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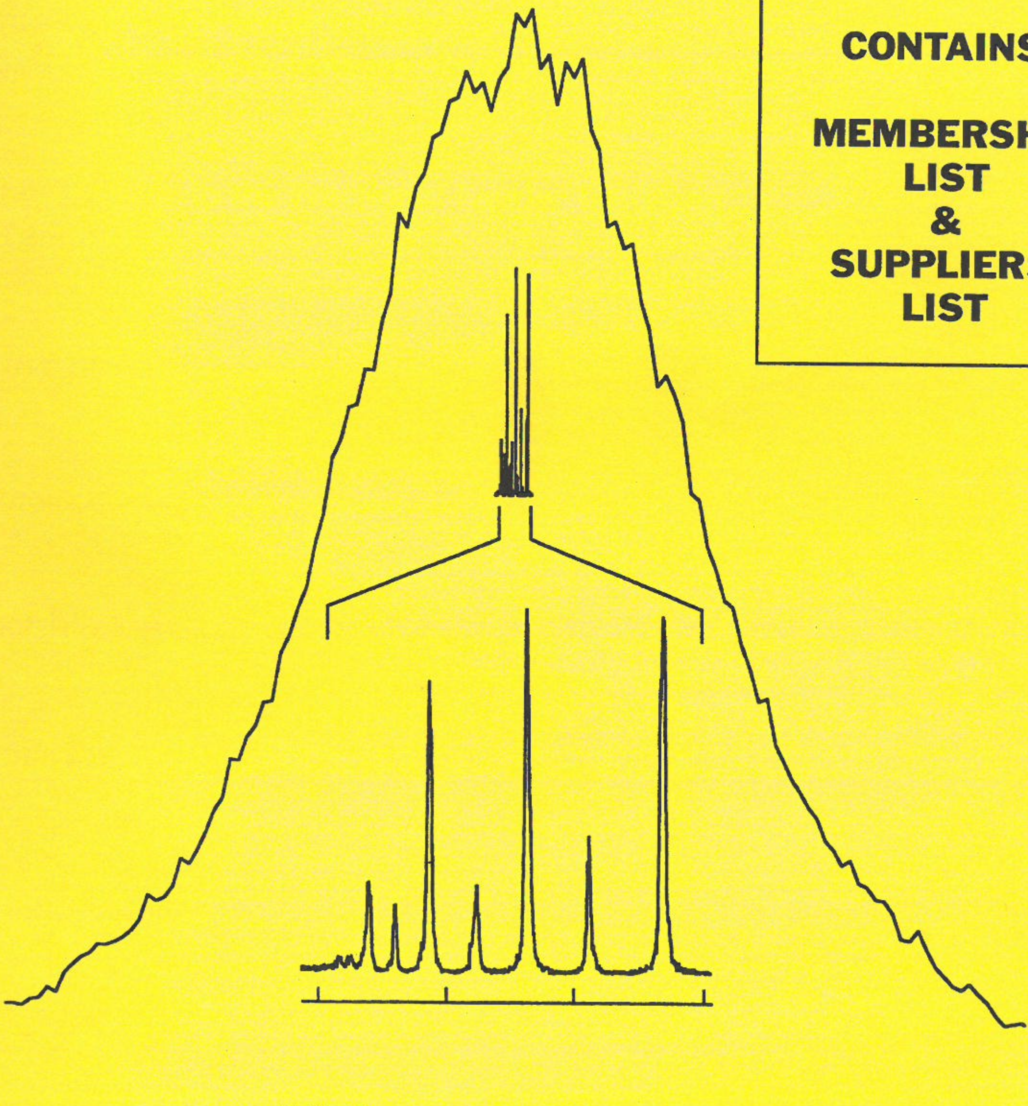

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Spectral characteristics of optical parametric oscillators (OPO'S) are discussed in the article by G.W. Baxter *et al* in this issue. This figure shows the broad band OPO spectrum overlaid on CARS spectra of nitrogen gas recorded with an injection seeded OPO.

A.O.S. News is the official news magazine of the Australian Optical Society. The views expressed in _A.O.S. News_ do not necessarily represent the policies of the Australian Optical Society.

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PRESIDENT'S REPORT

(This Report, with some amendments, was presented at the Society AGM held at NML in October)

There were a number of highlights for the Australian Optical Society over the past year, including the holding of the Tenth AOS Conference in Brisbane and the inaugural award of the AOS Medal.

AOS Conference: The strength of the optics R&D community in Australia was demonstrated at the Tenth AOS Conference in Brisbane, with over one hundred and fifty delegates and fifteen industry exhibitors. Bill McGillivray and his team performed a superb job in organising the meeting.

AOS Medal: The AOS initiated this award in 1994 to recognise outstanding contributions to the field of optics in Australia by a member of the AOS. The first recipient of the Medal was Bill James of James Optics, whose skills in optical manufacture, especially of aspheric surfaces, have produced many fine astronomical optics for Australian telescopes over the past thirty years. The Society has now called for nominations for the AOS Medal for 1996.

Postgraduate Prize: This award, to David Balaic of the University of Melbourne, provided travel assistance for him to attend the Annual Meeting of the Microbeam Analysis Society and present an invited talk. David talked on the use of tapered glass capillaries for X ray optics.

Young Optical Worker: This award was made to Mr Ron Bulla of the CSIRO Division of Applied Physics for his work on polishing silicon spheres for use as density standards and in experiments to determine Avogadro's number. Ron attended AOS X and presented a report on his work.

The Society was pleased to hear that the ARC has decided to make optics a priority research area. A document profiling optics in Australia coordinated by Ken Baldwin during his term as President was a key factor in this decision. There does not seem to be any way, unfortunately, that optics research can be recognised as such in the ABS classification scheme used by the ARC, so the impact of the decision is weakened. Discussions are underway with the ARC to address this issue.

With this year's Annual General Meeting two Councillors who have played a major role in Society activities have indicated their desire to stand down. George Smith from the Department of Optometry at Melbourne University has been our longest serving Councillor with eleven terms. In addition to his duties as Councillor, he has compiled the Optics Suppliers Index which appears regularly as a supplement to the News. Bob Oreb from CSIRO is not far behind George, with ten terms. Bob has also worked as an Associate Editor for the Newsletter. On behalf of the Council and all Members, I thank George and Bob for their efforts.

Kieran Larkin from the Physical Optics Department at the University of Sydney is standing down as Treasurer after three terms. His contributions in keeping the financial accounts of the Society running smoothly have been invaluable. I would like to thank Kieran for the excellent job he has done. As outgoing Treasurer, Kieran will remain on Council.

You will have also seen in the last AOS News an invitation by our present Editors, Judith Dawes and Martijn de Sterke, to take over their duties in 1996. (We have now found an editor, Duncan Butler from CSIRO [ex Melbourne]). Judith and Martijn have continued the fine traditions of our previous editor Phil Wilksch in providing to the membership what must be one of the best value for money society journals anywhere. I thank Judith and Martijn for their efforts and wish them all the best in the upbringing of their Junior Editor.

The Annual Meeting this year was moved forward in the year (in conformance with constitutional provisions) so that by 1996 and for all years thereafter the AGM can be held around the AGM which which are to be enacted the following fiscal year. The most obvious of these is a change in membership fees. At the AGM a motion was put by the Treasurer that fees for ordinary and corporate members be increased. At present the ordinary member fee of $20 barely covers the cost of producing the Newsletter and for the last several years the Society's accounts have been running at a loss. The new membership rates, which were approved at the meeting, are shown elsewhere in the News.

In conclusion I wish to thank all members of the outgoing Council for their efforts over the past year.

Chris Walsh.

FROM THE EDITORS

This issue contains a membership list and a list of Australian optical suppliers. We thank Kieren Larkin, as well as George Smith and Chris Chantler for compiling them.

With the issue before you our term as Editors of AOS News has come to an end. In all there were 7 issues we took care of. We thank the authors who contributed articles in this period. We are also grateful to the Associate Editors, many of whom made our life considerably easier. We wish Duncan Butler, who will take care of the upcoming issues the best of luck.

Judith Dawes
Martijn de Sterke

SPECTROSCOPY WITH PULSED TUNABLE OPOS

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Introduction

This article concentrates on recent developments in the design, operation and spectroscopic applications of pulsed optical parametric oscillators (OPOs), that operate as broadly tunable laser-like sources of coherent radiation in the nanosecond regime. The spectroscopic potential of OPO devices has long been recognised [1, 2], with their solid-state character and high efficiency offering substantial advantages over the ubiquitous dye laser. Moreover, the wide tuning range of an OPO opens up prospects for laser spectroscopy in otherwise inaccessible spectral regions, such as the near- and mid-infrared.

Despite some significant early progress more than twenty years ago [1], the spectroscopic potential of OPOs has not readily been realised. Numerous research laboratories have dark recesses to which their early OPO systems have been relegated, either optically damaged or used occasionally as "one-wavelength-at-a-time" instruments, rather than the continuously scannable spectroscopic workhorses that they were originally intended to be. This is attributable to several critical factors: low optical damage limits and high oscillation thresholds in commonly available OPO gain materials; the relative complexity of OPO cavity designs necessary to achieve narrowband, continuously tunable operation; the need for intense, pulsed lasers with adequate temporal and spatial coherence for use as OPO pump sources.

Within the last five years, these problems have tended to diminish [2], with the availability of new OPO materials and high-quality pump sources (particularly single-mode Nd:YAG lasers). An increasing number of tunable OPO systems is becoming commercially available and spectroscopists are now exhibiting intense interest in the cost-effectiveness and practical potential of such systems. We leave it to the laser manufacturers (one of whom adopted the motto "Good-bye to Ti: and Dye" to announce a new tunable OPO system) and their customers to determine the balance between the various forms of tunable, nanosecond-pulsed lasers over the next few years, both in the market place and in the laboratory.

The emphasis in this short article is on OPO devices that are continuously tunable, with optical bandwidth sufficiently narrow (~0.1 cm^{-1}, ~3 GHz or less) to generate rotationally resolved molecular spectra, with pulse durations of a few nanoseconds, and with moderately high output energy (0.1 – 100 mJ per pulse) [3, 4]. The radiation from such devices is sufficiently intense and coherent for several forms of nonlinear-optical spectroscopy, as well as efficient nonlinear-optical wavelength extension into otherwise inaccessible spectral regions. We use this domain of operating characteristics to limit the extent of our survey, but it should be borne in mind that there has been much complementary progress on developing both CW and ultrafast-pulse optical parametric devices [5].

How a pulsed OPO works

An OPO is *not* a laser: the intrinsic process that allows an OPO to operate is nonlinear-optical in nature, rather than one involving population inversion (as in the case of a laser). Nevertheless, much of the terminology of lasers is also applicable to OPOs. In conventional optical parametric generation, coherent pump radiation interacts with the third-rank nonlinear-optical susceptibility tensor $\chi^{(2)}$ of a suitable non-centrosymmetric crystal and generates two additional radiation fields. These are referred to as the *signal and idler waves*, with circular frequencies ω_S and ω_I, respectively (where it is customary to take $\omega_S \geq \omega_I$); the corresponding wavelengths are λ_S and λ_I. The pump, signal and idler waves in an optical parametric device are subject to two conservation conditions, the first of which corresponds to *energy (or frequency) conservation*:

$$\omega_P = \omega_S + \omega_I , \qquad \ldots (1)$$

where ω_P is the frequency of the pump wave. If this is narrowband, as from a single-mode pump laser, then the *sum* of signal and idler frequencies is tightly constrained. The second conservation condition is essentially *momentum conservation* and takes the form of a *phase-matching condition*. This is expressed in terms of the three wave vectors $\mathbf{k}_j$, with j = P, S or I; these have magnitudes $k_j = n_j \omega_j / c = 2\pi n_j / \lambda_j$, where n_j is the refractive index at vacuum wavelength λ_j and c is the speed of light. The wave vectors combine vectorially, as follows:

$$\mathbf{k}_P = \mathbf{k}_S + \mathbf{k}_I + \Delta\mathbf{k} , \qquad \ldots (2)$$

where $\Delta\mathbf{k}$ is a (typically small) phase-mismatch increment. This causes the signal and idler waves to have an intrinsically broad bandwidth: even if the sum frequency (ω_P) is fixed by eq. (1), their difference ($\omega_S - \omega_I$) is not fixed and ω_S and ω_I are not separately well-determined.If it is assumed (as a crude approximation) that the three waves are collinear and that $\Delta\mathbf{k}$ is zero, then the signal frequency can be expressed simply in terms of the refractive indices n_j :

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$$\omega_S = \omega_P (n_P - n_I) / (n_S - n_I) \quad \ldots (3)$$

$$\lambda_S = \lambda_P (n_S - n_I) / (n_P - n_I). \quad \ldots (4)$$

These relationships (3) and (4) are generally only approximate in practice, but they help us to see qualitatively how the signal and idler waves can be forced to tune simply by changing one or more of the refractive indices (for instance, by rotating a birefringent crystal, by variation of temperature, or by applying an electric field). Control of the phase-matching conditions in the nonlinear-optical gain medium of an optical parametric device therefore determines the output frequencies ω_S and ω_I. It also critically influences other performance characteristics such as the single-pass optical gain, the threshold for parametric oscillation, and the corresponding signal and idler optical bandwidths.

The choice of nonlinear-optical crystal for optical parametric devices depends on various factors [1, 2], including: the symmetry class of the crystal, since only non-centrosymmetric crystals (also capable of piezoelectric response) can have non-zero $\chi^{(2)}$ tensor components; the magnitude of $\chi^{(2)}$, to ensure a sufficiently big optical nonlinearity; the capability of growing large crystals of high optical quality, to maximise path-length in a wide-aperture, blemish-free nonlinear-optical medium; the transparency of the material at all three wavelengths (λ_S, λ_I and λ_P) to enable the device to operate over as wide a tuning range as possible; the optical damage threshold, particularly at the nominated pump wavelength, but also at signal and idler wavelengths in high-gain devices; the refractive indices, dispersion and birefringent properties of the crystal, which need to be suitable for phase matching to be established; low thermal coefficients of refractive index, to minimise temperature sensitivity. Two other critical factors influencing the choice of a particular nonlinear-optical material for a given purpose are the cost and availability of crystals of suitable size and quality; such factors are quite volatile in the case of some of the newer materials which are in high demand for OPO applications. Much recent work, including our own [2 – 4, 6], has concentrated on the crystal β-barium borate (BBO), which has proved well suited to OPO applications covering the wavelength range 0.4 – 2 µm. A set of OPO output tuning curves for this material is shown in Fig. 1, demonstrating remarkably high conversion efficiency [2, 3].

In its simplest form, a pulsed OPO comprises just three optical elements: a nonlinear-optical crystal (such as BBO) that can be oriented to control the phase-matching condition and a pair of mirrors to form an optical cavity that is resonant at either λ_S or λ_I. Special mirror coatings, with suitable broadband reflectivity/transmission characteristics and high damage thresholds, are intrinsic to satisfactory OPO operation. The tuning curves in Fig. 1 were obtained with three interchangeable sets of cavity reflectors, to cover the full spectral range of the OPO, and with a BBO crystal (7 mm x 7 mm x 15 mm, 30° cut for Type-I phase matching) pumped at 355 nm by an injection-seeded single-mode Nd:YAG laser, with an incident pump energy of ~315 mJ per 5 ns pulse. For optimal OPO performance, it is vital for the pump laser to have good shot-to-shot stability and beam quality, with no "hot spots".

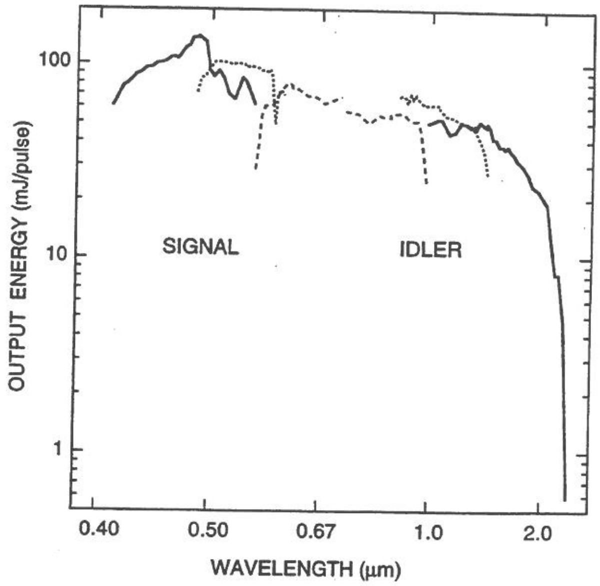

Figure 1 : Tuning curves for the signal and idler outputs of a free-running BBO OPO, with observed pulse energies displayed on a logarithmic scale. The tuning curves were generated by varying the BBO crystal angle and comprise three pairs of plots (solid, short-dashed, and long-dashed lines), corresponding to signal and idler outputs for each of the three cavity mirror sets. Pump conditions stated in text.

A number of factors determine the effective spectroscopic bandwidth of radiation emitted by such a "free-running" OPO (containing no wavelength-selective elements) based on a given nonlinear-optical medium such as BBO [1, 2, 6]. These include: the wavelengths λ_S, λ_I and λ_P; the type of phase matching; the refractivity, dispersion and absorption of the OPO medium; the crystal dimensions; the cavity reflectivity and effective number of passes of the resonated wave; the bandwidth, divergence, pulse duration and pulse energy of the pump radiation. The signal and idler waves are found to have optical bandwidths that are wavelength-dependent, increasing markedly as the degeneracy point ($2\lambda_P = \lambda_S = \lambda_I$) is approached. Under normal operating conditions well above oscillation threshold, the optical bandwidth of a pulsed BBO OPO is found to be greater than at threshold [6], owing to the oscillation of transverse modes within a finite pump-beam diameter. This gives rise to a substantial trade-off between minimising the optical bandwidth of a free-running OPO and maximising its output power.

In most spectroscopic applications, where the narrowest possible bandwidth with the highest output power is desired, such a trade-off tends to be counter-productive. However, there are some multiplex spectroscopic situations [4] where broadband OPO operation is an advantage and others [6] where medium-band operation of a free-running OPO can be contrived by exploiting the spatio-spectral properties of the OPO output beam. In the latter case, it has been possible to narrow the optical bandwidth of broadband OPO radiation by almost a factor of five, simply by spatial filtering; this approach (and its potential for industrial diagnostics) has recently been demonstrated by recording a degenerate four-wave mixing spectrum of the D-lines of sodium in a flame [6].

Injection-seeded OPO operation

The optical bandwidth of a simple free-running OPO is typically tens of cm^{-1}, depending on the operating wavelength and other factors, and is unsuitable for many spectroscopic applications. Operation of a nanosecond-pulsed OPO with narrow optical bandwidths approaching the transform limit can be achieved by means of wavelength-selective elements, such as intracavity gratings and etalons [1, 2, 7], and this approach has been employed in various commercial OPO designs. An alternative approach, on which our work has concentrated [2 – 4, 6], is to employ *injection seeding* with narrowband, tunable radiation from a low-power external source used to control the wavelengths and optical bandwidth of the OPO output. Injection seeding separates the wavelength-control function of the OPO from that of power amplification, and greatly simplifies OPO construction.

The mechanism of injection seeding of a pulsed OPO is understood qualitatively in terms of oscillation threshold effects: modes of a singly-resonant OPO cavity with which the frequency of the seed radiation coincides tend to oscillate first, depleting the pump wave so that no other modes are able to build up appreciably for the duration of the pump pulse [2, 3]. Narrowband injection seeding of an OPO by low-intensity tunable laser radiation can therefore substantially reduce the optical bandwidth of the OPO output radiation and facilitate continuous tunability. Such OPO wavelength control falls into two categories: narrowband amplification of the seed radiation (at either ω_S or ω_I); narrowband up-conversion (if the seed is at ω_I) or down-conversion (if the seed is at ω_S) of the seed radiation.

In early work [2 – 4], we employed injection seeding by pulsed tunable dye lasers (some of them bigger and more elaborate than the OPO itself) to achieve continuously tunable, narrowband operation of a pulsed BBO OPO; this approach has been applied with optical bandwidths of ~0.1 cm^{-1} (~3 GHz) to actual spectroscopic problems. More recently [6], we have used low-power, CW radiation from a single-mode external-cavity diode laser (ECDL) to injection-seed a passive ring-cavity BBO OPO at its idler wavelength. The intrinsically narrow bandwidth of a CW ECDL seed source enables the pulsed OPO output wavelengths to be scanned continuously with optical bandwidths of ~0.01 cm^{-1} (~300 MHz), approaching the transform limit for the pulses. The efficacy of this ECDL-seeding approach is demonstrated in Fig. 2. Trace (a) is a typical spectral profile for the signal output from a free-running linear-cavity BBO OPO at an angle-tuned wavelength of 607 nm. This broad spectral curve, recorded in a single shot of the OPO by a monochromator equipped with a diode-array detector [2, 6], has a FWHM optical bandwidth of 15 cm^{-1}, too large for many spectroscopic applications. Traces (b) and (c) are coherent anti-Stokes Raman (CARS) spectra of nitrogen gas at low pressure. As will be explained in the next section, such CARS measurements require tunable radiation at 607 nm. This is generated by a BBO OPO, with its optical cavity arranged in the form of a triangular "ring" and injection-seeded at its 855-nm idler wavelength by light from a single-mode ECDL [6]. The uppermost CARS spectrum (b) is plotted on the same optical frequency scale as the broadband spectral profile (a) of the free-running OPO, while the lower CARS spectrum (c) is expanded ten times; each CARS spectrum comprises a continuous scan of the OPO output of >1 cm^{-1} (>30 GHz). The linewidths in these CARS spectra are consistent with an optical bandwidth of 0.01 cm^{-1} (300 MHz) for the OPO signal radiation, so that ECDL-seeding of an OPO is seen to narrow the spread of its output frequencies by a factor of 1000 or more. This is consistent with our recent fluorescence-detected measurements [6] of Doppler-free two-photon absorption in rubidium vapour with 780-nm idler radiation from an ECDL-seeded BBO OPO.

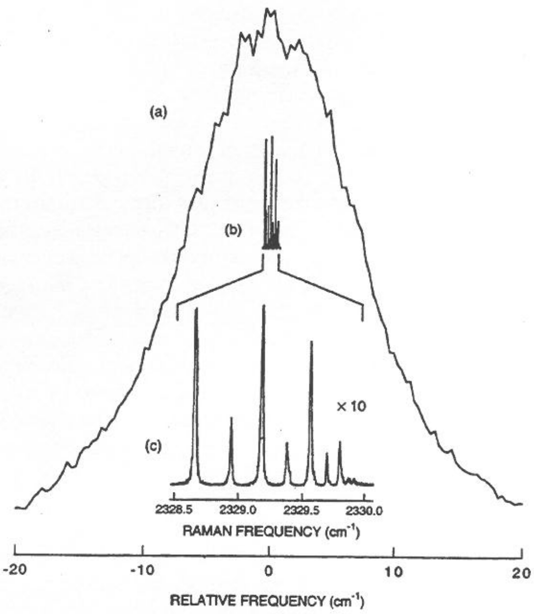

Figure 2: Evidence of the spectroscopic characteristics of signal output radiation from a pulsed tunable BBO OPO at a wavelength of 607 nm. Trace (a) corresponds to a free-running linear-cavity BBO OPO, showing a broad spectral profile with a FWHM optical bandwidth of 15 cm^{-1}. Traces (b) and (c) are CARS spectra of nitrogen gas at 300 K and 75 Torr, recorded with a ring-cavity BBO OPO injection-seeded by an ECDL; this demonstrates spectral narrowing of the continuously tunable OPO radiation by a factor of 1000 or more.

In using narrowband injection seeding to achieve continuous tuning of an OPO without mode-hopping, it is usually considered necessary to vary the OPO cavity length actively as the seed frequency is scanned. However, our experiments [6] show that it is possible to avoid such instrumental complications if the OPO ring cavity is slightly misaligned (by tilting one of the mirrors by 5 – 10 mrad in the horizontal, phase-matching plane), thereby reducing its effective finesse and smoothing out the sharp, widely separated resonances that occur when the cavity is well aligned. In addition, piezoelectric "dithering" of the OPO cavity length can be useful in reducing the effect of minor intensity fluctuations that are sometimes observed as the seed wave-

length is scanned. The OPO signal and idler wavelengths can then be scanned continuously by tuning the single-mode ECDL seed radiation, as is necessary to generate spectra such as that in Figs 2 (b) and (c). A key feature of our technique is that the OPO cavity is operated passively, such that it is not necessary to lock the OPO cavity length to the seed laser wavelength.

Example: OPO CARS spectroscopy

We conclude by considering briefly an area of molecular spectroscopy, OPO CARS, in which OPOs assume the role traditionally played by tunable dye lasers. This serves to illustrate the type of application to which the coherence and spectroscopic characteristics of pulsed tunable OPO radiation are suited.

Coherent anti-Stokes Raman spectroscopy (CARS) is well established as an industrial sensing technique, particularly for combustion diagnostics [8]. It comprises a coherent four-wave nonlinear-optical process, in which two laser beams – the Raman pump and Stokes waves, with frequencies ω_{Pump} and ω_{Stokes} respectively – interact with a Raman-type resonance in the nonlinear-optical susceptibility $\chi^{(3)}$ of an optical medium, at a difference frequency $\omega_{Raman} = (\omega_{Pump} - \omega_{Stokes})$. This generates a coherent anti-Stokes wave with frequency $\omega_{CARS} = (2\omega_{Pump} - \omega_{Stokes})$ and directional properties determined by phase-matching conditions.

It is customary to record a CARS spectrum by fixing the Raman pump frequency ω_{Pump} and scanning the frequency ω_{Stokes} of the Stokes radiation, normally generated by a tunable dye laser. Our research [2, 4] shows that pulsed tunable OPOs provide a viable alternative to dye lasers as sources of tunable coherent Stokes radiation. An experimental schematic diagram for various forms of OPO CARS measurement is shown in Fig. 3.

Three distinct approaches to OPO CARS are practicable. In each case 532 nm radiation from the single-mode Nd:YAG OPO pump laser forms the fixed-frequency Raman pump beam, while various forms of OPO operation are used to generate the accompanying Stokes beam that is overlapped temporally and spatially with the Raman pump beam in the sample of interest. The resulting CARS output beam is separated from the co-propagating Raman pump and Stokes beams by means of optical filters and a monochromator. We have demonstrated these various forms of OPO CARS technique in the context of rotationally resolved Raman spectroscopy of nitrogen and oxygen in air at various temperatures [2, 4].

The *scanned* CARS approach depends on continuous narrowband tuning of the signal wavelength of an injection-seeded OPO (as described above), with a photomultiplier used to detect the CARS light transmitted by the monochromator. Our original scanned OPO CARS measurements [2, 4] were performed on nitrogen gas with an effective optical bandwidth of ~0.1 cm^{-1}, the Stokes beam being provided by tunable 607 nm signal radiation from a pulsed BBO OPO injection-seeded at the same wavelength by a tunable dye laser. More recently, higher-resolution scanned OPO CARS spectra of nitrogen have been measured with 607 nm tunable

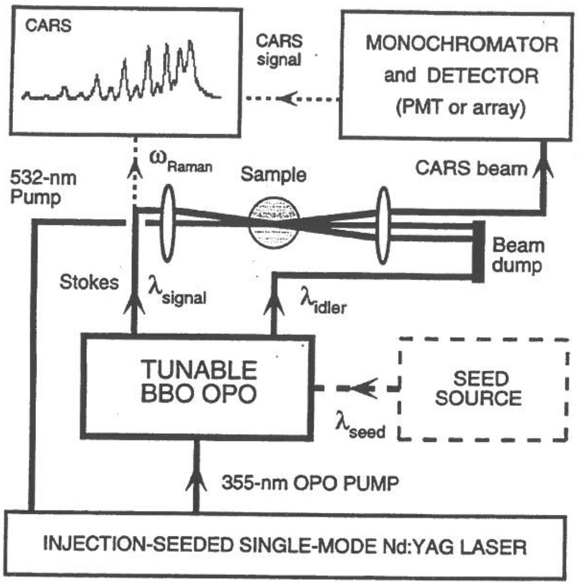

Figure 3: Schematic of a spectroscopic system for OPO CARS measurements, using a pulsed tunable BBO OPO. Radiation from a single-mode Nd:YAG laser system is the source of 355 nm OPO pump radiation and also of the narrowband 532 nm Raman pump beam for the CARS process. Visible OPO signal radiation (wavelength λ_{signal}) serves as the Raman Stokes beam, combined collinearly with the 532 nm Raman pump radiation and focused into the sample zone, while the accompanying OPO idler radiation (λ_{idler}) is rejected. The anti-Stokes beam generated by the CARS process is filtered, passed through a monochromator, and detected by a photomultiplier (in the case of scanned CARS) or photodiode array (in the case of multiplex or two-colour CARS). For scanned CARS experiments, the BBO OPO output wavelengths are controlled (see dashed portion) by injection seeding at the signal wavelength, with narrowband radiation from a low-intensity dye or diode laser; in the case of two colour CARS, a second seed laser is needed.

Stokes radiation from a pulsed BBO OPO that is injection-seeded at its idler wavelength with 855 nm light from a single-mode ECDL. The resulting spectra, such as those in Figs 2 (b) and (c), are continuously scanned over intervals of ~1.5 cm^{-1} (45 GHz) and are well simulated by a CARS computer code that allows for Doppler and pressure broadening. From this simulation, we infer that the optical bandwidth of the Raman Stokes radiation from the ECDL-seeded BBO OPO is ~0.01 cm^{-1} (~300 MHz), approaching the transform limit of the pulsed radiation itself.

Another approach to OPO CARS employs a free-running BBO OPO (with no injection seeding) to generate broadband Stokes radiation for single-shot *multiplex* CARS measurements [2, 4]. Here, a gated, intensified diode array is used to detect the full dispersed CARS spectrum in the exit focal plane of the monochromator and a detector-limited Raman spectral resolution of 0.35 cm^{-1} (1.0 GHz) has been realised. The ability to record an entire CARS spectrum instantaneously in a single laser shot avoids complications due to turbulence and other temporal fluctuations, compensating for the reduced sensitivity and spectroscopic resolution of the multiplex technique relative to scanned CARS.

A third OPO CARS variant comprises *two-colour CARS*, which relies on the ability of a free-running OPO to be injection-seeded at two (or more) independent optical frequencies falling within its intrinsically broad optical bandwidth. In the first realisation of this technique, we have employed two separate ECDLs operating around 855 nm to seed idler wavelengths of a single BBO OPO; these were adjusted to generate two signal wavelengths around 607 nm corresponding respectively to low- and high-J features in the rovibrational CARS spectrum of nitrogen gas. The two-colour CARS beam thereby generated was dispersed by a monochromator and captured by an array detector. The relative intensities of the two OPO CARS features thus monitored can be used for temperature measurements of nitrogen in air inside a furnace. As in multiplex CARS, two-colour OPO CARS spectra (and corresponding temperatures) can be collected within a single laser shot, so that the technique is amenable to investigations of reactive, turbulent or dusty combustion media and should enable studies of temporal or spatial fluctuations in temperature. This combination of OPOs and ECDLs generates a two-colour coherent light beam that is *spectroscopically tailored* for single-shot monitoring of two distinct features of a spectrum and offers the possibility of an instantaneous laser-based "thermometer" for air and other critical species in industrial environments.

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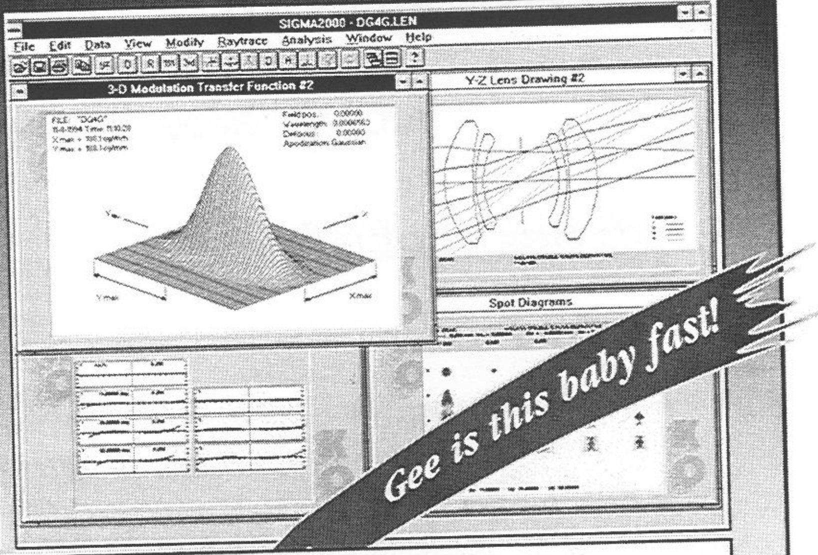
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A BEGINNER'S GUIDE TO THE FRACTIONAL FOURIER TRANSFORM

Part 2: A Brief History of Time Frequency Distributions

Kieran G. Larkin
School of Physics
University of Sydney 2006

Earlier this year (Vol. 9, Issue 2) I presented a potted history of the fractional Fourier transform (FractFT from hereon) and promised the "nitty gritty" in Part 2. A lot has happened since then; I've lost count of the new papers appearing with Fractional Fourier Transform in the title. Also my attention has been drawn to additional publications which further complicate the history of the FractFT[17]. Readers interested in specific details of the mathematical analysis are advised to consult the references given at the end of this article. The objective now is to present the main ideas behind the FractFT and discuss some applications.

The Fractional Fourier Transform & Propagation in GRIN Media

The FractFT arises most naturally in the analysis of optical propagation in graded index (GRIN) media. The well known SELFOC lens has an axially symmetric quadratic variation in refractive index. Ray propagation in such a medium can be shown to consist of periodically refocussing sinusoidal ray paths as shown in figure 1. One way of understanding this effect is to consider the GRIN medium as a series of thin lenses which gradually focus a diverging group of rays.

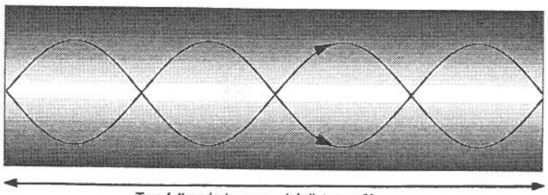

Figure 1 Ray propagation in a GRIN medium

Moving on now to the propagation of an optical field in such a medium... The self-modes of a quadratic GRIN medium are Hermite-Gaussian (H-G) functions. In fact these modes are the same as the familiar modes of a laser resonator. Conveniently, these modes can be shown to form a complete orthogonal set. In other words, any function can be represented as a summation of the H-G functions. Hence any distribution of the input field can be represented using H-G functions#. The propagation of this field can then be reduced to the simpler problem of the propagation of the individual (self-mode) H-G functions. High order modes propagate more slowly than low order modes so the field changes with axial position. A periodic re-imaging of the field occurs exactly as predicted by the ray propagation model.

A little mathematical notation can be used to summarise the situation. Firstly the propagation of each mode along the axis can be shown to be of the form

$$E_{lm}(x,y,z)=\Psi_{lm}(x,y)\,\exp(i\beta_{lm}z)$$

The field of each mode is E_{lm}. The basic H-G mode is Ψ_{lm} where l and m represent the order of the mode. A propagation factor for each mode is β_{lm} which represents the different speed of propagation as a function of l and m. There is clearly a periodic re-imaging over a distance $z=4L$ such that $4\beta_{lm}L=2\pi$. It can be shown that over a distance $z=L$ the input field is Fourier transformed. Over multiples of the axial distance L the input field is modified exactly in accordance with multiple applications of the Fourier transform. A possible definition of the FractFT is now apparent: the FractFT is the transform corresponding to propagation of a field along axial distances a fraction of the length L. Such a definition automatically satisfies the basic requirements suggested in Part 1 of this article, namely additivity, identity and commutativity. These three properties do not uniquely define the FractFT[18], however, propagation in GRIN media corresponds to the most interesting and useful definition. An equivalent property of the FractFT can be specified to ensure uniqueness. In the next section rotation of the Wigner distribution will be considered as such a property.

Interestingly the H-G polynomial representation includes an arbitrary scale factor in the Gaussian width. This scale factor re-emerges as a complication in the FractFT scaling property.

In summary, the FractFT can be defined analogously to the propagation of an (optical) electric field in a GRIN lens/fibre. The order of the FractFT here is directly proportional to the propagation distance. Propagation over successive increments is equivalent to propagation over the total of those increments. This behaviour is paralleled by the additive and commutative properties of the FractFT operator. Finally it is worth mentioning that Gauss-Laguerre polynomials are more convenient for studying propagation in systems with axial symmmetry, but most FractFT papers concentrate on H-G modes.

The Fractional Fourier Transform and the Wigner Distribution Function

The Wigner distribution function (WDF) is a concept which occurs naturally in the study of quantum mechanics. The Wigner distribution has also been found useful in the analysis of optical propagation problems [19, 20]. But, perhaps, the most important application of the WDF is in signal processing where the time and frequency analyses are required simultaneously. Conventionally a signal can be represented as function of time, and alternatively represented as a function of frequency (via the Fourier Transform). In certain situations, such as speech analysis, sonar, and radar, for example, the change in frequency spectrum over time is of interest. Strictly speaking, the frequency spectrum cannot be a function of time because Fourier analysis requires integration of the signal over all time. To get around this major difficulty a Short Time Fourier Transform (STFT) has been proposed with limited success[21]. The WDF presents another way of viewing time and frequency properties simultaneously with the added benefit of several mathematically tractable properties (which will not be considered here). The WDF of a one dimensional function is defined as follows:

$$W(x,u)= \int_{-\infty}^{\infty} g(x'-x/2)\, g^*(x'+x/2)\, \exp(-2\pi i u x')\, dx'$$

So x is a measure of the overlap of a function g with its complex conjugate g*. The parameter u is, as before, the spatial frequency. In signal analysis the corresponding parameters are time and frequency rather than position and spatial frequency. Time varying spectra can have very *distinctive* signatures when viewed in terms of their WDFs. The classic example given is a linear chirp – a tone with a linearly increasing frequency over a given time period. Figure 2 shows the WDF of a linear chirp. Some care and practice is needed for the correct interpretation of WDFs but in this very simple case the change in frequency with time is clear. Also shown in figure 2 are the WDFs of a single, pure tone $g(x)=\exp(-2\pi i u_0 x)$ and a single impulse $g(x)=\delta(x-x_0)$. It can be readily shown that the definition of the FractFT developed so far has a very simple interpretation in terms of the WDF. Simply stated, the WDF of a FractFT is identical to the WDF of the original function except for a rotation in the x–u plane. The amount of rotation is proportional to the fractional order. So, for order a = 1 the WDF is rotated $\pi/2$ radians; for order a = 4 the rotation is 2π (or 360°). Using the WDF an order a FractFT can be visualised as a (π a/2) radian rotation.

A potential use of the FractFT can now be seen. By suitably rotating the WDF of a chirp signal, the WDF can be made either a delta function in variable x or in variable *u*. In the former case a FractFT of suitable order converts a chirp signal into an impulse with a location related to the chirp parameters. Three immediate applications are obvious, i) to de-chirp signals, ii) to chirp signals, and iii) to compress or decode certain categories of signal. The GRIN media of the previous section provide a way of optically implementing such signal processing strategies. Optical processing can avoid the significant computational effort required to numerically evaluate either the FractFT or the FFT (Fast Fourier Transform), so very fast processing speeds may be attained.

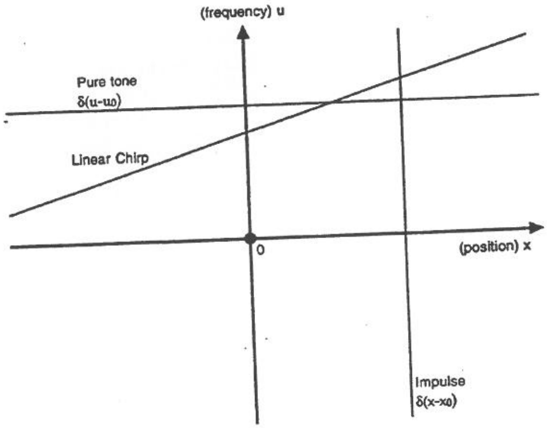

Figure 2 Wigner Distribution Function

The Fractional Fourier Transform and The Fresnel Transform

The Fresnel Transform is a little known transform[22] which can be defined using Fresnel diffraction in the same way that the Fourier transform can be defined using Fraunhoffer diffraction. Essentially, the Fresnel transform predicts the field in any plane parallel to the focal plane of the optical system shown in Figure 3. It has been shown that the Fresnel transform is equivalent to a suitable scaled version of theFractFT multiplied by a quadratic phase factor[23]. The equivalence is limited to a range of fractional orders typically $0 < a < 2$ (a=1 can be a problem!). This is just another way of stating the obvious; that Fresnel diffraction does not exhibit periodic refocussing typical of GRIN media.

A single lens system can be used to realise some properties of the FractFT. In many cases the additional quadratic phase factor associated with the Fresnel transform is not important because it is the intensity (modulus squared of the field) which is detected. When the quadratic phase prevents direct evaluation of the FractFT, additional lenses (one at the input plane , one at the output plane) can be added to counterbalance this phase. Alternatively measurements may be limited to spherical surfaces which exactly counterbalance the phases again. An added difficulty in the FractFT interpretation of the Fresnel transform is that the fractional order is a monotonic but nonlinear function of axial distance.

A number of systems have been proposed for the optical implementation of the FractFT. Just two design criteria (apart from nominal focal strength) have to be addressed. These are i) the scaling factor, and ii) the quadratic phase factor. Both of these are related to the chosen fractional order. Readers interested in optical systems for FractFT processing should consider a number of references[14, 24-31].

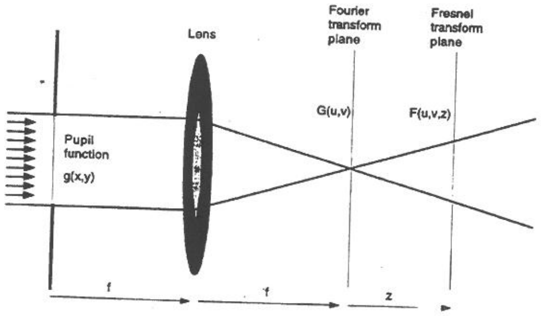

Figure 3 Fraunhofer and Fresnel Diffraction

Generalisations of the Fractional Fourier Transform

Just as the FractFT is an extension of the Fourier transform, the special affine Fourier transform[32, 33] or SAFT extends the FractFT. Here again the Wigner space viewpoint is most enlightening and calculus free (unless you want to prove it!). If the FractFT corresponds to a rotation in Wigner space then the SAFT corresponds to an arbitrary combination of shear, shift and rotation in Wigner space.

As mentioned earlier, free space propagation of field corresponds to a positional (or x) shear in Wigner space whereas the action of a lens corresponds to a frequency (or u) shear. A combination of three shears, such as *x-u-x*, can produce a pure rotation and hence a simple lens can produce a FractFT.

The SAFT may be useful as an alternative way to view and interpret field propagation in more general optical systems. Such an alternative may provide insight into seemingly intractable problems.

The Fractional Fourier Transform and Ray Propagation: The Fractional Legendre Transform

Propagation of a ray through an optical system can be represented - in a plane at least - by the ray position (r) and the ray angle (s). In figure 1 the ray height follows a sinusoid while the ray angle follows a cosinusoid as it propagates in the *z* direction. If the propagation of a ray bundle is plotted in a *r-s* diagram (figure 4) then propagation in a GRIN medium is seen to produce a rotation about the origin. The analogy with propagation and the WDF is strong.

The actions of a lens and free space propagation are shears in the *s* and *r* directions, respectively, further strengthening the analogy. The FractFT allows a function of position to be represented as a function of position and spatial frequency. In a similar way, a construction now called the fractional Legendre transform[34] allows a function of ray position to be represented as a function of a new parameter. This new parameter is a linear combination of both position and angle.

The useful application of such a transform occurs in the Hamiltonian optics of certain optical systems which exhibit singularities of both the point (ie position) characteristic and the angle characteristic. The fractional transform allows a new intermediate characteristic type some where between the point and the angle characteristic to be defined so that a singularity is avoided.

Applications of the Fractional Fourier Transform

The two main applications mentioned so far are:

A) Alternative interpretation of optical propagation in both GRIN media and conventional optical systems, and

B) Processing of signals with specific time-frequency and space-frequency signatures.

In many cases the FractFT is just used as a conceptual aid to help visualize certain aspects of propagation. It should be mentioned that the FractFT is based on a paraxial scalar approximation not unlike that of the Fresnel transform. So, in systems with high numerical aperture (such as microscopes) the approximation is invalid.

Recently some computational aspects of the FractFT have been investigated[10, 35]. It seems that the discrete FractFT can be used for the efficient calculation of the FFT of sparse datasets[11]. The well known trick of zero

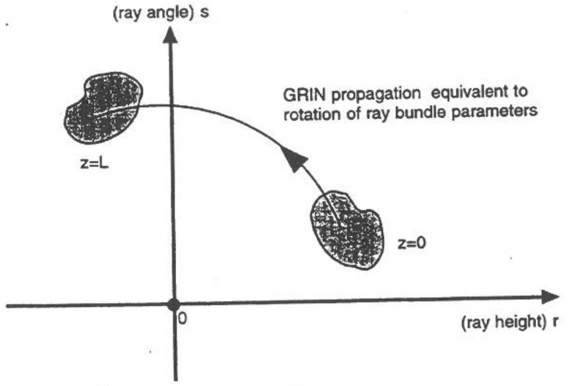

Figure 4 Ray height-angle (r-s) diagram

padding a dataset to get improved resolution in the FFT can be modified so that all redundant zero multiplications are avoided. The method also allows the calculation to be confined to a selected region of frequency space, further improving efficiency. Ironically this may mean that the calculation of Fresnel diffraction in optical systems can be speeded up considerably allowing improvements in calculation time and/or accuracy.

Finally...

Observant readers may have noticed that a mathematical definition of the FractFT has appeared nowhere in this article. The omission is deliberate.

Cynical readers may have noticed that the FractFT is a surefire method of generating periodic citations. I believe, as might less cynical readers, that the rapid dissemination of these ideas will have a beneficial effect.

Anagrammatical readers will surely have noticed the connection between FRACTIONAL FOURIER TRANSFORM and ASTRONOMIC NARRATOR FLUFFIER as well as REFRACTION AFFIRMS LUNAR ROOT.

Most other readers will have completely missed this article. If, by some chance, you have read this far please confirm my hopes/worst fears and email your comments to: K.Larkin@physics.usyd.edu.au

Acknowledgements

I would like to thank Colin Sheppard for numerous stimulating discussions. John Sheridan provided some insight into the conceptual uses of the FractFT and also a number of useful references. Thanks are due also to Miguel Alonso for numerous obscure references which further undermine the accepted view of the FractFT's historical development. There is always a sneaking suspicion that the FractFT was originally conceived (along with the FFT) by C.F. Gauss and hidden in some obscure neo-classical latin manuscript.@

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Facts and Figures About the AOS Membership

By Esa Jaatinen, Hon. Treasurer AOS

At the AOS annual general meeting held on Thursday the 12th of October, at the CSIROs Division of Applied Physics, I had the privilege of being elected as the honourary treasurer for the society. As such I am enthusiastically looking forward to the challenge of keeping the society's finances in order for the next year, or failing that a really good holiday in Bali.

With the end of year drawing near the first task before me, as you will all already know, is to mail out the 1996 subscription renewal notices. To do this I first had to familiarise myself with the AOS database and all of its mysteries. While playing with my computer and the database I became aware of some facts and figures regarding the AOS membership that I thought others might also be interested in.

On the 1st of November 1995, there were 355 financial members of the society compared to 270 in 1994 which represents a growth of around 30%. By financial I mean that these members have paid their 1995 subscription fees. Of the 355, 210 have regular membership, 14 are corporate, 5 are life members and only 40 are students. The remaining 86 members joined at AOS 10 in Brisbane and their membership type will not be known until they, hopefully resubscribe in 1996. From these figures it seems that the number of student members is disproportionately low. Particularly as the generous prizes that the AOS offers should provide the incentive for students to join. Perhaps then we need to advertise our presence and benefits of membership more widely than we currently do. We can all play a part here by encouraging friends and students to join.

Apart from the paid up members there are those from the 'other' side - the unfinancial members. On the 1st of November there were 55 members in all who still had not paid their 1995 subscription fees, 42 of which are regular members, 3 are corporate and 10 are students. This group represents close to 15% of the entire membership and, for a non-profit organisation like the AOS, a sizeable chunk of the annual income for 1995. The financial situation is exacerbated by the fact that in 1995 our subscription fees, even if all of them had been received, would not have covered our expenses. A full treasurer's report for 1995 will be published in a later AOS Newsletter but in rough terms the expenditure for 1995 was close to $30 per member which is well in excess of the $20 and $5 subscription fees charged of members and students respectively. Fortunately this year was an AOS conference year and the profits from AOS 10 helped significantly to balance the books. However conference profits are an irregular form of income and cannot always be relied on. Therefore as subscriptions are the only regular source of income for the society, it is important that we all pay them as promptly as possible to enable the society to function properly and maintain all the services it provides for its members.

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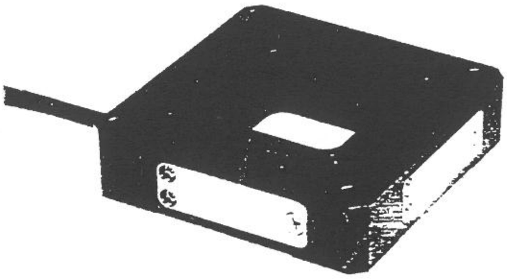

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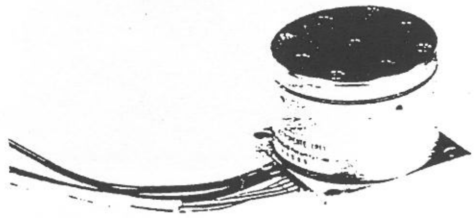

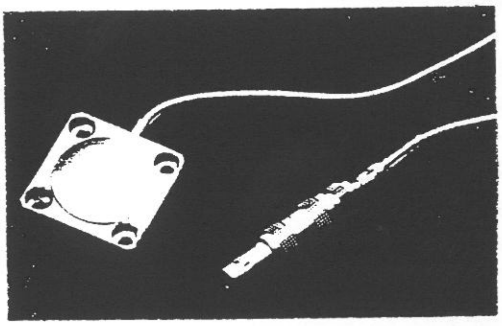

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The new PI D-015, through D-100 capacitive displacement sensors offer ≤0.1 nanometer resolution and 0.05% linearity, the best in the industry. Displacement ranges are 15 to 100 μm (up to 300 μm with slightly reduced specs). Sensors and electronics are compatible with PI's line of piezoelectric micropositioning systems. For micropositioning of optics & fibres, micro-lithography, scanning microscopy, interferometry.

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ICO NEWSLETTER

Commission Internationale d'Optique ◆ International Commission for Optics ◆ October 1995

ICO XVII set for Taejon, Korea
Submission deadline: January 31, 1996

Every three years, the International Commission for Optics holds a major conference on optical science and technology. ICO XIV, held in 1987 in Quebec (Canada), was followed by ICO XV in 1990 in Garmisch Partenkirchen (Germany) and by ICO XVI in 1993 in Budapest (Hungary). In 1996, the location is Taejon, Korea and the dates are August 19–23, 1996.

The theme of ICO XVI is "Optics for Science and New Technology." Topics include: Imaging and Non-Imaging Optics, Optical Technology and Surface Characterization, Optical Physics, Information Optics, Lasers and Laser Spectroscopy, Non-Linear Optics and Quantum Optics, Opto-Electronic, Astronomical and Atmospheric Optics, Medical Optics and Biological Optics, and Sensors and Metrology.

ICO XVII will be organized by the Korean Optical Society on behalf of the International Commission for Optics. Co-sponsoring organizations include the National Academy of Science of the Republic of Korea, the Korean Science and Engineering Foundation, the Korean Federation of Science and Technology Societies, the Optical Society of America, SPIE -the International Society for Optical Engineering, the IEEE Laser and Electro-Optics Society and the International Union of Pure and Applied Physics. Support has been granted by Samsung Electronics Co., Ltd., Hyundai Electronics Co., Ltd., LG Electronics Co., Ltd. (Gold Star), Daewoo Heavy Industry Co., Ltd., Samsung Camera Industry, Hyundai Camera Industry and Anam Optical Industry. ICO XVII will consist of plenary sessions, invited and contributed oral communications, combined oral and poster presentations, and panel discussions. A table top exhibit is being organized. All participants will take part in a full day excursion to the historical site of Kyongju.

The recent ICO Prizes and ICO Galileo Galilei Award will be presented at the award ceremony and the recipients will give an invited lecture about their works. Invited speakers confirmed at this stage include S. Chi (Taiwan), S. Chang (Korea), J. Ojeda-Castaneda (Mexico), C.H.B. Cruz (Brasil), E. Desurvire (France, ICO Prize 1994), A.K. Ekert (UK), K.M. Johnson (USA), S. Kawata (Japan), T. Kamyia (Japan), H.J. Kong (Korea), O. Kocharovskaya (Russia), J.H. Lee (Korea), C.M. Lee (Korea), L. Liu (China), D. Maystre (France), A.L. Mikaelian (Russia), M. Namgoong (Korea), S. Odoulov (Ukraine), H.M. Ozaktas (Turkey), J. Perina (Czech Republic), D. Psaltis (USA), A. Rebane (Switzerland, ICOPrize 1993), G.C. Righini (Italy), C. Gomez Reino (Spain), T. Szoplik (Poland), H. Thienpont (Belgium), H.J. Tiziani (Germany), J. Turunen (Finland), and B.Y. Zel'dovich (USA).

The second announcement and call for papers is being mailed by all ICO Territorial Committees and is available from them. Additional copies may be obtained from the ICO Secretariat or from the ICO XVII Congress Secretariat, Prof. B.Y. Kim, Dept. of Physics, KAIST, 373-1 Kusong-dong, Yusong-gu, Taejon 305-701, Korea, fax +82-42-869 5527, e-mail yoonkim@sorak.kaist.ac.kr.

Taejon is approximately a two-hour drive south of Seoul, Korea. Taejon is located in the central part of Korea and has traditionally been a center for commerce and transportation. In recent years, it has emerged as a major city for Science and Technology. Many university, government, and industrial laboratories are located in Taedok Science Town. Together with the nearby Taejon High Technology Industry Area, Taedok Science Town is one of the most important science and technology complexes responsible for the industrial development of the growing national economy of Korea. The world Expo'93 was held in Taedok Science Town and attracted 10 million visitors. For the transportation of participants in ICO XVII, a shuttle bus service will be arranged from Seoul Kimpo Airport One and Two to the meeting location. Train and regular express bus service is also available.

The International Commission for Optics cordially invites you to seize this unique opportunity to discover Korea and interact with the fast growing Korean optical community during a widely international event covering virtually all of optics.

OC'96 to be held in Sendai, Japan

The International Topical Meeting on Optical Computing is held biennially under the auspices of a steering committee established by the International Commission for Optics in conjunction with the European Optical Society, the Optical Society of America, and SPIE - the International Society for Optical Engineering. The previous meetings were held in Minsk in 1992 and Edinburgh in 1994. In the even years, topical meetings on Optical Computing are usually organized by the Optical Society of America.

OC'96 will take place at the Sendai International Center, Sendai, Japan, 21-25 April 1996. Sendai can be reached in an hour and 42 minutes by the Tohoku Shinkansen "Bullet" train from Tokyo. OC'96 will be held in parallel with the International Topical Meeting on Photonics in Switching, PS'96, and a joint session will be planned. The OC'96 chairpersons are Y. Ichioka of Osaka University for the Organizing Committee, T. Kurokawa of NTT for the Steering Committee with M. Ishikawa and K. Kubota as co-chairs, M. Takeda of Electro-Communications University for the Technical Program Committee with T. Hara and T. Yatagai as co-chairs, and H. Ito of Tohoku University for the Local Arrangement Committee. The submission deadline is November 1995. For a copy of the call for papers and for all other questions, please contact the OC'96 Secretariat, c/o Japan Convention Services Inc., Nippon Press Center Building, 2-2-1 Uchisaiwai-cho, Chiyoda-ku, Tokyo 100, Japan, fax +81 3 3508 0820, e-mail oc'96@csl.ntt.jp. Information is also available on the World Wide Web through http://www.csl.ntt.jp:oc_ps96 and by anonymous ftp from ftp.cl.ntt.jp, directory /pub/oc_ps96.

INTERNATIONAL COMMISSION FOR OPTICS
GALILEO GALILEI AWARD FOR 1996

Award Nomination Form

Full name of nominee :______________________________

Nominator's name and address :______________________________

Nominator's signature: ______________ Date __________

Date of birth of nominee:____________________

Business Address:______________________________

Academic background

College or University:______________________________

Location:______________ Major field: ______________

Degree:______________ Year awarded:______________

Academic Honors:______________________________

Position

Employed By: ______________________________

Dates:______________________________

Duties: ______________________________

Publications

(attach a separate sheet)

Patents, unpublished reports, papers presented at meetings, etc. (attach a list of those you deem pertinent)

Honors and Awards

Outstanding contributions for which the candidate is nominated for this award (attach a separate sheet) with consideration of the circumstances under which these were achieved.

Return this nomination form, together with supporting information, no later than March 15, 1995, to:

Prof. M.J. Yzuel
Chairperson of the ICO Galileo Galilei Award Subcommittee
Department of Physics, Edificio C
Universidad Autónoma de Barcelona
08193 Bellaterra (Barcelona), Spain
fax (34) 3 581 2003

Notes:

* The Rules of the Galileo Galilei Medal are included elsewhere in the present Newsletter.
* The nominee's contributions should be documented, as well as the circumstances that justify the award (see sections 2.2. and 2.3 of the Rules).
* The recipient will be invited to give a presentation based upon his/her achievements at the next appropriate ICO General Meeting.

INTERNATIONAL COMMISSION FOR OPTICS
ICO INTERNATIONAL PRIZE IN OPTICS (1996)

Award Nomination Form

Full name of nominee:

Nominator's name and address:

Nominator's signature: Date:

Date of birth of nominee:

Business address:

Academic Background

College or University :

Location: Major field:

Degree: Year awarded:

Academic honors:

Position

Employed by:

Dates:

Duties:

Publications

(attach a separate sheet)

Patents, unpublished reports, papers presented at meetings, etc. (attach a list of those you deem pertinent)

Honors and Awards

Scientific achievements for which the candidate is nominated for this award (attach a separate sheet).

Return this nomination form, together with supporting information, no later than March 15, 1996, to:

Prof. T. Asakura, Chair
ICO Prize Committee, Research Institute for Electronic Science
HokkaidoUniversity
Sapporo 606, Japan
fax (81) 11 758 3173

Notes:

* The Rules of the ICO Prize are included elsewhere in the present Newsletter.
* The nominee's contributions should be documented according with these Rules.
* Nominators are encouraged to generate supporting letters; each supporting letter must come from a different country or ICO Territory and bring additional information on the case. The number of supporting letters will not be a selection criterion.
* The recipient will be invited to give a presentation based upon his/her achievements at the next appropriate ICO General Meeting.

ICO Prizes and Awards

The calls for applications for the ICO Prizes and Awards are normally issued every October with a deadline of March 15 of the following year. This issue of the ICO Newsletter therefore combines the two calls for applications for the "ICO Prize" and for the "Galileo Galilei Award" for 1996. It is appropriate to repeat here the rules applicable and point out to the sharp distinction that exists between the two.

ICO Prize Rules

ICO has established in 1982 the ICO Prize, to be given each year to an individual who has made a noteworthy contribution to optics, published or submitted for publication before he or she has reached the age of 40. (Specifically, the Prize winner must not have reached the age of 40 before December 31 of the year for which the Prize is awarded). The character of the work of successive Prize recipients should preferably alternate between predominantly experimental or technological and predominantly theoretical. The "noteworthy" contribution in optics is measured chiefly by its impact (past or possibly future) on the field of optics generally, opening a new subfield or significantly expandingan established subfield in research or technology. The Prize consists of a citation and a cash award of US $ 1000. Carl Zeifl have agreed to donate in addition the Ernst Abbe medal. Every year, the ICO Prize Committee issues a call for nominations that is published in the ICO Newsletter, receives the nominations and selects the recipients for approval by the Bureau at its next meeting. The award needs not be made each year if the Prize Committee so chooses. The Prize is preferably given to an individual, but it can be shared by two persons. Eligibility for the Prize is not excluded by previous prizes awarded to the individual. The selected Prize winner is then announced in the ICO Newsletter and, if possible, in one or more optics journals. The prizes are presented at each ICO General Meeting and the Prize winner is asked to deliver an invited talk at that Meeting.

About the ICO Prize

The ICO Prize was established in 1982 ; previous award winners are :

1982 Antoine Labeyrie, France
1983 James Fienup, USA
1984 J. Christopher Dainty, Great Britain
1985 Sergei I. Stepanov, USSR
1986 Kensuke Ikeda, Japan
1987 Alain Aspect, France
1988 no prize (The 1988 prize was changed to1989 in order to coincide with the year of award).
1989 Demetri Psaltis, USA
1990 Rosario Martinez-Herrero, Spain
1991 David A.B. Miller, U.K.
1992 Wolfgang Peter Schleich, Germany
1993 Aleksander K. Rebane, Estonia
1994 Emmanuel Desurvire, France and USA.

The ICO Prize Committee, consisting of T. Asakura, Chair, K. Chalasinska-Macukov, J.W. Goodman, A.W. Lohmann, D. Malacara, is now seeking nominations for the 1996 Prize.

Rules applicable to the Galileo Galilei Award

1. The Galileo Galilei medal of ICO is awarded for outstanding contributions to the field of optics which are achieved under comparatively unfavorable circumstances.

2.1 The outstanding contributions in the field of optics should refer to :
- ◆ fundamental scientific questions or problems, or
- ◆ research or development of optical methods or devices, or
- ◆ scientific or technical leadership in the establishment of regional optical centers.

2.2 "Comparatively unfavorable circumstances" refers to difficult economic or social conditions or lack of access to scientific or technical facilities or sources of information.

2.3 The outstanding contributions must be documented by internationally acknowledged publications.
Exceptionally, reports can be considered, provided that they are made available to the Award Committee.

3. The award is normally given to one person. Exceptionally, however, if a collective contribution is judged to be worthy of the award a team of several persons may be selected.

4. Every year, the ICO Committee for the Regional Development of Optics issues a call for nominations that is published in the ICO Newsletter, receives the nominations and selects the winner for approval by the Bureau at its next meeting. The award need not be given every year if the Bureau so chooses.

5. The award consists of:
a) the Galileo Galilei Medal,
b) funding of registration and approved local expenses at the next ICO General Meeting, where the winner will give a presentation based upon his/her achievements,
c) special attention and appropriate measures of ICO to support the future activities of the award winner.

About the Galileo Galilei Award

The award was established by the 1993 General Assembly of ICO and will be awarded annually from 1994 onwards. The Italian Society of Optics and Photonics, SIOF (Societa Italiana di Ottica e Fotonica) has agreed to support ICO's initiative and donate the silver medal with the portrait of Galileo Galilei to be given to the recipient.

The Award will contribute to one of the missions of the International Commission for Optics: it will recognize the promotion of Optics under difficult circumstances.

A subcommittee of the ICO Committee for the Regional Development of Optics has been established for the Galileo Galilei Award. It consists of M.J. Yzuel, Chair, H.H Arsenault, T. Asakura, G.G. Mu and J. Perina. The 1994 and 1995 recipients will be announced shortly. The Galileo Galilei Award subcommittee herewith invites readers of this Newsletter to nominate candidates for the 1996 award. It is convinced that there are many outstanding possible nominees and is looking forward to receiving the nominations.

International Commission for Optics

International Commission for Optics. Bureau members: President: A. Consortini; Past-President: J.P. Dainty; Treasurer: R.R. Shannon; Vice-Presidents: T. Asakura, K. Chal-asin' ska-Macukow, S.S. Lee, F. Merkle, G.G. Mu, G.T. Sincerbox, C.H.F. Velzel, M.J. Yzuel; Secretary: P. Chavel.

International Commission for Optics, secretariat: B.P. 147, 91403 Orsay cedex, France, phone (33)1 69 41 68 44, fax (33)1 69 41 31 92, e-mail: Pierre.Chavel@iota.u-psud.fr

Optical Society of America, 2010 Massachusetts Ave., NW, Washington, DC 20036; 202/223-8130; fax 202/223-1096; e-mail: postmaster@osa.org