Compact blue laser devices

By William P. Risk

For the first several years of its existence, the laser was said to be a solution in search of a problem. Now, three decades after the demonstration of the first laser, practical applications are driving the development of new types of lasers. Several applications of current interest require compact sources of blue or green light. Optical data storage (where the short wavelength provides high storage density), undersea communications (where the blue light passes more easily through seawater), and large-screen displays (where blue and green are needed to make a full-color display) are a few examples of applications for which the development of small blue laser devices is considered important.

Blue lasers powerful enough to be useful for these applications—such as argon-ion lasers—are unsuitable because of their large size and large consumption of electrical power or cooling water. Semiconductor diode lasers, on the other hand, are very small and very efficient, but so far have been limited to near-infrared and, more recently, red wavelengths. A blue semiconductor diode laser has been sought for many years, but the fabrication of *p-n* junctions in semiconductor materials capable of emitting blue light has proven to be a very difficult technical challenge.

While progress has been made, a practical blue laser diode suitable for the applications mentioned above is probably many years away. On the other hand, remarkable advances in laser diode technology have yielded new sources of radiation at wavelengths from 630 to 1100 nm that can be "upconverted" using nonlinear optical techniques to produce light in the violet-to-green spectral range.

Two approaches have been investigated for upconversion of infrared laser diodes. In the first approach, a crystal having nonlinear optical susceptibility is used to produce light at half the wavelength (twice the frequency) of an infrared diode laser or diode-pumped solid-state laser through the process of second-harmonic generation (SHG). As shown in Fig. 1(a), the infrared light from a diode-laser is focused into the nonlinear crystal, and some fraction of the infrared photons are converted to blue ones. The fraction converted depends on the inherent nonlinearity of the particular crystal used, and on the intensity of the infrared beam. It also depends on whether or not the interaction is cumulative over the entire length of the crystal, a condition known as "phasematching."

Phasematching is obtained when the infrared beam and second-harmonic beam travel at the same speed in the crystal. In most materials, blue light travels more slowly than infrared light due to dispersion. The usual technique for obtaining phasematching is to use a birefringent crystal in which the speed of a lightwave depends on its polarization. By arranging for the infrared light to have the polarization that travels more slowly and the blue light to have the polarization that travels more rapidly, the speeds of the infrared and blue waves can be equalized.

Establishing this condition for a particular wavelength of interest generally requires adjusting the crystal temperature or properly choosing the direction of propagation of the light through the crystal. Much of the challenge of applying this approach to the development of miniature blue lasers has been finding suitable combinations of lasers and nonlinear materials so that phasematching can be obtained. Furthermore, a practical nonlinear material must provide phasematching that is reasonably insensitive to deviations in temperature, direction of propagation, and wavelength.

The other approach that has been investigated does not use nonlinear crystals, but instead relies on nonlinear pumping of blue/green solid-state lasers. As shown in Fig. 1(b), certain solid-state laser systems have blue/green laser transitions that can be excited using infrared pump photons. The figure shows the energy level diagram for a laser ion excited by sequential absorption of two pump photons, although it is also possible to excite the laser transition by energy transfer processes involving two laser ions. This approach to blue light generation has developed more slowly, but a number of systems producing violet,

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blue, or green light from longer wavelength pump sources have recently been demonstrated.

So far, most of the effort toward developing compact blue laser devices has concentrated on approaches using the nonlinear properties of crystals. These approaches fall into two categories: frequency doubling of diode-pumped solid-state lasers and direct frequency doubling of semiconductor diode lasers. A third approach, frequency mixing of diode lasers and diode-pumped solid-state lasers[1] has also been explored, but will not be discussed here. Some of the results obtained with these schemes are discussed below. While upconversion lasers using nonlinear pumping have been limited mainly to low-temperature operation, efficient conversion of infrared diode laser light to green light has recently been demonstrated and will also be discussed below.

Upconversion of diode-pumped solid-state lasers

GaAlAs laser diodes with spatial and spectral mode properties suitable for efficient direct frequency doubling have only recently become available at power levels exceeding a few tens of milliwatts. High-power GaAlAs laser diode arrays, with powers of several hundred milliwatts, have been available for several years, and the output powers have steadily increased since their introduction in the early 1980s. In general, these high-power devices have a multimode spectrum and irregular spatial modes that prohibit their use for direct frequency doubling. However, they make excellent pump sources for solid-state lasers such as Nd:YAG or Nd:YLF. The radiation from such GaAlAs lasers can be efficiently absorbed by the laser crystal despite a multimode spectrum, and while the irregular spatial distribution of the beam is unsuitable for SHG, the beam can be focused to a spot small enough for efficient pumping of the TEM_{00} mode of the solid-state laser. The solid-state laser can then be upconverted using frequency doubling or sum-frequency mixing, with the nonlinear crystal placed inside the laser cavity to take advantage of the high intensity of the intracavity laser field. The process of pumping the solid-state laser acts like a "mode converter" to transform the poor spatial mode and multimode spectrum of the diode laser, which cannot be efficiently upconverted directly, to the TEM_{00} spatial mode and narrowband spectrum of the solid-state laser, which can be upconverted efficiently.

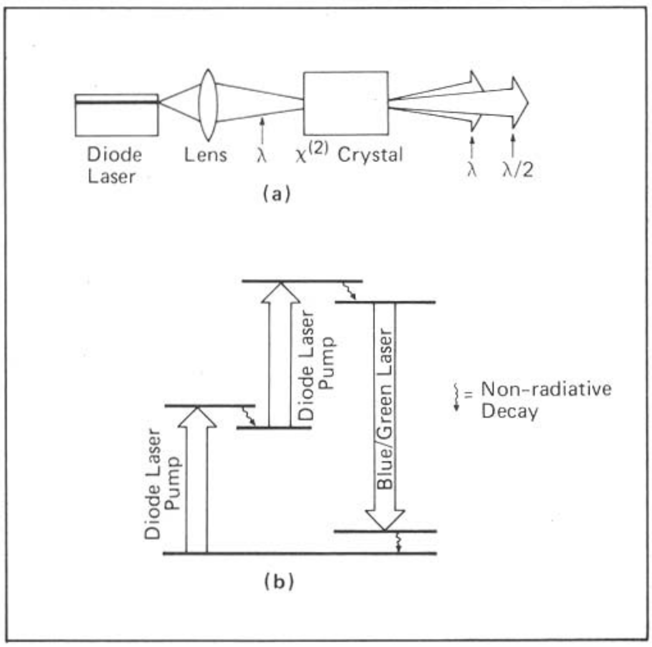

FIGURE 1. Techniques for making compact blue laser devices: (a) direct frequency doubling of a diode laser or diode-pumped solid-state laser using a crystal having a second-order (χ^2) nonlinear susceptibility; (b) nonlinear pumping of a blue/green laser transition by sequential absorption of two pump photons.

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Generation of green 532-nm light by intracavity frequency doubling of a diode-pumped 1064-nm Nd:YAG laser is well-known.[2] Blue light at 473 nm can also be generated from diode-pumped Nd:YAG, using frequency doubling of the 946-nm laser transition. Operation of a laser at this wavelength is more difficult than at 1064 nm, due to the lower gain-cross-section of the laser transition, and the reabsorption of the 946-nm photons by the Nd:YAG crystal. These two effects cause the pump power required to reach the lasing threshold to be higher for a 946-nm than for a 1064-nm Nd:YAG laser. However, once above threshold, the efficiencies can be comparable.

Potassium niobate can be used for frequency doubling the 946-nm Nd:YAG laser. To achieve phasematching for this wavelength, the crystal must either be heated to approximately 185°C[3] for propagation along the a-axis of the crystal, or the crystal must be cut with a particular orientation to permit frequency doubling at room temperature.[4]

The arrangement in Fig. 2 was used to generate approximately 9 mW of 473 nm light by frequency doubling of a diode-pumped 946-nm Nd:YAG laser.[4] The beam from a 0.5-W diode laser was collimated and passed through a cylindrical lens to reduce the astigmatism and ellipticity of the beam and focused into the Nd:YAG laser crystal. One cavity mirror was deposited directly on the flat end of the Nd:YAG laser crystal; a separate mirror with 5-cm radius-of-curvature was used to form the near-hemispherical cavity. A $KNbO_3$ crystal, cut at the appropriate angle to permit phasematched SHG at room temperature, was placed inside the laser cavity in proximity to the Nd:YAG crystal.

The performance of this laser is particularly sensitive to the length of the Nd:YAG laser crystal. Normally, for instance in a 1064-nm laser, it is desirable to make this crystal long in order to absorb most of the pump light. In this case, however, the Nd:YAG crystal reabsorbs a significant fraction of the 946-nm photons it emits, and the greater the length of the rod, the greater the loss due to this reabsorption. Hence, there is an optimum length that is a compromise between increasing the absorption of the pump and decreasing the reabsorption loss. A Nd:YAG crystal of a particular length will give the maximum blue output. As an example, in the experimental configuration of Fig. 2, changing the length of the Nd:YAG crystal from 1 mm to 1.5 mm increased the output power at 473 nm from 3 mW to 9 mW. The output blue beam had essentially a TEM_{00} Gaussian profile.

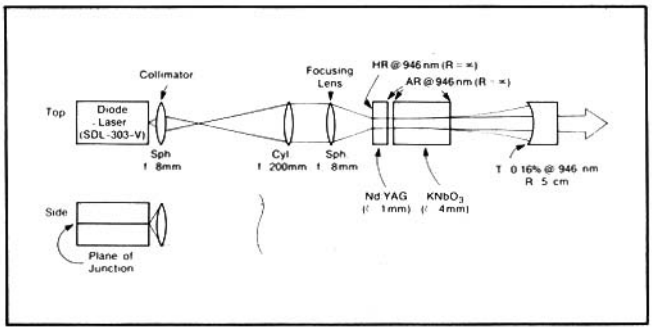

FIGURE 2. Experimental configuration for generation of 473 nm light by intracavity frequency doubling of a diode-pumped 946-nm Nd:YAG laser.

One potential advantage of upconversion of diode-pumped solid-state lasers lies in the possibility of scaling to higher powers. Direct frequency doubling requires the diode lasers to have very good spatial and spectral mode properties, and there is a practical limit to how much power such a device can generate while maintaining these properties. With diode-pumping of a solid-state laser, the considerations are somewhat relaxed since the mode properties of the pump laser are less of a constraint. In addition, a greater variety of device configurations can be considered to take advantage of the higher power pumps available[5] than is possible in direct doubling.

Direct frequency doubling of diode lasers

The most attractive use of nonlinear crystals for upconversion of laser diodes is for direct frequency doubling as shown in Fig. 1(a). Unfortunately, even with the best frequency doubling crystals and laser diodes available today, only a very small fraction of the infrared power would be converted to the blue (roughly 0.1–1%) in a single-pass of the infrared light through the nonlinear crystal. Although it has been investigated experimentally, this single-pass approach has, at best, produced blue powers on the order of 1 milliwatt. Much of the recent work in direct doubling of diode lasers has therefore concentrated on finding ways of enhancing the conversion efficiency to yield higher powers.

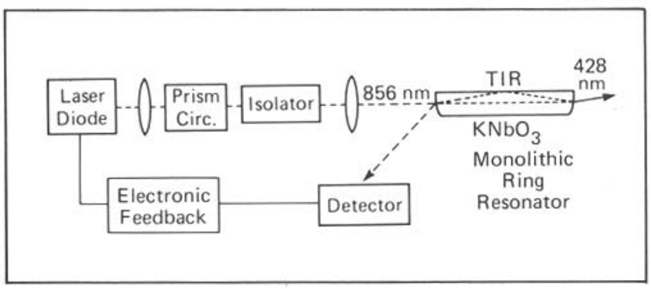

FIGURE 3. Experimental configuration for generation of 430 nm light by direct frequency doubling of a GaAlAs laser diode using a monolithic ring resonator for efficiency enhancement.

One method for improving the conversion efficiency is to build up the infrared power inside an optical resonator (Fig. 3). If the frequency of the incident light coincides with one of the resonant frequencies of the cavity, the circulating power level inside the resonator can build up to a level many tens of times larger than the incident power. Since the second-harmonic power increases as the square of the infrared power, tremendous increases in the blue output power can be achieved by placing the nonlinear crystal inside the resonator. However, to obtain such improvements in the conversion efficiency, the laser diode providing the infrared light must have a single-frequency spectrum and good spatial mode properties to permit efficient excitation of the resonant mode of the passive cavity.

GaAlAs laser diodes with good spatial and spectral mode properties at powers in excess of 100 mW have been developed only recently. Several research groups [6–9] have demonstrated frequency doubling of these lasers using potassium niobate as the SHG crystal. Phasematched frequency doubling of 860 nm light is obtained at room temperature for propagation along with the crystalographic a-axis. Goldberg and Chun[7] have recently reported generation of 24 mW at 420 nm by frequency doubling of a 167 mW diode-laser source. In their experiments, the frequency of the diode laser was scanned across the resonance of the passive nonlinear resonator, producing pulse of blue out-put power.

Making a source with a continuous-wave (cw) output requires that the frequency of the diode laser be locked to the resonant frequency of the passive nonlinear cavity. Kozlovsky and Lenth[8] have reported generation of 40 mW of 430 nm light using an active electronic feedback technique to lock a 140 mW, 860 nm diode laser to a monolithic potassium niobate ring resonator (Fig. 3). Rather than using electronic methods to lock the diode laser to the cavity, optical feedback can be used to lock the frequency of the diode laser to that of the passive nonlinear resonator. Dixon *et al.*[9] have recently reported generation of 0.2 mW of 430 nm light with the 12 mW diode laser locked to the nonlinear cavity through optical feedback.

The combination of GaAlAs laser diodes and $KNbO_3$ doubling crystals is one that has evolved because of the maturity of GaAlAs laser diode technology and because $KNbO_3$ is one of the few SHG materials that can be phasematched for efficient frequency doubling of GaAlAs laser wavelengths. Now, however, advances in diode laser technology are producing sources with wavelengths throughout the 900 to 1100 nm range, making possible the use of other interesting nonlinear materials.

For example, the nonlinear material potassium titanyl phosphate ($KTiOPO_4$, KTP) has been used for frequency doubling of 1064 nm Nd:YAG lasers[10] and for generation of 459 nm blue radiation by frequency mixing of 809 nm and 1064 nm lasers[1], and is known from these experiments to have attractive phasematching properties. However, the shortest wavelength that can be frequency-doubled in KTP is 994 nm, which is outside the wavelength range of GaAlAs lasers. Special strained-layer InGaAs diode lasers emitting 994-nm radiation have recently been frequency doubled in KTP to produce blue-green light at 497 nm, and characterization of the process with a tunable dye laser showed that it has broad tolerances for deviations in temperature, angle, and wavelength from the ideal phasematching conditions.[11]

For instance, Fig. 4 shows how the 497-nm output power changes as the temperature of the crystal is changed. Unlike $KNbO_3$, where the temperature must be controlled to a fraction of a degree, with KTP the temperature may vary over an extraordinarily large range before phasematching is degraded. Hence, combining strained-layer InGaAs lasers with KTP, or other nonlinear materials, may make it possible to generate blue/green wavelengths unaccessible with GaAlAs lasers, with possible practical advantages over the combination of GaAlAs lasers and $KNbO_3$.

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Finally, the development of waveguide frequency doubling techniques for direct upconversion of laser diodes should be mentioned. Waveguide devices have the potential advantage of very high efficiency, since the interacting waves can be confined to a small area over a long distance. In addition, dispersion mechanisms present in a waveguide can permit SHG to take place at wavelengths not possible in bulk material. Small size and potential integration with other devices are further motivations for development of waveguide frequency doublers.

Although a practical waveguide technology for efficient

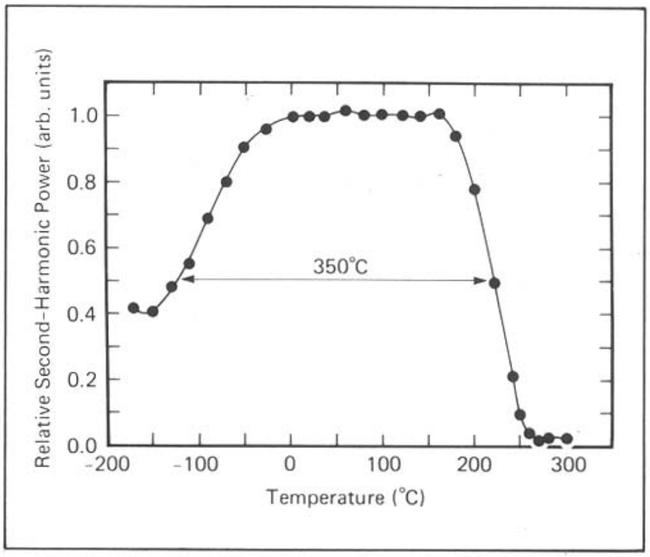

FIGURE 4. Variation of 497-nm power generated by frequency doubling of strained-layer InGaAs laser diodes in KTP as a function of the temperature of the KTP crystal.

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upconversion of diode lasers has not been identified, a number of approaches are being investigated experimentally. Waveguides fabricated in lithium niobate by titanium indiffusion or proton exchange have been extensively developed for communications applications and are now being investigated for upconversion of diode lasers. Bulk $LiNbO_3$ lacks sufficient birefringence to permit phasematched SHG of blue light. However, in a waveguide, phasematching to radiation modes ("Cerenkov doubling") makes generation of blue light possible.[12] Periodic inversion of the ferroelectric domain structure of $LiNbO_3$ can be used for "quasi-phasematching," and this approach has permitted generation of blue light in a guided mode of the waveguide.[13] Fabrication of waveguides in KTP has also recently been reported[14], and preliminary frequency doubling experiments have been conducted.[15,16]

Nonlinearly-pumped blue/green lasers

Rather than building infrared lasers and using the process of second-harmonic generation to convert infrared photons to blue ones, one can seek solid-state laser materials with strong laser transitions in the blue and green regions of the spectrum. However, traditional pumping schemes for such lasers require the pump photons to have higher energy, and therefore shorter wavelength, than the laser photons. It is possible, in some cases, to find solid-state lasers that can be pumped by photons with lower energies than the emitted laser photons. For example, absorption of one pump photon may excite the laser ion to a long-lived intermediate state, from which absorption of a second pump photon can excite the upper laser level [Fig. 1(b)]. Alternatively, two ions that have been excited to the intermediate state may cooperate in an energy transfer process in which one ion gives up its energy to the other and returns to the ground state, while the other ion is excited to the upper laser level.

Several rare-earth laser ions doped into crystalline hosts have been examined as candidates for the kinds of pumping schemes described above. In particular, erbium doped into the host crystals $YLiF_4$ and $YAlO_3$[17] has been investigated for lasing around 550 nm. Pumping of the green laser with infrared lasers in the 790 to 860 nm range is possible using both two-step absorption and energy transfer schemes. Neodymium ions in the host crystals LaF_3 and $YLiF_4$ have been examined for blue emission, pumped by one infrared laser and one yellow laser, or by one yellow laser alone.[18] Thulium ions in $YLiF_4$ have recently been explored for lasing at 450 nm by pumping with one red laser and one infrared laser.[19] All of the lasers examined so far work best at cryogenic temperatures. Room temperature operation would be highly desirable for most applications, and has recently been demonstrated for the Tm:$YLiF_4$ laser.[20] The mechanisms that degrade the performance of the laser at higher temperature are under investigation.

Green erbium lasers are good candidates for diode-pumping since they have strong absorption lines in the GaAlAs diode laser wavelength range. The Er:$YLiF_4$ laser has been pumped using a high-power multimode laser diode at 792 nm,[21] where the relatively broad absorption line is compatible with the broad spectral output of the diode laser. However, the absorption of the laser diode was still relatively weak, and only 100 μW of output power at 550 nm was obtained. The temperature of best operation was 40 K. Pumping on the stronger, but much narrower, 802-nm absorption line requires a single-frequency pump source.

Figure 6 shows that an output power of 2.3 mW was obtained with 95 mW of pump power from a single-frequency GaAlAs laser diode, using the experimental configuration of Fig. 5.[22] The performance of this laser when pumped by the laser diode is essentially indistinguishable from that obtained pumping with a dye or titanium:sapphire laser, indicating that no limitation on laser performance is introduced as a result of the spatial or spectral mode properties of the diode laser.

Future directions

Developing compact blue lasers has depended on finding combinations of lasers and nonlinear materials compatible for upconversion and on finding configurations that permit an efficient interaction. So far, the lasers available have been limited to GaAlAs laser diodes at wavelengths in the 700 to 900 nm range and to solid-state lasers that could be pumped by these laser diodes. Now, this spectral range is being extended as strained-layer InGaAs lasers are being developed in the 900 to 1100 nm range for direct frequency doubling and for pumping new solid-state lasers. Red AlGaInP lasers are becoming available that may extend the spectrum of available lasers down to 630 nm.

New nonlinear materials continue to be developed. KTA, in which the phosphorus in KTP is replaced by arsenic, has higher nonlinear coefficients than KTP and many of the same broad phasematching tolerances. Periodically-poled $LiNbO_3$ offers new possibilities for phasematching interactions. Organic materials continue to be explored because of their large nonlinear coefficients. The use of waveguides for efficiency enhancement, especially in nonlinear materials like KTP and $LiNbO_3$, is being actively explored and appears to offer interesting options for the development of very small blue light sources. Nonlinearly-pumped lasers continue to be investigated for better understanding of the physics of upconversion laser operation and for discovery of new lasers, with particular attention to the possibilities of diode-pumping and room temperature operation.

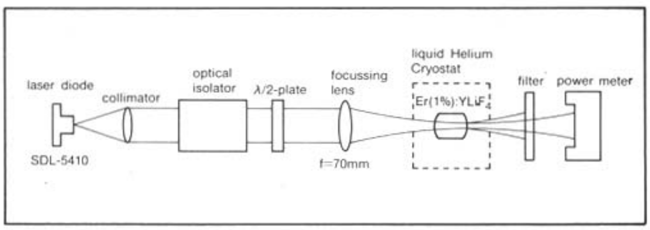

FIGURE 5. Experimental configuration for generation of 550-nm light by diode-pumping of an Er:YLiF$_4$ upconversion laser.

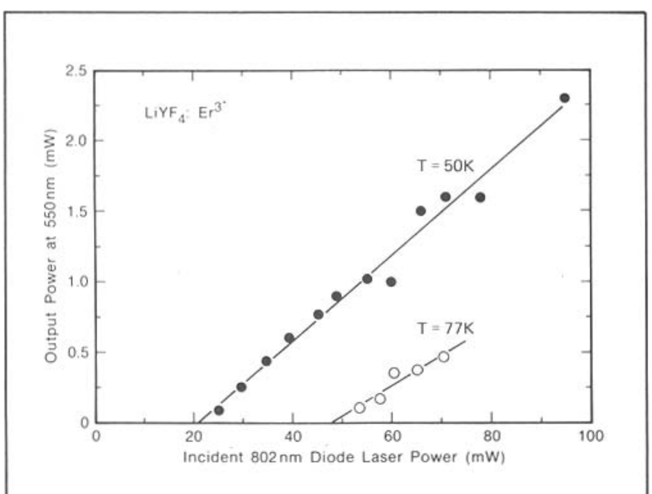

FIGURE 6. Green output power vs. incident pump power for the Er:YLiF$_4$ laser.

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