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Some thoughts on 38 years of lasing

D.C.Hanna
Optoelectronics Research Centre
University of Southampton

My first sight of a laser beam was in the Spring of 1963, during a year spent, as a graduate trainee, at the Great Baddow Research Labs of the Marconi Company. Midway through that year I was very fortunate to be offered participation in a project to construct a He-Ne laser. Having graduated the year before, with a mathematics degree from Cambridge University, I was acutely conscious of my limited knowledge of experimental physics, particularly when it came to dealing with RF power supplies, vacuum systems and the like. In my inexperienced hands the whole of this ‘home-made’ laser seemed to consist of hazardous and life-threatening unknowns. So, when, as a result of my ministrations, it first sprang into life and lased before my eyes, no-one could have been more delighted and surprised than I. This intensely rewarding experience formed a number of attitudes that have endured over the ensuing 38 years.

The suggestion by Allister Ferguson, as editor of J.Phys.D, that an issue of the journal should mark my 60th birthday, and hence my 38th year of lasing, was immensely flattering. I offered no resistance. I am very grateful to the many friends and colleagues, who also failed to resist the editor’s persuasive powers and agreed to contribute to this special issue. All of them are acknowledged leaders, and therefore have numerous calls on their time. I am sorry to have been the cause of an additional imposition on their busy schedules. To show solidarity I have been involved, with the help of co-workers, in a couple of contributions to this issue. I was also prevailed upon to contribute an introductory paper. So, in the following few pages I would like to take the opportunity to revisit some of the things that have occupied my misspent youth, acknowledging colleagues along the way. Just to emphasise that I have no intention of stopping at this point, at various places scattered through the text there are hints on how I might continue to misspend my time, lasing on into the future. I also decided to give this account in pretty much the chronological order since, although this is not the tidiest form of presentation, it does reflect the way research often proceeds, or perhaps fails to proceed.

Returning to the occasion of my laser baptism, one of my recollections is of the care and thought that had to be put into devising a mirror alignment technique suitable for a low gain laser, blessed with an invisible infrared beam travelling through a narrow bore tube. Over the years much more challenging alignment problems have presented themselves. Invariably the best basis for successful alignment has been a detailed, quantitative understanding and prediction of the relevant beam and resonator behaviour. The seminal papers of Fox and Li[1] and Boyd and Gordon[2] on the modes of laser resonators proved invaluable in helping me to understand the alignment requirements of my He-Ne laser-to-be. These were essentially the first research papers that I read, and they made a lasting impression, inculcating a great respect and admiration for well-constructed and informative publications. Seeing the experimental mode characteristics agree so well with their theory gave me an enduring interest in areas relating to laser beams and resonators. Any knowledge that I acquired in these areas always seemed to pay handsome dividends in terms of guiding experiments to a satisfactory conclusion. To make a more general point, it always seemed that experiments were more exciting if one had a set of detailed expectations, preferably quantitative, before starting the experiment. The outcome of the experiment was then always likely to be rewarding. If it agreed with expectation, confirming one's predictive ability, then the reward of self-congratulation was allowed. If it did not follow expectations, then the reward could be even greater. It could mean that something new, and more interesting had been discovered.

Returning to the He-Ne laser experience, the agreement I found between theory and experiment, gave me a general expectation for future encounters with lasers: that they should be well-behaved and amenable to quantitative analytical description. Essentially this meant an insistence that the laser should operate in a single mode. If a laser did not meet this criterion then my priority would be to make it do so, on the grounds that the results from experiments using the laser would otherwise be degraded. A sizeable fraction of my research effort has been directed at this task, in one way or another. This task is likely to be an unending one, presenting itself time and again as new lasers emerge, since many of these lasers are of a size that gives them an inherent tendency to multimode operation. Even fibre lasers, which in their lower power embodiments gave freedom from multimode tendencies, are now, in the quest for higher power, entering the parameter space where multimode tendencies reappear.

With my thirst for knowledge about lasers stimulated at the Marconi Labs, it was quickly apparent that the best way to satisfy this thirst would be by total immersion, in a PhD programme. Of the various nascent laser research activities around the country, the group at Southampton University, under Alec Gambling and Bob Smith, particularly appealed to me and I enrolled as a research student, under their joint supervision in the autumn of 1963. Part of the appeal was that I would work on a ruby laser, which seemed to offer more adventurous opportunities than the He-Ne laser since, with the much higher power available, it gave entry to the exciting new field of non-linear optical effects.

The high power of the ruby laser was however achieved at some cost to convenience of use, such as its painfully slow repetition rate. One had to become adept at interleaving some other useful activity between laser shots. To me, the more serious limitation of the ruby laser was its multimode output. The typical beam quality of early ruby lasers was so far from diffraction-limited that to describe its beam in terms of transverse modes seemed almost irrelevant. However a paper by Orazio Svelto and co-workers [3], showed that single-mode operation (transverse and longitudinal modes) could be obtained from ruby rather straightforwardly. From then on there seemed to be no remaining excuses for tolerating multi-mode operation This view was reinforced by a sabbatical period that I spent in Orazio Svelto's lab in Milan in 1970-71. Development of mode-selection techniques then became a priority when, on returning to Southampton and having settled on optical parametric oscillators as an interesting research area, a single-mode pump was seen as essential. By now neodymium lasers with their advantageous 4-level scheme were beginning to challenge and displace ruby as the preferred high-power source. So, it was with a Nd $CaWO_4$ laser, (we still could not afford the latest material, Nd:YAG) that we introduced the idea of electronically simulating the action of a saturable absorber [4]. This technique, now referred to as 'prelase' Q-switching, provided a simple and effective means of selecting a single longitudinal mode.

Armed with this pump laser, parametric oscillation in proustite, Ag_3AsS_3 , gave a rather impressive tuning range, from 1.22μm to 8.5μm [5], which as far as I am aware, still remains a record in terms of the octaves covered by an OPO. The research student who achieved this, Barry Luther-Davies, was spurred on by the offer of a bottle of champagne per octave. In the end three bottles were awarded despite the result being a little shy of three octaves. Further progress was prevented by optical damage to the proustite crystal. While the single-mode pump was very beneficial in reducing the likelihood of damage it could not protect against overzealous striving for more champagne.

This damage to the proustite crystal had a significant effect on my choice of future research. It coincided with an unrelated decision by RSRE to terminate their growth programme for proustite. Thus, at the very moment of success with proustite, capitalisation on the results was frustrated. My decision at that point was to opt for nonlinear materials that did not depend on supply by a third party. Hence there followed a period of a number of years working with alkali vapours and then with high pressure H_2 and CH_4 gas, still with the aim of generating widely tunable infrared radiation, but this time through stimulated Raman scattering. Tunability, in this case, was to be provided by the pump laser, for which the most obvious candidate at the time was a pulsed dye laser.
The requirement of narrow line-width operation and convenient tunability prompted a new laser resonator design. This used prisms to provide one-dimensional beam-expansion onto the grating [6], thus avoiding the more critical alignment tolerance of the standard, 'Hansch-design', [7] with a telescope beam-expander. With this dye-laser and a heat-pipe oven containing the alkali vapour, one had a simple scheme for extensive tuning ranges in the infrared via stimulated electronic Raman scattering. A summary of this work is included in the monograph, 'Nonlinear optics of free atoms and molecules' co-authored with my colleagues David Cotter and Michael Yuratich [8].

However, while the 'low-technology' of the heat-pipe oven gave a home-made nonlinear medium that was very effective, doubts occurred about the reliability and acceptability of living with a highly reactive high temperature vapour. These doubts were at their strongest whenever the hazardous operation of recharging the oven with alkali metal had to be repeated (wisely left to David Cotter). In the end these doubts urged a change in direction. So, high pressure gases became the object of attention as a nonlinear medium. However, having given up the benefit of resonant enhancement, higher pump intensities were then needed. Three different approaches to meeting the power needs were investigated, using Nd:YAG lasers as the most convenient pump source for the demonstration. The first involved using a telescopic resonator to increase the TEM_{00} mode size. The second was to use mode-locked pulses to achieve high peak power. The third, following the example of Rabinowitz [9], was to use a hollow glass capillary as a wave-guide to confine the pump-light [10]. Each of these approaches had fruitful consequences even if not in quite the anticipated way.

Our interest in the telescopic resonator came from results of Paul Sarkies [11] who demonstrated its ability to provide a large TEM_{00} mode size and hence a large single-mode output energy. Our motivation was to develop an analysis of the modal characteristics of such a resonator and then use this as a design tool to push the TEM_{00} performance further. It was gratifying to see how successful this approach proved to be, providing further support to the notion that the behaviour of 'real-world' lasers should be amenable to quantitative description. By adding our previously developed 'prelase' Q-switching technique [4] a clean single-mode behaviour was obtained, which then allowed careful characterisation of the Stimulated Raman process [10, 12].

The large threshold reduction gained from spatial compression via the capillary wave-guide also provided motivation for our subsequent interests in waveguide lasers. More immediately it suggested analogous benefits, of reduced pump energy requirements, via temporal compression, i.e. by using mode-locked pulses. An actively mode-locked Nd:YAG laser was therefore acquired and with it the benefits in reduced threshold energy for the shorter pulses were amply confirmed [13]. The frequency-doubled output of this laser was then used to synchronously pump a dye laser [14] which, in turn, provided a tunable pump with sufficient power to drive the stimulated Raman process. Having reached this point, with the capability to generate tunable infrared radiation it was already apparent that there was a better and simpler way to do this; simply cut out the dye-laser and the Raman medium, and replace these with an OPO, although this time in the form of a synchronously-pumped OPO (SPOPO), and making use of the new nonlinear materials that had recently emerged, such as BBO and KTP.

Our first SPOPO, operated in 1988, using BBO [15], was pumped by a train of mode-locked pulses within the envelope of a Q-switched pulse. The results, obtained later in 1988 [16], by changing the crystal to KTP, with its larger nonlinearity and hence lower threshold, gave encouragement that, before long, it would be possible to build a SPOPO driven by a cw mode-locked laser. This became the goal, since it was seen that such a source could at last embody many of the key advantages that OPOs could offer, at pump-power levels free from risk of material damage. To reach this goal one had to make a choice between an actively mode-locked pump, with rather long pulses, typically 50-100ps, and therefore needing multiwatt average power, or a source of significantly shorter mode-locked pulses. We opted for the latter, via the (then) recently developed technique of additive-pulse-mode-locking (APM), which brought with it the convenience of being compatible with the power capabilities of diode pumps. A certain amount of development was needed for the APM laser source and its resonant frequency-doubler [17], which then served two generations of research students before being pensioned off in favour of a commercial descendent, from Microlase, the company formed by Allister Ferguson. This experience with the design of APM lasers was also put to very good use by my colleague John Barr and his students [18,19]. Their delivery of an APM Nd:LMA laser to the Rutherford Laboratory, to serve as the master oscillator for Vulcan, gave that laser the distinction, briefly, of being, at 35TW, the world's most powerful laser then in operation [20,21].

We finally achieved the cw-mode-locked-pumped SPOPO, using KTP, and a diode-pumped APM Nd:YLF pump, in 1991 [22,23]. Meanwhile, however we had been preceded by the work of Edelstein et al in 1989[24] who had also used KTP, pumped by a mode-locked Ti:Sapphire laser in an intra-cavity pumping arrangement. Further development of SPOPOs still continues, for example using Quasi-Phase-Matched (QPM) materials, and increasingly directed to using fibre lasers as pumps. We revisit this later, and now return to the chronological order of events.

An important event in this chronology was the creation, in 1989, of the Optoelectronics Research Centre at Southampton University, as the result of a major research award from the SERC (later renamed EPSRC), thus establishing its national status as an Interdisciplinary Research Centre. This gave considerable scope for long-term planning and allowed a broad spectrum of interrelated activities to flourish. Significant elements in this spectrum were various developments of coherent light sources, with an emphasis on their miniaturisation. These activities encompassed fibre lasers, wave-guide lasers and bulk lasers, all capitalising on the rapid developments taking place in diode pump lasers. Added to these source developments was a programme to fabricate QPM nonlinear materials, inspired by the pioneering work from the group of Bob Byer [25]. In particular the SPOPO benefited enormously from the introduction of periodically poled lithium niobate (PPLN) as the gain medium. Many of these activities were deliberately entangled, to ensure cross-fertilisation, while at the same time a healthy degree of competition (for internal funds) was fostered. This entanglement complicates the attempt, below, to provide separate descriptions of the four main strands in which I had an active interest; bulk lasers, fibre lasers, waveguide lasers and PPLN/SPOPOs.

In the area of bulk lasers one of the main thrusts has been towards higher powers, or more correctly higher brightness, since the requirement of single mode operation was retained. This strategy was based on (i) expectations of further significant power increases and cost reductions for diode pump lasers, and (ii) the greater versatility and scope for applications that comes with higher power, e.g. through easier access to nonlinear optical effects. Progress to higher power does however pose significant challenges. These include devising means for coupling the notoriously ill-shaped beam from a high-power diode laser bar into the gain medium, then dealing with the removal of heat from the laser medium and also coping with the inevitable thermal distortions with their threat to beam quality. In each of these areas my colleague, Andy Clarkson, who provides a paper to this issue [26], has made crucial contributions. Perhaps the most important of these was the invention of a beam-shaping technique, to convert the very asymmetric beam from a high power diode-bar into a symmetric square beam, with no reduction in brightness [27]. This high brightness pump, with tens of Watts of power, opened up many possibilities, from pumping fibre lasers, to intense pumping of low gain, 'difficult', laser transitions, such as three-level transitions. In general, with a higher pump-brightness, there is a greater flexibility available in designing for reduced thermal problems. For example it allows the pump region to be extended longitudinally, thus reducing the severity of local heating. The accompanying paper by Andy Clarkson elaborates this point, and reviews some of the ways to alleviate the thermal problems in solid-state lasers. Here I shall only briefly mention some examples of improved performance, achieved as a result of having a high brightness pump. It is important to emphasise that many of the performance improvements, those for Nd:YLF being a particularly good example [28], have also required detailed study of the spectroscopy and of the thermal lensing characteristics [29,30,31], to help identify the heat deposition mechanisms. Nd:YLF had acquired a reputation for unheralded and catastrophic self-destruction. However, armed with this detailed knowledge of its thermal characteristics, one can now design for its safe operation at much higher power levels.

Some examples of improved performance from using the beam-shaped output from a diode bar are :

17 Watts at 2µm from a TmYAG laser [32]. This is an example of a transition that has been seen as 'difficult', on account of its quasi three-level nature. Despite its inconvenience, resort to low temperature operation has been the usual remedy. The above result was at room-temperature.

11 Watts of TEM_{00} output at 1053 nm from a Nd:YLF laser [33]. This is the lower gain transition of Nd:YLF, the higher gain 1047 nm transition usually being favoured. However the high pump brightness allows intense pumping, thus achieving the desired high gain, and at the same time allowing one to benefit from the markedly more benign thermal lensing behaviour on the 1053 transition. This is a useful object lesson on the influence that pump brightness can exert over design, completely turning the tables on the usual design assumptions.

Many further examples could be given, including the 946nm [34], 938nm [35], 1123 nm [36], and 1338 nm transitions in Nd:YAG. With these low gain transitions, requiring intense pumping, the presence of strong aberrations in the thermally-induced lens was identified, and the usual compensation by simple spherical optics is therefore ineffective. Also, strong thermally-induced birefringence is present. Novel approaches for correcting both of these problems, via resonator design [37] and a simple birefringence compensator [38], have been necessary to achieve high brightness performance on these low gain transitions.

This discussion has concentrated on the transverse mode behaviour. A few words should also be said about novel approaches to achieving single longitudinal mode operation. An intriguing observation [39] that an acousto-optic modulator could induce unidirectional oscillation in a ring laser, prompted us to investigate whether this might offer a practical route to single frequency operation. An explanation for the unidirectional behaviour, in terms of a physical mechanism, was lacking, so, after first confirming that the effect was real, robust and practical [40, 41], a concerted attempt was made to identify the underlying mechanism. This proved quite challenging since it turned out that, not only was the behaviour due to a weak effect that grew to significance by accumulating over very many cavity round-trips, but there were two distinct mechanisms that were typically entangled in a puzzling and confusing way. With great care and persistence these two effects were disentangled and identified [42, 43, 44] with the result that a quantitative design procedure can now be used to put these effects to good use.

This unidirectional mechanism combined with the prelase Q-switch technique gives a very effective route to single frequency operation [45].

Another intriguing observation has also led to a technique useful for single frequency operation. This arose from experiments on intracavity second harmonic generation, aimed at achieving multiwatt green output from diode-bar pumped Nd:YAG and YLF lasers,[46, 47]. It was found that the presence of the second harmonic generator could suppress mode-hopping in the laser, despite changes in laser cavity-length corresponding to frequency changes of many tens of mode-frequency spacings [48]. Again a weak mechanism is responsible, whose effect becomes robust due to accumulation over many round-trips. This gives a very effective route to mode-hop-free single-frequency operation at the multiwatt level either for the harmonic or the fundamental. In Nd:YLF we have used this to produce 10 Watts of 1053nm or 6 Watts of 527nm [49]. In addition to providing these useful outcomes, both of these single-frequency selection techniques provide good illustrations of a general point, that weak effects can exercise a robust dominance over the behaviour of an oscillator. Since there is no shortage of weak effects, one can look forward to many more intriguing phenomena yet to be revealed.

Before starting an approximately chronological discussion of fibre lasers, this seems a suitable place to mention an example of a fruitful entanglement, in this case between bulk lasers and fibre lasers. It has been interesting to watch the change of attitude towards fibre lasers. Initially they were seen as exclusively low power devices, and no challenge to the supremacy in power of bulk lasers. This attitude began to change as cladding-pumped fibre lasers began to go well beyond the 10 Watt level. In some quarters the change of attitude has gone so far in favour of fibre lasers that the bulk laser is seen as some kind of dinosaur, whose extinction is looming. Instead I find myself advocating a middle road, where fibre lasers and bulk lasers join in a hybrid scheme, both bringing those features for which they are best suited. A specific example of such a scheme is one that we have recently demonstrated [50] in which a high-power Tm-doped fibre laser is used to pump a Tm- or Ho-doped bulk laser. The fibre laser offers a very high brightness pump source, efficiently pumped by high-power diode bars. Its output wavelength can be tuned to matched to an absorption transition in the bulk laser e.g by using a fibre Bragg grating. The heat input to the bulk laser can be minimised by in-band pumping i.e. setting the pump wavelength very close to the emission wavelength. This three-level scheme requires intense pumping, but that is precisely what the fibre laser offers. My colleague Andy Clarkson and I plan to investigate this hybrid scheme in some detail, attracted by the thought that the long-established supremacy of Nd:YAG might be challenged in this way.

When, in 1984, my colleague Anne Tropper enquired in the Optical Fibre Group about the possibility of putting Neodymium ions into the core of a silica fibre, she had in mind a spectroscopic experiment. Examination of the ions' behaviour could answer questions of a fundamental nature about the glass structure. In fact this simple enquiry set in train a process that led in the end to the development of fibre lasers and amplifiers. So, one should not ignore the role that curiosity-driven research can play, even if serendipitously, in the creation of major new technologies. With the problem of rare-earth doping of fibres solved by our colleagues in the Optical Fibre Group, [51] there was a sudden frenzy of research into fibre lasers and amplifiers. I and my colleagues Anne Tropper and Allister Ferguson (also then in the Physics Department at Southampton), collaborating with Dave Payne and his colleagues in the Electronics Department (these were the days before our forces were joined by the formation of the ORC) divided up the cornucopia of research opportunities that these doped fibres offered. Since Erbium-doped fibres, with their clear potential for telecom applications, were a key interest of Dave Payne's group, we gave our attention to a number of transitions in other rare-earths. Since these had not been looked at in a fibre structure there was the excitement of visiting virgin territory. Doped fibres had a number of attractive features, amongst which were the broad tuning ranges, and high gains, which could be achieved for low pump powers, even for three-level transitions and transitions with low quantum efficiency and weak pump absorption. Besides offering tunability [52], the broad line-widths had obvious relevance for mode-locking and an early interest in this was taken by our editor, Allister Ferguson, in the form of frequency-modulation mode-locking of a Nd fibre laser[53].

One dopant that particularly attracted our attention was Ytterbium, that had been totally neglected as a bulk laser, in favour of Neodymium, since it had a quasi-three-level transition and its pump band was not ideal for lamp pumping. These drawbacks were irrelevant in a fibre context. They were also seen later to be irrelevant in the context of diode-pumped bulk lasers. Our interest in Yb was that it had a rather simple energy-level structure and spectrum, implying that the ions would be free from a number of competing processes, such as nonradiative decay, upconversion and excited state absorption. The Yb system therefore promised to be a very 'clean' system to study, ideal for looking at the basic features of fibre laser operation. We were not disappointed in this. Starting with the first demonstration of an Yb-doped fibre laser [54] , it has continued to attract our attention over the years, as a widely tunable laser [55, 56], as a laser well-suited to high power cladding-pumped operation [57], as a high power amplifier [58,59], as a mode-locked laser [60] etc. It is interesting to see how the status of this previously neglected dopant has changed , to the point where Yb-doped fibre is now the preferred candidate for the highest power fibre laser developments. It looks as though it still has a great deal more to offer.

Another interest we had in Ytterbium arose from its role in energy transfer, whereby the Yb ion after excitation could pass its excitation energy to another rare-earth, present as a co-dopant in the medium. The Er-Yb system looked particularly interesting as it effectively conferred a larger absorption cross-section on the Er ion and would therefore allow shorter fibre lengths to be used. We had already carried out a number of experiments, inspired by earlier work of Gapontsev [61], on bulk phosphate glass lasers, in the form of a rod co-doped with Yb and Er, and end-pumped by a Nd laser. This had provided a 1.55μm source [62], that could be operated cw [63] and mode-locked [64]. Indeed the work of Orazio Svelto's group has since shown that bulk lasers based on these Er-Yb glasses provide ideal stable sources for telecom applications. Attempts to transfer this co-doped scheme to a fibre geometry were first made using bulk phosphate glass as the core material, but this did not produce high quality fibre. Success had to await the perfection of co-doping techniques in silica, and our first demonstration [65, 66] followed shortly after that of Snitzer and co-workers [67]. The Er-Yb fibre laser is now seen, after extensive development, as an important element, not only for telecom devices, where it offers high power amplifiers at 1.5μm, but more generally for various applications requiring high power in the 1.5μm region. Further discussion of this aspect of the Er-Yb system is given by Johan Nilsson and colleagues in this issue [68].

Another dopant that attracted our interest was Thulium and, from our first demonstration of Tm-doped fibre laser operation [69], it has continued to attract, in particular for its potential as a very high power laser. In fact our early interest in its high power operation involved using a Nd:YAG laser as pump, exploiting a very weak absorption of Tm in the extreme wing of a transition. Just over 1 Watt of output, around 2 μm was obtained [70], at that time a significant milestone. This result highlighted the fact that fibre laser output power was primarily constrained by how much pump power could be launched into the fibre core. The Nd:YAG laser did not suffer from this constraint since its high brightness allowed an efficient launch directly into the core. For pumps of lower brightness the use of cladding-pumping comes to the rescue. Even then, if a high power diode laser is used as pump, the demand on diode beam brightness is exacting, calling for careful beam-shaping. To date, the highest power achieved with a Tm-doped fibre is 14 Watts [71], based on a cladding-pumped arrangement and using beam-shaped diode-bars. Again there is much scope for building on this figure and, as already mentioned, there is the prospect for major power-scaling via a hybrid scheme in which multiple fibre sources pump a bulk laser. In this issue Johan Nilsson and colleagues also review high-power and tunable operation of Tm and Yb fibre lasers [68]

Anyone working on silica fibre lasers, and seeing the strong visible side-light emission, due to upconversion processes, could not fail to have their thoughts turn to upconversion lasing. The Praseodymium ion was particularly spectacular in its display of colours, and prompted us to make some spectroscopic measurements to quantify its upconversion laser prospects [72]. Alas, it provided a reminder that the eye is superbly well-adapted to sensitive detection of visible light, but showed that in silica the various upconversion processes were hopelessly weak as far as upconversion lasing was concerned. The conclusion was that a host glass with a much lower phonon energy than silica was needed, so that non-radiative decay in general became slower. The best candidate for this was ZBLAN glass, whose fabrication into fibre was being developed at, amongst other places, the British Telecom Research Labs. Samples of this fibre, with various dopants, were eventually made available to us by BTRL under a successful collaboration lasting several years.

Starting with Tm-doped ZBLAN fibre our initial investigations [73] were into the 2μm transition, already familiar from Tm-doped silica. However the reduced non-radiative decay rates turned many more transitions into good candidates for lasers or amplifiers. One such transition in Tm gave amplification around 810nm [74], and since this presented a viable amplifier for the first telecom window, we investigated its amplifier performance in some detail [75,76]. Meanwhile the potential for upconversion lasing was evident from the numerous visible emissions, and in fact it was Monerie and co-workers at CNET who were the first to demonstrate upconversion lasing in ZBLAN fibre [77]. Our first upconversion laser, in Pr-doped ZBLAN [78], was in the end well worth waiting for, as it produced three lasing transitions, in the red, green and blue. Subsequently, following Steve Grubb's demonstration [79] of a very efficient blue up-conversion laser in Tm ZBLAN, we made a detailed study [80] of this transition to see how far its performance, particularly its power, could be pushed. A blue output power of 230 mw was reached [81]. However this marked the end of our up-conversion laser work as it had become clear, by then, that for further advance one needed full control over the fibre fabrication. There was also a growing doubt about the practicality and durability of ZBLAN fibre, and therefore we turned our attention back to silica, in particular to its high power capability. Thus, while ZBLAN offered many more transitions and hence more operating wavelengths, the power levels achievable in silica now allow essentially continuous coverage of the near infrared via multiple Raman scattering. This is a repetition of a, by now, familiar lesson, that increased power gives greater versatility. This lesson is reinforced by the convergence between power requirements of nonlinear devices based on PPLN and the capabilities of the new generation of high power silica fibre lasers.

The advantages conferred by a wave-guide geometry, so evident in the case of fibre lasers, had also turned our thoughts to analogous advantages that might come with a planar wave-guide geometry. Anticipated advantages were low thresholds, high gains, perhaps upconversion lasing if guides could be made in materials of low phonon energy. Compared with fibres the easier access to the gain medium suggested that planar guides would simplify the addition of extra functionality, in the form of modulators, gratings etc. The first step that needed to be taken was that of fabricating guides in suitable laser media. These thoughts were first aired at an SERC 'town-meeting'. The value of such meetings, mixing together people from a range of backgrounds, was instantly confirmed when Peter Townsend, a participant, announced that with his ion-implantation apparatus at Sussex University he could make guides in YAG, or in pretty much anything else that we cared to name. A joint research proposal was rapidly prepared, and accepted, and soon after, there followed the first demonstration of a wave-guide laser, in this case NdYAG, fabricated in this way [82].

As experience with wave-guide lasers was gained, examining different dopants, different fabrication methods, e.g. epitaxial growth was explored in a collaboration with LETI [83], eventually the main effort focussed on their potential role as a simple and efficient means to enhance the brightness of a high power diode-bar laser. An embodiment of this principle can be in the form of a side-pumped planar wave-guide [84], with pump-light proximity-coupled into the guide possibly with a double-cladding arrangement [85], analogous to that used in high power fibre lasers, and also using an unstable resonator to provide mode-selection in the unguided planar dimension [86]. For this scheme close collaboration with Helmut Meissner has been important as his thermal-bonding technique [87] provides the most versatile way of meeting the guide design. Simple, compact, high brightness sources based on this approach could find many uses and indeed play a role in hybrid devices, being used themselves as pumps. Progress on these high power wave-guide lasers is the subject of a paper by David Shepherd and co-workers in this issue[86].

My account of our SPOPO developments was broken off at the point where we had made our first demonstration of a cw-pumped device using KTP. Our emphasis is now on the use of PPLN. However before becoming involved with PPLN a further important phase of development took place using LBO as soon as the material became available commercially. The excellent optical quality of LBO, its resistance to optical damage, its broad tuning range, its modest pump power requirement, which allowed singly-resonant operation with a diode-pumped Nd:YLF laser as pump, all contributed to the feeling that at last a truly practical SPOPO had arrived [88, 89, 90]. Indeed a commercial LBO-based SPOPO emerged from Spectra Physics, pumped in this case by a mode-locked Ti:sapphire laser. However, just as the LBO device was moving into a stage of maturity, a new nonlinear material was rapidly coming into prominence. This was Periodically-Poled Lithium-Niobate, PPLN.

My attention was first drawn to PPLN by work from Bob Byer's group demonstrating high efficiency harmonic generation in a PPLN sample produced by laser-heated pedestal growth [25]. The report of an e-beam-poling technique [91] provided a spur to action, and my then colleague Philip Russell was successful in persuading Jonas Webjorn to join us and accelerate our fledgling programme of periodic-poling. Success followed rapidly with an electric-field-poling technique [92], close on the heels of a report from Burns et al [93] of an E-field poling experiment. Our early experiments with PPLN were aimed at testing its effectiveness in frequency-doubling [94, 95]. Important measures of progress were [96] efficient frequency doubling to the blue (473nm), an OPO demonstration [97] and efficient frequency-doubling with picosecond pulses [98]. A more recent development has been the fabrication of HXLN, i.e. $LiNbO_3$ with a two-dimensional periodic pattern [99].

The efficient frequency-doubling with picosecond pulses pointed immediately to the suitability of PPLN for a SPOPO. This soon followed, first using green pump light [100], then using the (1047nm) fundamental output from an APM Nd:YLF laser [101], and then using a mode-locked Ti:sapphire laser as pump [102]. The large nonlinearity of PPLN, and hence the very large gains available, brought unexpected benefits as well as the expected. For example strong pulse compression could be obtained [103] and extended tuning, well into the infrared absorption-edge [104,105]. The high gain also prompted me to consider the possibility of using a fibre-feedback arrangement in a SPOPO. This has been successfully implemented [106] through a collaboration with Rudiger Paschotta and Ursula Keller at the ETH, and is the subject of an accompanying paper in this issue [107]

The high gain also allows the convenience of using a diffraction-grating as a tuning element in the SPOPO, easily coping with the typical insertion loss of the grating, which would be unacceptable in many other mode-locked sources. Our original motivation for using a grating was to allow very close approach to degeneracy, while maintaining single-resonant operation [108]. More generally it provides agile tuning and at the same time gives some protection against cavity-length-dependent tuning effects. We have carried out a detailed investigation of the operating characteristics of a SPOPO equipped with a feedback-grating, and the findings are presented in a companion paper in this issue [109].

While the large nonlinearity of PPLN has led to a significant reduction in pump power requirements, developments in fibre lasers have boosted their powers to the point where these two technologies are now compatible. In principle fibre-laser-pumped PPLN OPO devices can provide cw-pumped oscillators, Q-switched-pulse-pumped oscillators, synchronously-pumped oscillators and optical parametric amplifiers and generators. So far Q-switched devices [110, 111], a SPOPO pumped by a tunable mode-locked Yb fibre laser [112], amplifiers and generators [113, 114,115] have been demonstrated. OPOs pumped by cw fibre lasers can be expected to follow soon. Tunability of the fibre laser offers a convenient way to tune the OPO and a fibre MOPA configuration offers both versatility and scalability. This synergy between fibres and QPM materials promises a productive area for future source developments.

Concluding remarks

This historical tour has taken many more words than I had originally intended and my further comments should therefore be kept to a minimum. A great deal that could have been said has been omitted and I hope that colleagues past and present will not be upset if their work did not get the mention it deserves. I would like to express my deepest thanks to the many colleagues and students, who worked so prodigiously (hence the length of this article), and who made collaboration such a pleasure.

Of course, the danger with writing a retrospective view like this, is that it will be considered a sign that I now plan to stop. A few words are needed to dispel that notion. There is a great deal of unfinished business, developing the symbiosis between fibre lasers and QPM materials, plus the general goal of power-scaling, with the challenging constraint of striving for the maximum possible coherence. Marrying fibres and bulk lasers will be part of this strategy for brightness-scaling. An aim for all this optical power is its deployment in the structuring and processing of material, particularly targeting techniques for structuring on the meso/nanoscale. My colleagues are already working at this and I suspect there will be enough work in this field to keep people busy for at least another 38 years….

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