wayne Rowlands

ADVERTISMENT

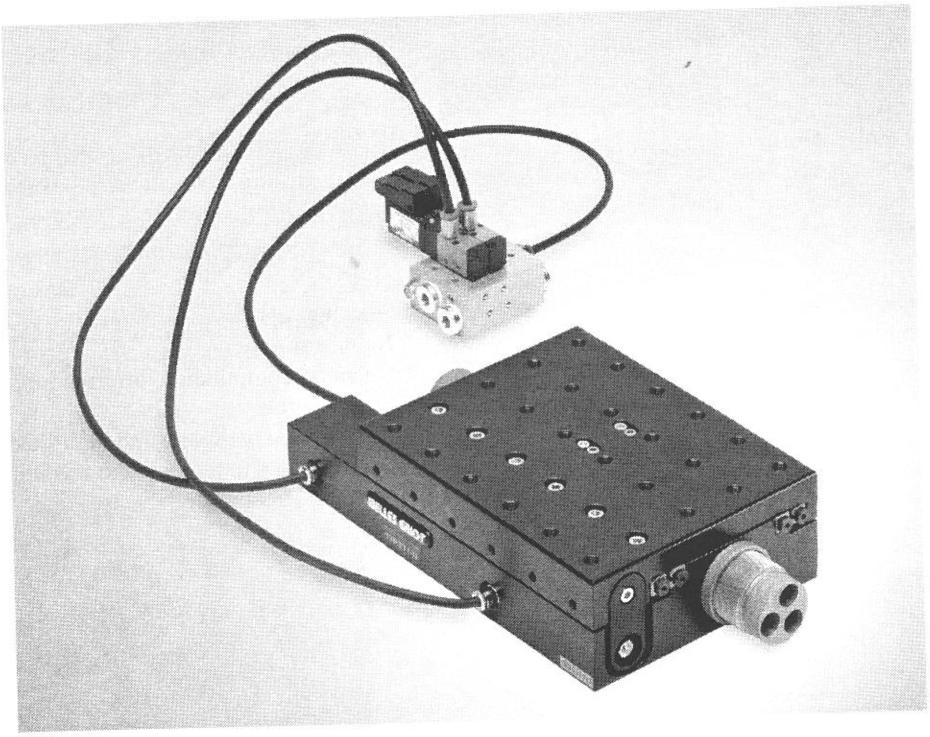
Lastek Press Release

Pneumatic Fibre Alignment Stage

Melles Griot has introduced a new range of pneumatic linear translation stages for fibre-alignment applications. These robust stages provide fast, repeatable movement of loads up to 50 kg. Designed specifically for process-automation applications in telecom component manufacturing, these stages are perfectly suited for load/unload positioning and for positioning accessories like adhesive dispensing and curing equipment.

With easy-to-adjust end stops, these pneumatic stages can rapidly move equipment up to 75 mm and position it with 2-micrometer repeatability. Lightweight aluminium construction and cross-roller bearings provide speeds up to 100 mm/second.

These low-maintenance pneumatic stages are easily integrated with machine-vision prealignment and Melles Griot NanoMax™ positioning stages to precisely position fibres and components to within 10 nm.



LineSpec™ InGaAs PDA Systems

- PDAs for Telcom, 800 to 1700 nm, and for NIR Spectroscopy, 1100 to 2200 nm
- 256 and 512 pixel arrays, 250 μm x 50 μm pixel and 500 μm x 50 μm pixel sizes
- High sensitivity and high dynamic range
- Compact size, simple operation

These new InGaAs Photodiode Arrays, join our LineSpec™product family in answering the need for near infrared multichannel detection. We offer models to cover two spectral ranges: 800 to 1700 nm and 1100 to 2200 nm. These PDA systems use compact detector heads with a single array of 256 or 512 pixels and a 12-bit ISA bus A/D board.

We offer several complete systems and sampling accessories to facilitate your data col-lection. All systems include the detector head, A/D board, thermoelectric cooler controller, all necessary cables, and the acquisition software. The difference lies in the useable wavelength region and the number and size of pixels.

For further information please contact:

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

Meetings Calendar

The following list of optics-related conferences is compiled from several sources and should be used as a guide only.

Date	Meeting 2002	Contact	Location
Apr 21-26	High Power Laser Ablation	SPIE	New Mexico, USA
Apr 23-25	Photomask Japan	SPIE	Yokahama, Japan
May 12-17	02UP - 13th International Meeting on Ultrafast Phenomena	OSA	Vancouver, Canada
May 19-24	CLEO - Conference on Lasers and Electro-Optics	OSA	Long Beach, USA
May 19-24	QELS - Quantum Electronics and Laser Science Conference	OSA	Long Beach, USA
May 26-29	Photonics Prague 2002 - 4th International Conference on Photonics, Devices and Systems	EOS	Prague, Czech Republic
May 28-31	46th International Symposium on Electron, Ion, and Photon Beams and Nanofabrication	OSA	Anaheim, USA
Jun 2-6	Photonics North (ICAPT '02)	SPIE	Quebec City, Canada
Jun 11-12	International Symposium on Photonics in Measurement	EOS	Aachen, Germany
Jun 22-28	IQEC 2002 - International Quantum Electronics Conference	OSA/SPIE	Moscow, Russia
Jul 7-11	International Symposium on Optical Science and Technology	SPIE	Seatlle, USA
Jul 8-11	AOS Conference (within AIP 15th Biennial Congress)	AIP	Darling Harbour, Sydney
Jul 8-12	Optoelectronics and Communications Conference	SPIE	Yokohama, Japan
Jul 14-17	Optical Amplifiers and Their Applications	OSA	Vancouver, Canada
Jul 17-19	International Conference on Smart Materials, Structures and Systems	SPIE	Bangalore, India
Aug 11-15	Seventh International Conference on Near-field Optics and Related Techniques	OSA	Rochester, USA
Aug 16-18	2nd International Conference on Imaging and Graphics	SPIE	Hefei, China
Aug 19-22	Third International Conference on Advanced Optical Materials & Devices	SPIE	Riga, Latvia
Aug 25-30	19th Congress of the International Commission for Optics	EOS	Florence, Italy
Aug 26-30	XIV International Symposium on Gas Flow & Chemical Lasers and High Power Lasers	SPIE	Wroclaw, Poland
Sep 1-6	ICEM-15 - 15th International Congress on Microscopy	EOS	Durban, South Africa
Sep 2-4	Nonlinear Guided Waves and Their Applications	OSA	Stresa, Italy
Sep 2-5	OWLS-VII: 7th Conference of the International Society of Optics Within Life Sciences	EOS	Luzern, Switzerland
Sep 22-25	ISOS 2002 - 6th International Symposium on Optical Storage	SPIE	Wuhan, China
Sep 29-Oct 3	Laser Science XVIII	OSA	Orlando, USA
Sep 29-Oct 3	25th International Congress on High Speed Photography and Photonics	SPIE	Beaune, France
Oct 14-18	Photonics Asia	SPIE	Shanghai, China
Oct 30-Nov 1	International Symposium on Biomedical Optics and Photomedicine	SPIE	Tokyo, Japan

Further information on the above conferences can be obtained from:

OSA
(The Optical Society of America)
2010 Massachusetts Avenue, N.W.
Washington, D.C. 20036-1023
USA

Tel: +1 202.223.8130
Fax: +1 202.223.1096
email: custserv@osa.org
www.osa.org

SPIE
(The International Society for Optical Eng.)
PO Box 10
Bellingham WA 98227-0010
USA

Tel: +1 360 676 3290
Fax: +1 360 647 1445
email: spie@spie.org
www.spie.org

EOS
(The European Optical Society)
Hollerithallee 8
30419 Hannover
Germany

Tel: +49-(0)511/27 88 -1 15
Fax: +49-(0)511/27 88 -1 00
email: no@lzh.de
www.europeanopticalsociety.org

INDEX TO ADVERTISERS

CORPORATE MEMBER ADDRESS LIST

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

Francis Lord Optics (Avtronics)
33 Higginbotham Rd
Gladesviile
NSW, 2111
Tel: (02) 9807 1444
Fax: (02) 9809 7136

Hadland Photonics Pty Ltd
19A Hampsbire Road
Glen Waverley
VIC, 3150
Tel: (03) 9560 2366
Fax: (03) 9560 8402
saleinfo@hadlandphoto.com.au
http://www.hadlandphoto.com.au

IATIA Pty Ltd
46 Rutland Road
Box Hill
VIC, 3128
Tel: (03) 9898 6388
Fax: (03) 9899 6388
iatia@iatia.com.au
http://www.iatia.com.au

Laser Electronics (operations) Pty Ltd
PO Box 221
Nerang
QLD 4211
Tel. 07 5596 0177
Fax. 07 5596 3530
las.el@s130.aone.net.au

Lastek Pty Ltd
GPO Box 2212
Adelaide
SA, 5001
Tel: (08) 8443 8668
Fax: (08) 8443 8427
alex@lastek.com.au
http://www.lastek.com.au

OptiScan Pty Ltd
PO Box 1066
Mt. Waverley MDC
VIC 3149
Tel: (03) 9538 3333
Fax: (03) 9562 7742
rogerw@optiscan.com.au
http://www.optiscan.com.au

Photon Engineering
PO Box 10269, Gouger St
Adelaide
SA 5000
Tel: (08) 8410 4599
Fax: (08) 8410 4544
photeng@ozemail.com.au
http://www.photon.on.net

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

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

X-Ray Technologies Pty Ltd
Level 14, 2 Lonsdale Street
Melbourne
VIC 3000
Tel: (03) 9655 9444
Fax: (03) 9650 1885
info@xrt.com.au
http://www.xrt.com.au

AUSTRALIAN OPTICAL SOCIETY
ABN 63 009 548 387

2002
Subscription Renewal Form

Postal Address

Title ____ Initials ____

First Name(s) ____

Surname ____

Employer/Institute/Company ____

Telephone Number ____

Facsimile Number ____

email ____

Affiliations (please tick) AIP ☐ OSA ☐ SPIE ☐

Main Activities (number up to three, in order of importance)

First ____ Second ____ Third ____

1 astronomical optics
2 atmospheric optics
3 communications and fibres
4 electro-optics
5 fabrication and testing
6 information processing
7 lasers
8 optical design
9 optical physics
10 radiometry, photometry & colour
11 spectroscopy
12 thin films
13 vision
14 quantum optics
15 nonlinear optics
16 teaching
17 holography
18 (......................................)
19 (......................................)
20 (......................................)

Email Notices: Notices will be sent to the email address provided. Do you wish to receive posted notices as well? *Yes* ☐ *No* ☐

SUBSCRIPTION RATES (inc. GST): Corporate: A$ 290 p.a. Member A$ 43 p.a. Student A$ 16 p.a.

PAYMENT METHOD *(please tick box)*

*Cheaue** ☐ *MasterCard* ☐
Money Order ☐ *Bankcard* ☐
Visa ☐

Send form and payment to: **A/Prof Stephen Collins, Hon Treasurer AOS**
OTRL (F119), Victoria University, PO Box 14428
Melbourne City MC, Vic 8001, AUSTRALIA
Tel: (+61) 03 9688 4283; Fax: (+61) 03 9688 4698
email: stephen.collins@vu.edu.au

Cheques payable to "THE AUSTRALIAN OPTICAL SOCIETY" (Please do not staple cheques to this form; use a paperclip)

If paying by credit card please complete ALL boxes in this authorisation. Incomplete forms cannot be processed.

EXPIRY DATE ___ / ___

CARD NUMBER ☐☐☐☐ ☐☐☐☐ ☐☐☐☐ ☐☐☐☐

CARDHOLDER ____ AMOUNT A$ ____

SIGNATURE ____ DATE ____