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Recent Developments in Visible Light Sources

D. C. Hanna

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Recent developments in visible light sources

By D. C. Hanna

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

This paper reviews some of the areas of development of compact efficient blue-light sources via frequency upconversion from low-power infrared diode lasers. The two main approaches reviewed are upconversion fibre lasers and second-harmonic generation. Through these upconversion techniques, blue powers in the several mW range can already be achieved starting with $\preceq$ 100 mW of diode-laser power. Issues which remain to be solved include the development of cheap and simple means of frequency control and stabilization if these sources are to meet the needs of widespread consumer-oriented applications in compact disc systems.

1. Introduction

Compact visible laser sources—blue lasers in particular—are currently a very active area of research and development. In the near infrared region, semiconductor diode-laser sources, with their small size, high efficiency, reliability and low cost, have found very widespread applications, with optical communications and compact disc (CD) systems being among the most important. The first semiconductor lasers to be developed into practical devices were based on AlGaAs material, operating in the range *ca.* 750–860 nm. These lasers provided sources both for telecommunications, in the 'first' telecommunications window, and for use in CD systems at 780 nm. Later developments in telecommunications have pushed semiconductor laser devices to longer wavelengths (1.3 μm for the 'second' telecommunications window and 1.5 μm for the 'third window') to take advantage of the lower propagation losses for silica fibres at these longer wavelengths.

Meanwhile, for CD systems there is a major benefit to be gained from going to shorter wavelengths, since this allows the light from the diode laser to be focused to a smaller spot. Thus, the data can be recorded at a higher density on the disc. The total density of stored data can in fact be of the order of λ^{-2} bits per unit area, where λ is the light wavelength, since individual bits of data can be placed on the disc with a spacing of *ca.* λ along the data track, and a similar spacing between adjacent turns of the spiral track. A standard compact disc system, operating with a diode laser at 780 nm, has 650 Mbytes stored on a 130 mm diameter disc, with 1.6 μm spacing between data pits, a read-out rate of 1.5 Mbit s^{-1} and a total playing time of just over an hour. Increases in the data storage capacity, total playing time and data reading rate are all seen as having a major impact on future consumer markets for multimedia applications and for extended play, say two hours, of video with high quality reproduction. The combination of a number of developments, i.e. in improved optical elements, data-encoding and electronics, combined with a move

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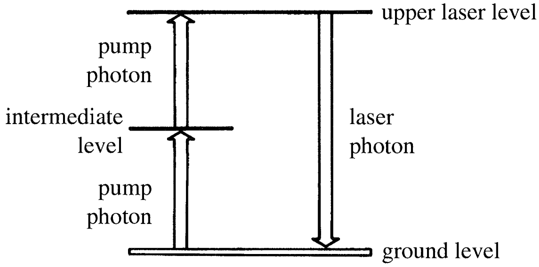

Figure 1. Schematic energy level diagram for an upconversion laser. Sequential absorption of two (or more) photons is followed by emission of a single, more energetic, laser photon.

to somewhat shorter wavelength diode lasers (635 nm), now make possible such an upgrade in performance. Shorter wavelengths would provide scope for significant further extension of capacity and performance. It is this goal that provides a motivation for much of the development work on compact blue–green light sources.

The cost of such a light source is all-important for these consumer applications and this overriding consideration forces a common feature on the various approaches being considered, namely that the light source must have as its primary source of photons a semiconductor diode laser. The direct approach is to develop a wide band-gap semiconductor diode laser operating in the blue. This is an approach that has made considerable progress over the past few years since the first demonstration of such a laser in ZnSe-based material (Haase 1991). Alternative semiconductor materials, such as GaN, which has already yielded high brightness LEDS, as reported by Nakamura (1994), also show promise as future blue semiconductor diode lasers.

While progress with blue semiconductor lasers continues to be made at an encouraging rate, there is nevertheless still a long way to go to achieve the sort of power requirements and device lifetime that are needed for typical CD applications. These call for powers of a few mW for read-only use and the output beam quality must be diffraction-limited, i.e. the laser must operate in a single spatial mode. The laser must have a low-noise performance, corresponding to a relative intensity noise (RIN) of better than $-120\,\mathrm{dB\,Hz^{-1}}$. For writing applications a higher power is needed, a few tens of mW, with a capability for modulation at *ca.* 50 MHz. A device lifetime of *ca.* 5000 h is required, and, for consumer applications, cost must be within the region of a few tens of dollars.

With the uncertainty over the time needed for blue semiconductor lasers to reach such levels of performance, alternative routes to compact blue sources are being vigorously pursued. Two alternative routes are attracting particular attention. Both of these start from an AlGaAs diode laser, with its proven record of meeting the demands of price, lifetime, etc., and then converting its near-infrared output to the visible region. One approach involves the nonlinear optical process of second-harmonic generation, while the other involves pumping a so-called upconversion laser, in which the infrared diode laser pumps a laser-active ion in sequential steps (see figure 1) to a highly excited level from which it emits a single, and hence more energetic, laser photon. The essential requirement for each of these approaches is that the frequency upconversion should be efficient, even at the low-power levels (say up to 50–100 mW) implied by the requirement that the diode laser be cheap. This requirement of high conversion efficiency for low pump power has attracted interest to the use of a waveguide geometry, since this allows a high intensity to be maintained over useful lengths of medium even with modest pump power.

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In this paper we review the progress being made by these two approaches, i.e. direct frequency doubling of a diode-laser and diode-laser-pumped upconversion lasing.

2. Second harmonic generation

The dependence of generated second-harmonic power $P_{2\omega}$ on incident fundamental power P_ω, in a nonlinear crystal of nonlinear optical coefficient d, and length ℓ, is given by

$$\frac{P_{2\omega}}{P_\omega} \propto \frac{d^2 \ell^2 P_\omega}{A}, \tag{2.1}$$

where A is the area of the fundamental beam in the nonlinear medium. This equation assumes perfect phase-matching for the second-harmonic process, i.e. equal phase velocities for the fundamental and harmonic waves.

This phase-matching requirement proves to be one of the most restrictive of requirements, in that the inability to satisfy phase-matching eliminates many otherwise attractive nonlinear materials. The conventional way of achieving phase-matching is via the use of birefringence ('birefringence phase-matching'). The principle here is that differences in fundamental and harmonic phase velocities, due to dispersion of the medium, can be compensated by using the refractive index difference for ordinary and extraordinary waves in a material having a large enough birefringence. Fine tuning to achieve the exact phase-matching condition can then be made in a number of ways: by temperature tuning the crystal to alter the refractive indices; by tilt of the crystal, (for unguided waves where one has freedom to vary the propagation direction) thus changing the extraordinary refractive index by altering the propagation direction relative to the optic axis; by changing the fundamental wavelength so as to alter both the dispersion and birefringence. It has to be appreciated that there is not a wide scope for choice of fundamental wavelength, since this must fall within the range offered by cheap diode lasers. Temperature tuning can be a useful means of tuning, but temperature control can be a costly complication. Nor is angular tuning really a practical option, since, in fact, for optimum conversion efficiency it is necessary to focus the pump beam to as small an area A as possible (to maximize the right-hand side of equation (2.1)). This in turn means that spatial separation of the fundamental and harmonic waves, due to double-refraction walk-off, cannot be tolerated, since the beam size of the fundamental would need to be enlarged to a size greater than the extent of walk-off. So, in fact, one is restricted to the so-called 'non-critical' phase-matching condition, also known as 90° phase-matching, where the fundamental wave propagates at 90° to the optic axis, since this direction eliminates walk-off. This, however, means that the birefringence must have just that value that allows phase-matching for that 90° orientation. Thus, the requirement on birefringence is a very restrictive one. When one adds to this the need for a large nonlinearity d, the number of suitable materials becomes very limited. In fact, $KNbO_3$ is the material which best meets these various requirements (Günter 1979). It has a large optical nonlinearity, and allows non-critical phase-matching for AlGaAs diode laser wavelengths, thus allowing generation of blue light in the region of 430 nm.

For the non-critical phase-matching arrangement, focusing of the fundamental beam can be taken down to a spot size for which diffraction spread from the focused spot begins to become significant over the length of the crystal. This implies a minimum spot area of the order of $\ell\lambda$, so that the second-harmonic power $P_{2\omega}$ behaves as

$$\frac{P_{2\omega}}{P_\omega} \propto \frac{d^2 P_\omega \ell^2}{\ell \lambda} \propto \frac{d^2 P_\omega \ell}{\lambda}. \qquad (2.2)$$

Under this optimum focusing condition, the second-harmonic power scales linearly with crystal length ℓ, and conversion efficiency is usually specified in % $W^{-1}\,cm^{-1}$. For the case of $KNbO_3$, the appropriate value is *ca.* 3% $W^{-1}\,cm^{-1}$ for generation of 430 nm light, so that, for example, *ca.* 3 mW of harmonic light would be generated with *ca.* 300 mW of pump and a 1 cm long crystal. Conversion efficiencies approaching this value have been achieved in practice with various lasers (see, for example, Busse 1993), including high-power diode lasers such as master oscillator power amplifier devices (MOPA) with *ca.* 1 W of infrared power in a diffraction-limited beam.

However, considerations of cost, and of overall energy efficiency, are a strong motivation for developing efficient harmonic generation schemes that can make use of lower power diode-laser devices. The two main approaches that have been followed are, either to use resonance enhancement of the fundamental intensity, by means of a Fabry–Perot resonator, or to use a waveguide configuration, thus allowing a smaller area for the fundamental mode, which, as indicated by equation (2.1), reduces the fundamental power required for a given efficiency.

The design principles for the enhancement of second-harmonic efficiency via a resonance cavity have been described by Ashkin (1966), and an extended discussion given by Koslovsky (1988). The principle involves placing the nonlinear crystal in a Fabry–Perot resonator, (preferably of a ring configuration, so that a single harmonic output beam is created), which resonates the fundamental wave and thus, as a result of the higher fundamental intensity incident on the nonlinear crystal, gives a higher conversion efficiency. Losses of the fundamental wave are of paramount importance for the effectiveness of this resonance-enhancement cavity. Ideally, the fundamental loss due to conversion to the second harmonic should dominate over losses from other causes. With low losses the resonator can have a high resonator Q, so that the resonated fundamental intensity can be greatly increased relative to the intensity incident on the resonator, hence allowing efficient conversion to the second harmonic. Using such an approach where the nonlinear medium $KNbO_3$ was used and fabricated as a monolithic element with polished and coated surfaces to provide a resonant ring path, Kozlovsky (1990) obtained an overall conversion efficiency of 40% from a 105 mW diode laser to 41 mW blue light at 428 nm. This result amply confirms the ability to produce a high SH conversion efficiency from a low-power diode. However, the scheme does involve considerable sophistication and complexity, which, in turn, have cost implications. Thus, the diode laser needs to be a single-frequency device, and some locking scheme is needed to maintain the diode-laser frequency in resonance with the enhancement-cavity mode frequency. Well established procedures for achieving this frequency locking exist; however, it remains a challenge to realize a very simple and cheap solution to the locking requirements. On the other hand, a concomitant benefit of the careful stabilization is that a low RIN is achieved. Kozlovsky (1990) reported a RIN value of -120 dB Hz^{-1} at 5 MHz, thus meeting the specification for typical optical memory reading applications.

While this frequency doubling in a monolithic $KNbO_3$ enhancement resonator has met the technical specification needed for the blue source, the $KNbO_3$ component, with its demanding manufacturing tolerances, is not compatible with a low-cost realization. An alternative approach has been to use a waveguide configuration in the second-harmonic crystal, thus allowing a high conversion efficiency to be achieved

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with low input power and yet without the use of resonance enhancement. The principle here is to use a small area A for the interaction region and yet to maintain a long interaction length. Whereas, in a bulk medium, diffraction places a limitation on the minimum area *ca.* $\ell\lambda$ to which the beam can be confined over a length ℓ, this restriction is lifted when the light is confined in a waveguide. Then, in principle, since a guide of dimensions equal to a few wavelengths is possible, an area of the interaction region of the order of a few λ^2 is possible, with an interaction length limited only by practical considerations such as the propagation loss of the guide, or the maximum length that the waveguide fabrication process permits. Even with guide lengths of only a few mm, the benefit in terms of reduced power requirement for a given conversion efficiency is considerable. This reduction in power requirement is given by the ratio $A_{\text{bulk}}/A_{\text{guide}} \sim \ell\lambda/(\text{few } \lambda^2)$, $\sim \ell/(\text{few } \lambda)$. Enhancement by two orders of magnitude is easily feasible, so that, in principle, conversion efficiency would go up from the *ca.* 3% $\text{W}^{-1}\,\text{cm}^{-1}$ quoted above for $KNbO_3$ to several 100% $\text{W}^{-1}\,\text{cm}^{-2}$ for a guide in a medium of the same nonlinearity. These figures imply several mW of harmonic power generated from *ca.* 100 mW of fundamental, even for a guide length of a few mm.

To achieve such numbers in practice it is first necessary to fabricate channel waveguides of high quality in a highly nonlinear material. While waveguides have been fabricated in $KNbO_3$ by ion-implantation (Fluck 1992), more attention has been directed to the use of $LiNbO_3$, a highly nonlinear material with a well-established waveguide fabrication technology, and to KTP, where waveguide fabrication has also been very successfully developed. In addition to the ability to make waveguides one must also have the ability to phase-match the second-harmonic generation process. $LiNbO_3$ as a bulk crystal does not have sufficient birefringence to allow phase-matched SHG to wavelengths in the blue spectral region. This limitation can, however, be overcome by a technique known as quasi-phase-matching.

In quasi-phase-matching the material structure is modified from the usual single-domain structure into a periodic-domain structure, where the domains are periodically reversed in polarity, i.e. in the case of $LiNbO_3$ (see figure 2) the z-axis is periodically reversed in direction. The fundamental light propagates perpendicular to the domain boundaries.

The idea of quasi-phase-matching was first proposed by Armstrong (1962) in a seminal paper on nonlinear optics. Briefly, the principle is as follows. In second-harmonic generation, if exact phase-matching is not possible, a phase mismatch will develop between the radiated second-harmonic wave and the nonlinear polarization wave in the medium. The length of crystal over which a phase mismatch of π is developed is known as the coherence length ℓ_c. The second-harmonic wave reaches a maximum intensity at this length into the medium and then over the next length ℓ_c the harmonic wave reconverts back to fundamental, resulting in zero second-harmonic power after $2\ell_c$. In fact, the second-harmonic power versus crystal length undergoes an oscillatory behaviour, returning to zero every length $2\ell_c$ (figure 2). If, however, after a length ℓ_c, the sign of the optical nonlinearity is reversed, then the second-harmonic wave and the polarization wave would be correctly phased relative to each other for continued growth of the second-harmonic power. By reversing the sign of the nonlinearity after every length ℓ_c, the correct phase relation for cumulative growth of harmonic power is achieved. This is referred to as quasi-phase-matching. With this technique, any fundamental–harmonic wavelengths within the transmission band of the medium can be quasi-phase-matched simply by choice of the correct domain reversal period,

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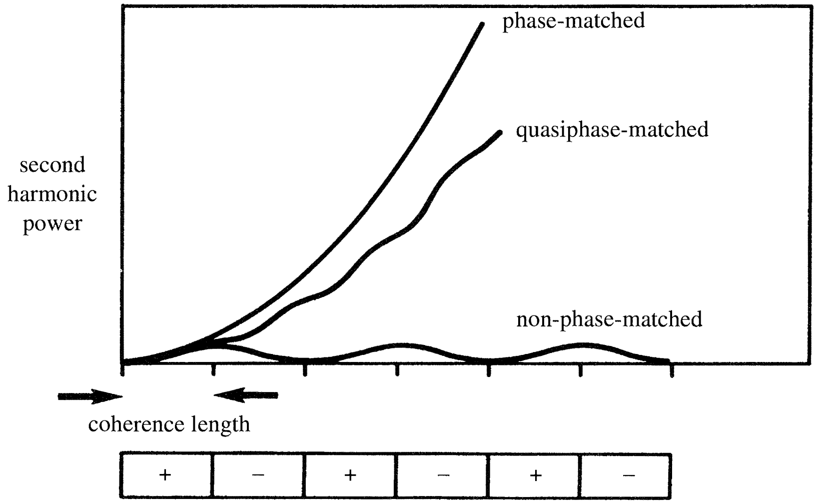

Figure 2. Quasi-phase-matching. The z-axis reverses direction after each successive coherence length ℓ_c through the nonlinear crystal. The figure shows schematically the domains with z-axis out of the page (+) and into the page (−). Second-harmonic power versus crystal length is shown for exactly phase-matched, quasi-phase-matched and non-phase-matched operation.

i.e. one period of the domain 'grating' is made equal to twice the coherence length for that process. Figure 2 shows the behaviour of second-harmonic power versus crystal length for the cases of perfect phase-matched, non-phase-matched and quasi-phase-matched situations. For the quasi-phase-matched case, in a medium of nonlinear coefficient d, where the period of the domain grating is $2\ell_c$, i.e. each domain width is ℓ_c, it can be shown that the second-harmonic efficiency is equivalent to that which would be achieved with perfect phase-matching in a medium of nonlinear coefficient $(2/\pi)d$. So, there is a reduction of $(2/\pi)$ in the effective nonlinear coefficient. However, in practice, this is more than offset by the fact that one can now access a larger nonlinear coefficient which would not normally be available for use in a conventional birefringence phase-matching geometry. There, typically, the fundamental and harmonic waves have orthogonal polarizations, in order to use the index difference of ordinary and extraordinary polarization to offset the index difference due to dispersion. As a consequence, one can only access the appropriate non-diagonal coefficient (d_{31} in the case of $LiNbO_3$). With quasi-phase-matching, the need for birefringence phase-matching is eliminated, and both harmonic and fundamental can have the same polarization, thus allowing access to the much larger diagonal nonlinear coefficient (d_{33} in $LiNbO_3$). The effective d coefficient is thus some three times larger in quasi-phase-matched $LiNbO_3$ compared to the coefficient used in birefringence phase-matching.

So, quasi-phase-matching provides a major enhancement of the utility of nonlinear media allowing access to large nonlinearity, and allowing phase-matching for any wavelengths within the transmission band, in particular for blue second-harmonic generation. Techniques for achieving periodic domain reversal have now been demonstrated in $LiNbO_3$ (Jundt 1991; Ito 1991; Webjörn 1989, 1994), $LiTaO_3$ (Åhlfeldt 1991; Mizuuchi 1992; Yamamoto 1992) and KTP (van der Poel 1990; Yamamoto 1994), each of which has a large nonlinearity and a transmission range which extends to the blue region. Each of these materials also has well-developed procedures for producing high-quality waveguides. A number of experiments have now been re-

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ported (see, for example, Mizuuchi 1992; Yamamoto 1992; Yamada 1993) in which blue light generation at powers of several mW has been achieved by quasi-phase-matched second-harmonic generation from diode lasers of *ca.* 100 mW output power. Conversion efficiencies in the region of many hundreds of % W^{-1} cm^{-2} have been demonstrated (Yamada 1993).

So, as with the resonance-enhancement technique, this approach allows generation of the required power levels from low-power diode lasers. In this scheme, the tolerance on diode-laser frequency stability is relaxed compared to the resonance-enhancement scheme, with typical acceptance bandwidth for the harmonic generation being of the order of *ca.* 0.07 nm cm for 850 nm doubling in $LiNbO_3$, $LiTaO_3$ and KTP (Bortz 1994). With frequency-tuning rates with temperature of *ca.* 0.3 nm °C for diode-lasers and temperature acceptance bandwidths of *ca.* 2 $°C^{-1}$ cm (Bortz 1994), it is clearly necessary to provide some means of maintaining frequency compatibility between the diode laser and the frequency doubler. Temperature controllers provide an obvious, but expensive, option. One approach (Shinozaki 1991; Risk 1993) has made use of Bragg reflection from the periodic domain grating (where the domain grating has an associated refractive index grating) to provide a feedback control of the diode-laser wavelength. Commonality of the feedback grating and quasi-phase-matching grating can relax the degree of temperature control needed. The development of simple and cheap means of maintaining the required wavelength matching remains an important challenge.

3. Upconversion lasers

Like second-harmonic generation, upconversion lasing provides a means of converting an input of ‘pump’ photons to an output of higher energy photons. There the similarity between the processes ends, and, in fact, the radical differences between them have a significant effect on their relative merits and demerits. We briefly consider these.

First, in the upconversion process there is no phase coherence between the pump light and the upconverted laser output. There is therefore no analogue to the phase-matching requirement. Considerable practical simplification results from this fact. Thus, the coherence requirements on the pump light are greatly relaxed, and there is no need for temperature control either of the laser medium or of the pump diode laser. On the other hand, this absence of phase coherence means that unlike harmonic generation, where a single-frequency fundamental input results in a single-frequency harmonic output, the output of the upconversion laser will not be single frequency unless measures are taken to deliberately select a single frequency. Optical memory applications typically call for RIN specifications that imply the need for single-frequency operation, so upconversion lasers need to address the non-trivial problem of single-frequency selection.

Another limitation of upconversion lasers is the slow response to amplitude modulation. Even though the pump light, if provided by a semiconductor laser can easily be directly current modulated at hundreds of MHz, the response of the upconversion laser is limited by the lifetime of the upper laser level. Typically, this will be in the region of tens of microseconds, so that modulation rates are restricted to tens of kHz, too low for most optical memory writing applications. Thus, an external modulator, with its implications of extra complexity and cost would be required—a significant disadvantage compared to schemes which can exploit direct modulation of a semiconductor laser.

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Against these disadvantages of upconversion lasers must be set their considerable advantages of simplicity and efficient operation at high power levels, particularly in the form of fibre lasers. The first upconversion laser was, in fact, in the form of a rare-earth-doped bulk crystal, the rare earth being the laser active ion, pumped by a pulsed flashlamp, and requiring liquid nitrogen cooling (Johnson 1971). Subsequent developments of bulk lasers have led to much easier operation, aided particularly by the use of laser pumping, and have now reached the point where blue lasing has been achieved at room temperature (Thrash 1992). Nevertheless, it has been in a fibre laser configuration that upconversion lasers have shown their most impressive results. In such a fibre laser, the core, with typical dimensions of a few μm diameter, is doped with laser-active rare-earth ions. The first of these upconversion fibre lasers demonstrated blue lasing at low temperature in a thulium-doped fluoride glass fibre (Allain 1990*a*), but was quickly followed by impressive results, at room temperature, from a holmium-doped ZBLAN (an acronym, based on the constituents zirconium, barium, lanthanum, aluminium and sodium) fibre (Allain 1990*b*). Subsequent demonstrations of efficient green and blue lasing have been made for a number of schemes based on rare-earth doped ZBLAN fibre (Smart 1991; Whitley 1991; Grubb 1992; Funk 1994).

The use of ZBLAN fibre, rather than the standard silica fibre as used in telecom applications, is based on the need for a material with a reduced phonon energy compared to that of silica. In upconversion lasing, it is important that the intermediate level(s) (see figure 1) and the upper laser level, should not have their lifetimes significantly shortened by non-radiative decay processes. Multiphonon emission is one such non-radiative process, by which the ion can drop from an excited electronic level across the energy gap to the next level below it, and so on downwards. The probability of such a decay process is strongly dependent on the number of phonons that need to be created to remove the energy corresponding to the energy gap—more phonons result in a lower rate. So, one strategy is to use energy level schemes where intermediate and upper laser levels are well spaced from levels below them. Another strategy is to use a host medium for which the maximum phonon energy is as low as possible. This has given prominence to fluoride glasses, of which ZBLAN is the most developed.

All the demonstrations of visible upconversion lasing in fibres have been made in fibres of ZBLAN or closely related compositions. This glass, and fibres made from it, were originally seen as having particular promise for ultra-low-loss fibres, lower in principle (although not, so far, in practice) than for silica, by virtue of the infrared absorption edge being shifted to longer wavelengths than for silica. The advent of the erbium-doped (silica) fibre amplifier removed this need for ultra-low-loss fibre. However, this original goal of low loss had pushed the state of development of ZBLAN fibre to the level where sufficiently high-quality fibre was available for very convincing demonstrations to be made of upconversion lasing.

Once the fibre losses are low enough, the benefit of a fibre geometry over a bulk geometry can be enormous, leading to a reduction in threshold power requirements of at least one or two orders of magnitude. The benefit of a waveguide (fibre) geometry, as discussed earlier in the context of second-harmonic generation, is that, compared with a bulk medium, a waveguide permits confinement of the pump beam to a much smaller area, of the order of a few times λ^2 compared with *ca.* $\ell\lambda$, where ℓ is the length of bulk medium required. The minimum useful value of ℓ is that required to ensure that substantially all of the pump light is absorbed. This will typically be not less than a few mm. Hence, the same pump intensity can be achieved in a guide with two or three orders of magnitude less power than for a bulk system. In addition, the pump confinement provided by the guide allows a considerable length of fibre to be used, limited ultimately by the propagation losses that can be tolerated. Typical fibre losses in ZBLAN fibre allow lengths of many m to be used without a serious penalty of losses. This freedom in a low-loss fibre geometry to use long lengths of medium means that low doping concentrations of the active ion can be used, so that ion–ion interactions can be suppressed, if so desired. Since some of the ion–ion energy transfer process may be deleterious to the upconversion process, this freedom gives fibres an advantage over bulk media, which are necessarily short and, hence, heavily doped.

To get an idea of the power requirements for an upconversion laser in a fibre geometry, one need only calculate the power required to achieve saturation of the pumping transition, i.e. the power required to take a significant fraction of the ground-state population to the intermediate level (figure 1). A similar power for the second step, from intermediate level to upper laser level, would then lead to a sizeable fraction of the ground-state population in the upper laser level, this being the basic requirement for a significant gain to be achieved. The saturation pump power is *ca.* $h\nu_{\mathrm{p}} \cdot A/\sigma_1\tau_{\mathrm{i}}$, where σ_1 is the absorption cross section for the first pumping step, τ_{i} is the lifetime of the intermediate level, ν_{p} is the pump frequency and A is the area of the doped fibre core. Typical values of these parameters for a rare-earth dopant in ZBLAN glass (where τ_{i} may be tens to hundreds of microseconds), and core areas, for monomode fibre, of *ca.* $10^{-11}\,\mathrm{m}^2$, lead to pump saturation powers of a few mW. This indicates that low-power diode pump sources would be able to pump an upconversion laser. These estimated figures are borne out in practice, with pump powers as low as *ca.* 10 mW sufficient to reach threshold.

Upconversion lasing in rare-earth-doped ZBLAN fibres has been demonstrated for the following rare earths: Tm, Ho, Pr, Er, Nd. We briefly review some of the most recent results achieved with Pr, and Tm, since these have both yielded diode-laser-pumped operation in the blue (480 nm) and blue–green (492 nm) regions.

The first observations of upconversion lasing in Pr:ZBLAN were made by Allain (1991), and Smart (1991). In the work of Smart (see also Tropper 1994), pumping was achieved using two pump wavelengths, at *ca.* 1020 nm and 835 nm, to achieve sequential excitation from the ground state, to the intermediate level $^1G_4$, and then to the upper laser level $^3P_0$ (see figure 3). Lasing was then observed at blue (491 nm), green (520 nm), orange (605 nm) and red (635 nm) wavelengths. This was the first demonstration of room-temperature operation of a blue upconversion laser. In the work of Allain (1991), a pumping scheme requiring only one pump source was demonstrated. In this case, the Pr-doped ZBLAN fibre contained Yb as a codopant. The pumping process involved Yb being pumped at *ca.* 835 nm, the Yb ion then transferring its energy to excite a Pr^{3+} ion, from the ground level to the $^1G_4$ intermediate level, from which a further absorption of a photon at the same pump wavelength then led to excitation of the upper laser level. The ability to achieve pumping with a single pump source (anywhere in the range 810–860 nm) represents a significant advantage, although in this first demonstration experiment it proved possible to achieve oscillation only on the red and not on the blue or green transitions.

Since these first demonstrations of lasing in Pr ZBLAN, steady progress has been made in further developing this laser due in large part to improvements in fibre fabrication. Reduction in fibre core diameter has been achieved by going to a larger numerical aperture, and fibre propagation losses have been reduced to levels of a

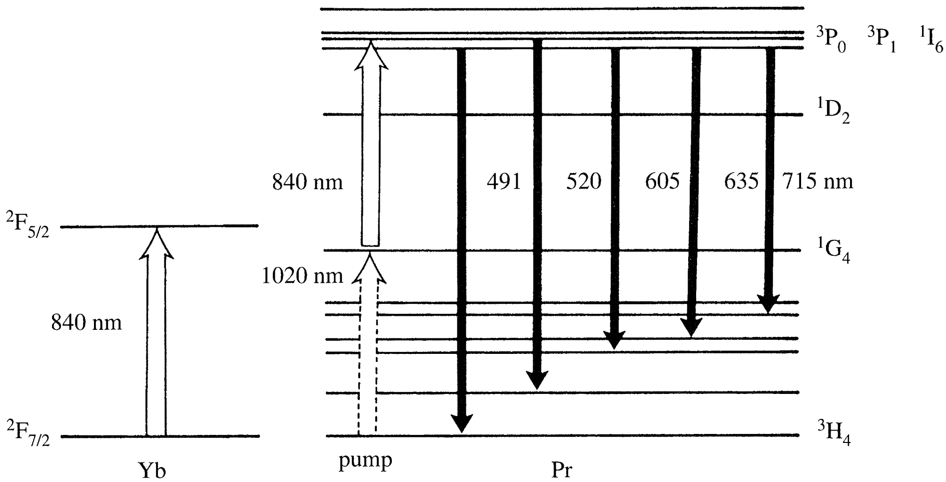

Figure 3. Energy level scheme of Pr upconversion laser. Pumping can either be achieved by sequential absorption of 1020 and 840 nm in Pr, or by absorption of 840 nm in Yb, followed by energy transfer from Yb to Pr ($^1G_4$) and then absorption of a further 840 nm photon in Pr.

few hundredths of a dB m^{-1}. A driving force behind these developments of ZBLAN fibre has been the effort aimed at optimizing the 1.3 μm Pr:ZBLAN fibre amplifier, for which level $^1G_4$ is the upper level of the amplifying 1.3 μm transition. Improved fibre, combined with improved pumping schemes, have now given greatly improved results. One approach, described by Pask (1994), involves a pumping scheme requiring a single initial pump source, based on the use of Yb-doped silica fibre, itself pumped at *ca.* 835 nm, and selected to lase at 1020 nm by way of a fibre Bragg grating. The Yb fibre output then consists of unabsorbed 835 and 1020 nm light, both of which are used to pump the Pr fibre. More recently, Xie (1995) has re-examined the Yb:Pr codoping scheme of Allain *et al.* (1991) and has been able to extend lasing to all of the visible transitions. This has been achieved with a single 100 mW diode laser as the pump source and power outputs of 2 mW at 490 nm, 10 mW at 635 nm have been reported. The efficiency of the blue emission is comparable to what has been achieved for frequency doubling of diode lasers. Other recent work on the Pr:ZBLAN system (Zhao & Fleming 1995; Zhao *et al.* 1995) includes the improvement of efficiency by arranging that the pump light is reflected back at the end of the fibre, thus achieving more efficient absorption in a shorter length of fibre. Performance levels include 30 mW of blue output with an overall conversion efficiency of 12%. There is much scope for further optimization, with the prospect of simple practical sources of a few to a few tens of mW of visible output being achievable from Pr:ZBLAN fibre using diode-laser pumping.

Another efficient upconversion scheme involves Tm:ZBLAN. It was shown by Grubb (1992) that a single pump wavelength (*ca.* 1123 nm was used) could efficiently pump the Tm ion to the $^1G_4$ level (see figure 4) in a three-step absorption process. Up-conversion lasing emission from $^1G_4$ at 480 nm was then obtained and, despite the three-step pumping process, the slope efficiency of this laser scheme has been in excess of 30%. Further studies of this laser scheme have indicated 1140 nm as the optimum pump wavelength (Barber 1994), and using as the pump source an Yb-doped silica fibre laser selected to operate at 1140 nm by a fibre Bragg grating, thresholds in the region of 10 mW have been demonstrated. This clearly indicates the scope for diode-laser pumping of this system. Diode-laser-pumped operation has now been

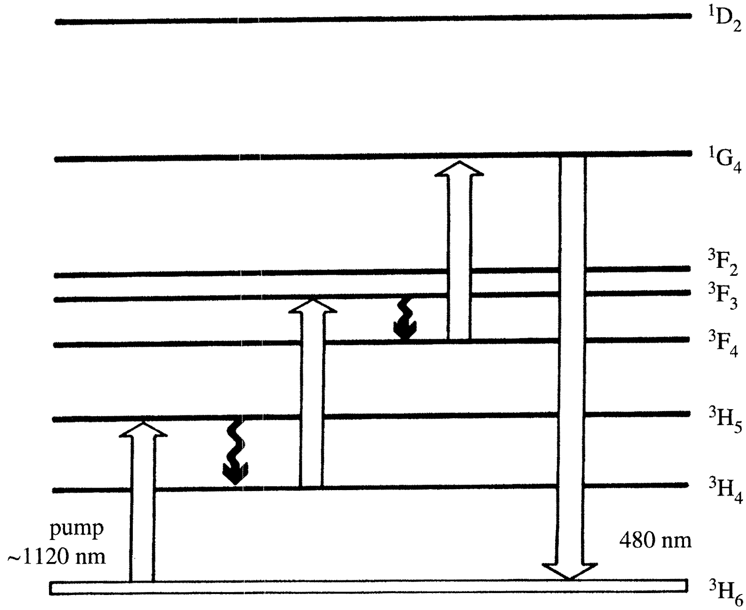

Figure 4. Energy level scheme for the 480 nm Tm upconversion laser. The three-step absorption can be achieved with three photons of the same wavelength, initially demonstrated for 1123 nm, but with 1140 nm later shown to be optimal.

reported by Sanders (1995). Two MOPA diode lasers were used, polarization-coupled into the Tm:ZBLAN fibre and producing over 100 mW of 480 nm output.

Thus, diode-pumped upconversion lasers are already able to demonstrate efficient blue operation at levels of tens of mW. Despite the fact that the guide is necessarily multimode at the visible wavelength, typically the output is found to be in the lowest order mode. Thus, the spatial quality of the output is excellent. Further work is needed to fully optimize these Pr and Tm systems, and work is now needed to address the issue of achieving single-frequency operation. It is also apparent in the Tm:ZBLAN system that there are deleterious absorption processes induced by the blue light which can cause a degradation of upconversion lasing performance. While these absorption processes appear to be reversible, it will be necessary to eliminate them if long-term reliable devices are to be realized. Progress to shorter wavelengths, already demonstrated in a Nd:ZBLAN fibre upconversion laser operating at 381 nm (Funk 1994), will be dependent on progress towards a better understanding and then elimination of these light-induced absorption changes.

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