New Folder Name Intro to Lasers

TECHNICAL
INFORMATION

LIGO-~~P960020~~-00-D
T930014

№ 1

Introduction to Diode-Pumped Solid-State Lasers

LIGHTWAVE Electronics Corp.
1161 San Antonio Road,
Mountain View, CA 94043

Introduction to Diode-Pumped Solid-State Lasers

The availability of powerful diode lasers with wavelengths suitable for pumping solid-state laser materials has made possible the realization of all-solid-state lasers. These devices provide stable output with long lifetime, high efficiency, ease of operation, reliability and robustness in compact packages. This is made possible by the long lifetime and inherent stability of the diode lasers and laser crystals. However this presents a challenge to the laser engineer: the development of a laser system design that fully capitalizes on the reliability of the components. The products developed by LIGHTWAVE Electronics provide examples of the innovative designs that are required to fully realize the reliability and utility of diode-pumped lasers. These products cover the full range of laser types: ultralow noise cw lasers; short pulse, high repetition rate Q-switched lasers; and ultrashort pulse mode-locked lasers.

The Advantages of Diode-Pumped Solid-State Lasers

Lasers based on solid-state materials have a distinct advantage over those based on liquids or gases, since the lasing medium has an inherent robustness and essentially infinite operational life. However, this property is far from fully exploited in conventional solid-state lasers that are based on laser rods pumped by flashlamps or arc lamps. These pump sources have operational lives of only a few hundred to a couple thousand hours at best. The durability of a solid-state laser material comes much closer to being fully utilized when it is combined with semiconductor diode pump sources, which have lifetimes of tens of thousands of hours. The availability of these pump sources is having a tremendous impact on the evolution of solid-state lasers. The benefits of this pumping approach have resulted in the development of new lasers that were previously impossible or impractical to realize with lamp pumping.

Solid-state lasers

The lasing medium of a solid-state laser is a crystal or glass host material containing a small fraction of active ions that have suitable properties for laser action. By far the most commonly used solid-state laser material is Neodymium-doped yttrium aluminum garnet, $Y_3Al_5O_{12}$, (Nd:YAG). This material has a unique combination of optical, thermal, and mechanical properties that are favorable for laser operation. It has a number of emission lines, with the primary one at 1064 nm. Another strong line at 1319 nm is well-matched to the minimum dispersion wavelength of silica optical fibers. Efficient laser performance of Nd^{3+} is also obtained in many other host crystals. A common choice for diode-pumped lasers is yttrium lithium fluoride ($YLiF_4$, or YLF), which has a higher energy storage capability than Nd:YAG, allowing higher peak powers to be achieved from pulsed lasers. The advantageous physical properties of YAG make it a commonly used host crystal for other ions, such as Tm^{3+} which yields an "eye-safe" wavelength at ~ 2000 nm. There are many other options for both lasing ion and laser host material, resulting in a myriad of solid-state materials in which laser operation can be obtained.

Solid-state laser materials are capable of every type of laser operation: in addition to continuous output (cw), the energy storage capability of these materials permits short pulse (nanosecond) and ultrashort pulse (pico- and femtosecond) operation using Q-switching and mode-locking respectively. One drawback to solid-state materials is that their emission generally is confined to the near infrared so they do not directly produce visible output. However, nonlinear frequency conversion in solid-state materials can be used to generate visible wavelengths.

Diode laser pump sources

Semiconductor diode lasers are small, highly efficient sources of narrowband light, with lifetimes of tens of thousands of hours. Tiny, single-spatial-mode diode lasers, with output powers of just a few milliwatts, are utilized as the optical source in compact disk players. By combining many tiny diode emitters in a single device to obtain a wider emitting aperture, much higher output powers can be achieved with this technology (Fig. 1). Diode laser arrays with high output powers that are capable of pumping solid-state lasers are produced commercially by a number of companies. Continuous output devices with up to 20 watts of power from a 1 cm long stripe, as well as quasi-cw pulsed devices with outputs of up to 100 W of peak power per diode stripe are available. (The quasi-cw devices typically are limited to pulse lengths of < 500 µsec and repetition rates < 1 kHz.) Even these high power devices are compact: they occupy no more than a few cubic centimeters when mounted on simple heat spreaders. The quasi-cw diodes can be stacked to obtain two-dimensional arrays with peak powers at the kilowatt level. The long stripe length of these high power devices makes them more difficult to use. Most commercial diode-pumped lasers utilize high brightness pump diodes that emit as much as a few watts from apertures a few hundred microns long.

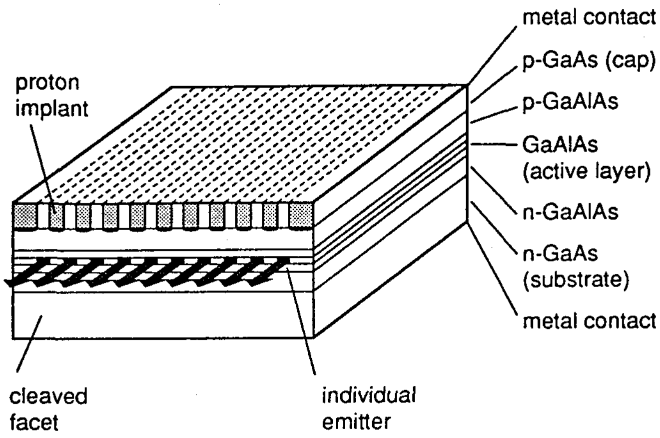

Fig. 1. The structure of a high power multi-stripe diode laser array. The layers on either side of the active layer act as cladding to confine the light in the laser mode.

Diode lasers have good electrical to optical conversion efficiency, typically around 25 – 50%. The output power as a function of current for a typical 1 watt diode laser is shown in Fig. 2.

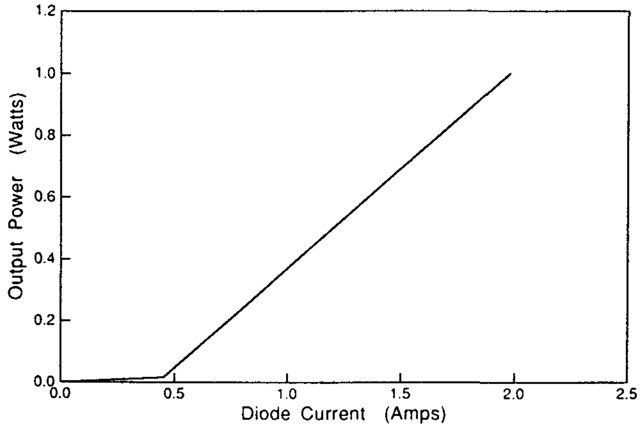

Fig. 2. Output power from a 1 watt multi-stripe diode laser array as a function of current.

Depending on the type of semiconductor material, various wavelengths can be achieved. The most common and highest power devices are based on GaAlAs; these emit over the 780 – 860 nm range. Longer wavelengths are available with InGaAs devices (910 – 980 nm) and AlGaInP diode lasers cover the red end of the visible spectrum (670 – 690 nm). While a given diode with a particular semiconductor composition will emit at one specific wavelength, variation of its operating temperature allows the wavelength to be tuned by ~0.3 nm/°C (GaAlAs).

The lifetime of diode lasers depends strongly on the operating conditions. To obtain long lifetime they typically are operated at 25–50% of the instant catastrophic failure power at which level they burn-out immediately. Lowering the operating current (i.e. output power) will extend the lifetime, as will reducing the diode temperature. The lifetime is a strong function of both of these parameters. It varies roughly as (Output Power)$^{-2.5}$ for fixed diode junction temperature, so that the lifetime doubles for a 25% decrease in output power. The lifetime increases exponentially as the temperature is reduced, with about a factor of two gain in lifetime for a 10°C decrease in temperature. Appropriate selection of the operating conditions will achieve extended lifetimes of tens of thousands of hours.

There are a few drawbacks to diode lasers. Typical diodes have an emission aperture that is ~1 μm high and hundreds of microns wide, with beam divergence angles of ~40° × 10° (FWHM). So the beam is close to diffraction-limited in one dimension, but more than a hundred times diffraction-limited in the other dimension. It is a challenge to collect and effectively utilize this rapidly divergent, asymmetric emission pattern. While diode lasers are very reliable under normal operating conditions, like many other semiconductor devices they are susceptible to damage from electro-static discharge (ESD) or voltage transients. Thus they must be handled carefully and electrically isolated. Also, these devices are not inexpensive, costing hundreds to thousands of dollars per watt of cw output power. However the expectation is that the cost of these devices will continue to fall as production volumes increase, as has been the case for other semiconductor devices such as computer chips. In particular, the advantages of diode-pumped lasers are expected to open up new laser applications leading to increased demand.

Diode laser pumping

Replacing the flash or arc lamp pump source of a conventional solid-state laser with a diode laser pump source has two main advantages. Firstly, the diode laser lifetime (tens of thousands of hours) is much greater than the lifetime of the discharge lamps (a few hundred to a couple of thousand hours). Extending the lifetime of the pump source by a factor of ten or more contributes greatly to the reliability and operational convenience of a laser, leading to reduced down-time and maintenance costs. For lasers that see modest use, say in a laboratory environment, the operational lifetime of the diode laser pumps may now exceed the anticipated useful life of the laser, i.e. the laser may be superseded by improved technology before the pump source dies. Probably the main area that benefits from the increased source lifetime are applications requiring "work horse" lasers that must operate daily or even continuously without interruption on a long term basis. In these applications down-time due to laser failure is essentially eliminated since the diode pump source will need to be replaced at most once every few years. This cuts maintenance costs and allows applications to be developed that would not be feasible with lamp-pumped or gas lasers.

The second major advantage of diode pumping is the increased efficiency of the laser. Gas discharge pump sources have broadband emission, which has poor overlap with the discrete absorption bands of the dopant ion in the crystal. As a result about 90% of the lamp pump energy does not contribute to laser operation (Fig. 3). In contrast, diode laser pump sources are narrowband and can be temperature tuned to allow their emission wavelength to coincide with the absorption band of a particular crystal. This results in highly efficient utilization of the pump energy. At LIGHTWAVE a cw Nd:YAG laser with an optical conversion efficiency of 60% has been demonstrated. Conveniently, the 808 nm absorption band of Nd:YAG falls in the wavelength range of GaAlAs diodes which are the best developed. In many cases the efficiency itself may not be an issue, given the low cost of electricity; however in some cases, such as operation in remote locations, or in aircraft and spacecraft (including satellites) electrical supply is at a premium. Even if the efficiency as such is not a major concern, the higher efficiency has other major benefits. The more complete utilization of the pump energy decreases detrimental thermo-optic effects (thermal lensing, thermal birefringence) that arise due to the deposition of excess heat in the crystal. This in turn results in improved beam quality and allows higher pulse repetition rates to be achieved. Also, improving the efficiency reduces the cooling system requirements. This allows moderate output powers to be attained without the need for any water cooling system as is required in lamp-pumped systems: passive conductive cooling to a heat sink or forced air cooling is sufficient. Another benefit of the higher efficiency is that the size of the power supply can be much reduced.

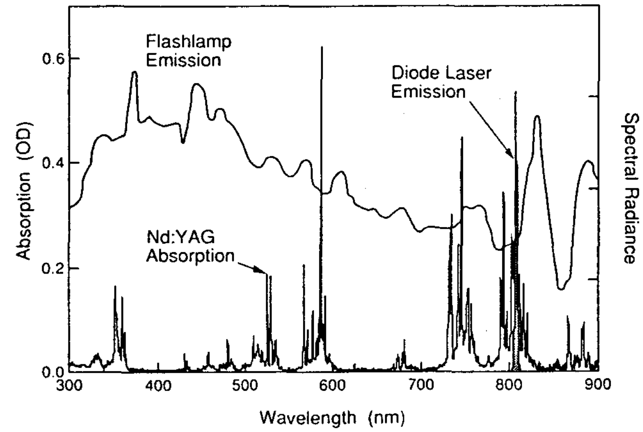

Fig. 3. Nd:YAG absorption spectrum compared with flashlamp and diode laser emission spectra.

Another major advantage of diode pumping is that these lasers can be quite compact, as a result of the small size of the diode pump sources and the high energy storage capacity of solid-state laser materials. This allows miniaturization of solid-state lasers that previously was not possible. Diode pumping has other benefits. Since the diodes are powered by low DC voltages, high voltages are eliminated, making the system safer and more efficient. In addition, diode-pumped lasers typically have lower noise due to the stability of the pump diodes, and can achieve shorter output pulses (especially at higher repetition rates) due to the shorter cavity lengths, than lamp-pumped lasers.

Diode-pumped lasers can be categorized as either side-pumped or end-pumped devices, as shown schematically in Fig. 4. In side-pumped designs the pump diode output is close coupled into the laser mode volume through the sides of the laser crystal with minimal or no additional optics, analogous to lamp-pumped lasers. This approach offers simplicity by eliminating coupling optics and allows high pump powers to be achieved since multiple diode pumps can be incorporated easily. However, these lasers have lower conversion efficiency (typically ~ 10%) due to the poor overlap between the pumped volume and the laser mode. End-pumped lasers use appropriate optics to collect and focus the diode light into the laser crystal so as to pump only the mode volume of the laser. They attain higher efficiency (typically ~ 30%) due to the improved pump absorption, the excellent overlap between the pump volume and the laser mode, and the higher pump densities. By ensuring that the pump volume is contained within the TEM_{00} laser mode, a TEM_{00} output beam is produced. So far, all LIGHTWAVE products have utilized the end-pumped configuration since its advantages make it a superior approach for most low and moderate power lasers.

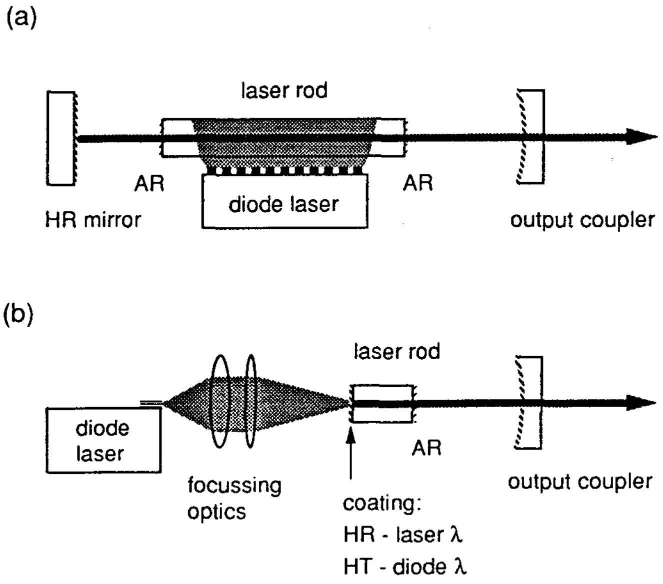

Fig. 4. The basic elements of a diode-pumped laser based on (a) side-pumping and (b) end-pumping. HR = highly reflective coating; AR = anti-reflection coating.

One may well ask: Why go to all the additional effort of building a diode-pumped laser, instead of just using the diode laser directly? Of course for many applications a diode laser is perfectly adequate. However diode-pumped lasers have numerous advantages over diode lasers. The main one is beam quality: diode-pumped lasers typically have fundamental spatial mode (gaussian, or TEM_{00}) beams and are able to produce powerful single-frequency output, while typical high power diodes cannot produce such high quality beams. Another major distinction is that diodes lack the energy storage capability of solid-state laser materials, so high peak power pulsed outputs cannot be obtained from diode lasers. Also diode-pumped lasers can have lower noise than diodes, and they produce different wavelengths that cannot be achieved with diodes. Consequently diode-pumped solid-state lasers can be thought of as a means for converting the output of a diode laser to achieve better spatial, spectral, and temporal performance; i.e. as a "mode converter", that improves the quality and nature of the light.

The only disadvantages of diode-pumped lasers at present are their fairly low output powers and higher cost per watt of output than other types of lasers, due to the limited output capability and high cost of diode lasers. However, diode-pumped lasers still can be price competitive when source reliability, facility costs, and lifetime are taken into account. The lower initial acquisition cost of other systems is often offset by installation costs (to meet cooling water and/or three-phase AC power requirements), higher operating costs (for replacement flashlamps or ion tubes) and particularly the effective cost of the frequent maintenance downtime. This frequently holds true in applications such as industrial processing or diagnostic equipment. Also, since it is difficult to make lamp-pumped lasers with low output powers, previously applications with low power requirements had to make use of lasers that were much more powerful than needed. Thus lower power diode-pumped lasers may be more costly per watt of output, but be no more costly than the lasers they replace.

Laser system assembly

The advent of diode-pumped lasers presents new challenges to the laser engineer. Careful design is required to obtain an overall system that is as reliable as the diode lasers and laser material, while maximizing the efficiency, short term and long term stability of these systems. This raises issues such as reliability of component mounting, and the lifetime of other components such as optical coatings and nonlinear optical crystals. As for other types of lasers, a synergy of optical, mechanical and electrical engineering is required.

Most diode-pumped lasers are compact and assembled from numerous small components. Conventional assembly techniques used for other types of lasers that are larger are either impractical, or result in structures that compromise the stability or reliability of the laser. In LIGHTWAVE products the components of the laser resonator and optical train are mounted using proprietary manufacturing techniques. These allow small optical components to be precisely positioned and then permanently fixed rigidly in place using solder, epoxy or other adhesives. This yields solid assemblies without any parts subject to misalignment or requiring maintenance. This improves short term and long term stability, both of which will be affected by even the slightest mechanical misalignments. With the appropriate choice of materials and structures, this type of construction has proven to yield rugged, compact, and reliable systems. LIGHTWAVE lasers are one-piece assemblies that contain no user-adjustable optical components such as mirror mounts. The fully assembled optics train is housed in a hermetically sealed package to protect the components from the operational environment. After assembly, all lasers are run for one week to verify stable operation before shipment.

A major concern of many diode-pumped laser users is the system lifetime. This is fundamentally limited by the pump diode lifetime. In LIGHTWAVE products the diodes are usually run cool and always operated below the manufacturer's rated current in order to extend the diode lifetime. Already, there are numerous LIGHTWAVE units that have been operational in industrial applications for more than 20,000 hours without diode failure.

Laser system electronics

In addition to the opto-mechanical components of the system, power supplies are required, not only to power the diode(s), but also to provide an interface to control and monitor the laser. These electronic support systems are housed in rugged cases and operate on standard wall plug AC power. Most LIGHTWAVE power supplies are microprocessor-based resulting in an intelligent controller that provides flexibility and ease of operation. The microprocessor monitors and controls all power supply and laser head internal functions. An alpha-numeric display on the front panel provides easy visual monitoring of the laser control functions, such as diode current, output power and laser head set points. Buttons on the front panel allow the operating configuration to be changed, and the microprocessor will maintain the desired final configuration. All lasers designed for use with microprocessor-based power supplies incorporate a memory chip which stores all the information related to head operation, such as the optimal diode current and temperature, and number of hours of operation. This allows laser heads and power supplies to be interchanged without readjustment. Battery backed-up memory in the power supply records operating settings as they are changed. When the system is turned on it will return to the last settings saved when it was turned off. A built-in RS-232 interface allows all key laser operations to be controlled remotely from a terminal or by a computer. Some lasers are available in original equipment manufacturer (OEM) versions that contain the essential electronics in the laser head so that the user need only supply DC voltages to operate the laser.

Design and Performance of LIGHTWAVE Products

The following descriptions of LIGHTWAVE laser products illustrate the innovative design approaches that can be used in diode-pumped lasers and the excellent performance they can achieve.

Ultralow Noise CW Lasers:

Single-Frequency Operation

Single-frequency operation of a cw laser produces very quiet, highly coherent output, which is necessary for many applications. A conventional linear laser cavity supports a standing wave, which for a given laser frequency leads to regions in the laser crystal where the light intensity is zero. This situation, known as spatial hole-burning, allows additional longitudinal modes (frequencies) to oscillate. To force such a laser to oscillate in a single longitudinal mode, additional tuning elements must be inserted into the optical cavity. These elements add loss and complication to the laser, resulting in reduced efficiency, lower output power, as well as unacceptable frequency jitter and drift. They also limit the frequency tuning capability of the laser.

An alternative is to use a ring geometry which supports a traveling wave. This eliminates the problem of spatial hole burning so that only a single, dominant longitudinal mode will oscillate. Conventional ring lasers employ a resonator composed of discrete mirrors with lasing occurring within a plane. However lasing will occur in both directions unless a unidirectional device (consisting of a polarizer, half-wave plate, and Faraday rotator) is inserted into the laser cavity to force lasing in only one direction. Again, these extra optical elements increase loss, robbing the laser of efficiency and power. Equally important, the presence of these elements leads to mechanical and acoustical instabilities which cause frequency broadening and increase frequency jitter and drift.

The Non-Planar Ring Oscillator

In 1985, Kane and Byer at Stanford University invented the highly novel non-planar ring oscillator (NPRO). It is a monolithic architecture where the entire laser cavity is within the Nd:YAG crystal. This design intrinsically incorporates the elements of an optical diode into a monolithic ring structure to achieve single longitudinal mode, unidirectional operation. This monolithic device is the most mechanically stable structure possible, which results in superior linewidth and frequency stability characteristics compared to other laser resonator structures. It also minimizes internal cavity losses by avoiding additional cavity elements, so that it has high efficiency. Thus it eliminates the shortcomings of conventional, discrete ring lasers.

The NPRO design is illustrated in Fig. 5. The diode pump light is focused into the Nd:YAG crystal at point A. This face of the crystal is coated to be highly transmissive at the pump wavelength, and partially transmissive at the lasing wavelength to act as an output coupler. Total internal reflection is used at points B, C, and D to obtain a ring laser mode that closes back upon itself at point A, where the output beam is emitted.

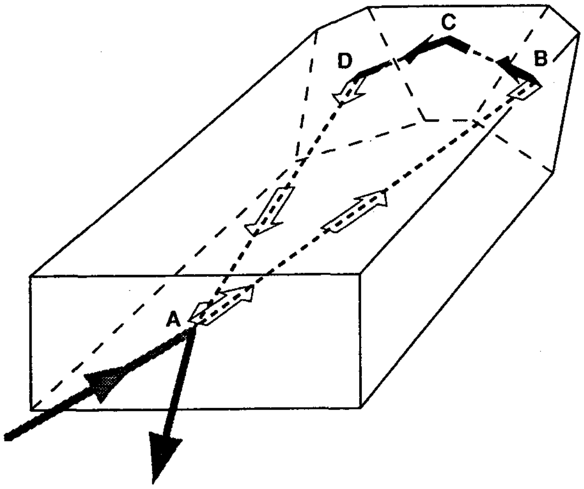

Fig. 5. The non-planar ring oscillator design. The arrows indicate the direction of propagation of the pump, lasing, and output beams.

All the necessary elements of a unidirectional device are incorporated in the NPRO design. The nonplanarity of the NPRO, which arises from the reflections at points B and D not being in the horizontal plane, results in polarization rotation that is analogous to the effect of a half-wave plate. By placing the crystal in a magnetic field the Nd:YAG itself acts as a Faraday rotator with non-reciprocal polarization rotation occurring along segments AB and DA. In one direction of propagation these effects add, while in the opposite direction they cancel, resulting in a different net polarization rotation for each direction. The non-normal incidence on the output coupler face of the crystal serves as a polarizer in the resonator resulting in less loss for one direction of propagation, making it the preferred lasing direction. LIGHTWAVE Series 12X lasers, and the Series 100 Seeder, are based on this patented NPRO design. It produces the quietest, most coherent single-frequency laser light commercially available. While the NPRO does not have the operational shortcomings of discrete element ring lasers, the challenge with this design is that the laser crystal must be fabricated to exacting specifications in order to achieve the required closed laser mode path. Monolithic ring resonators are a LIGHTWAVE specialty, and much effort has been expended in developing this technology.

By ensuring that the diode pump beam is confined within the lowest order spatial mode volume of the NPRO, a high quality TEM_{00} output beam is obtained. This output can be coupled into single mode fiber very efficiently. Fiber-coupled and isolated versions of these lasers are available from LIGHTWAVE.

Most LIGHTWAVE NPRO lasers are based on Nd:YAG, emitting at either 1064 nm (≤ 500 mW) or 1319 nm (≤ 300 mW). However, NPROs that emit at other wavelengths can be built. Notably, Series 124 lasers are also available with output at the "eye-safe" wavelengths of 2013 nm (Tm:YAG) and 2091 nm (Tm,Ho:YAG).

Frequency Stability of the NPRO Laser

Pumping the monolithic NPRO with a diode laser yields a powerful combination. This laser produces single-frequency output that is very stable both in frequency and intensity. The output has an intrinsic linewidth that is extraordinarily narrow; it has been measured by a number of researchers to be at or below the 1 Hz level. This is phenomenally small given that the frequency of the laser output is hundreds of terahertz! Another way of quantifying the stability of the output is to consider the phase noise, which is a measure of the linewidth over a short time period. This can be illustrated by mixing the output beams of two independent NPRO lasers on a photodetector. The signal from the photodiode contains the difference frequency between the laser outputs which can be displayed with a spectrum analyzer. The result of such a measurement is shown in Fig. 6, where a beat note frequency linewidth of 1 kHz is measured in a 10 ms time period.

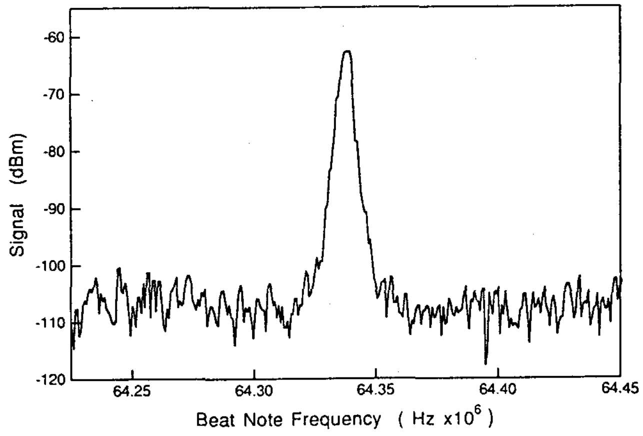

Fig. 6. Typical spectrum for the beat note of two NPRO lasers, demonstrating their narrow linewidth and low phase noise. The inferred linewidth is 3 kHz, which is the resolution bandwidth of the spectrum analyzer, i.e. this measurement is limited by the resolution of the instrument.

This result demonstrates that the laser has extremely low phase noise. A more detailed representation of the frequency stability of the laser is given in Fig. 7, which shows the frequency noise spectrum of the beat note over the frequency range 10 – 5000 Hz.

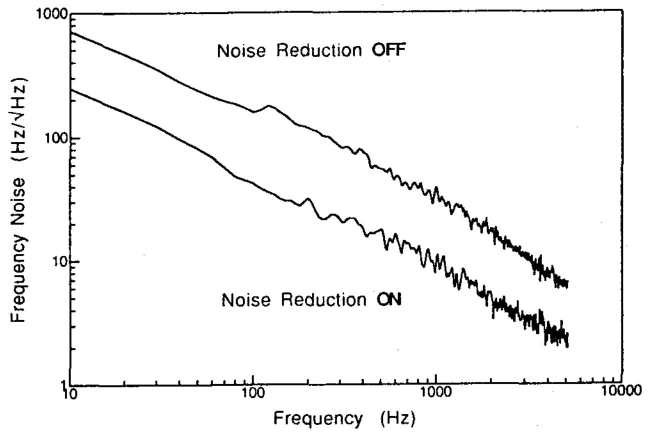

Fig. 7. Frequency noise spectrum of the beat note of two NPRO lasers. The noise is reduced when the active intensity noise reduction system (described below) is used.

Frequency stability over longer periods of time is referred to as jitter or drift depending upon the measurement period. Two principal effects come into play on different time scales. Frequency jitter is substantially affected by amplitude noise of the laser diode pump source. The diode laser power supply is designed to minimize current fluctuations, which translates directly into reduced frequency jitter. Frequency drift results from changes in the NPRO temperature, so that active temperature control is crucial for good long-term frequency stability. The NPRO crystal is mounted on a thermoelectric cooler (TEC) so that its temperature can be easily controlled. The long-term frequency stability has been optimized by careful design of the micro-environment around the Nd:YAG crystal and the temperature control electronics. This results in minimal frequency drift, typically less than 30 MHz per hour at constant ambient temperature.

Frequency Tunability

The ability to tune the output of a laser greatly enhances its utility. While the ultimate limit on the tunability of a laser is its gain-bandwidth, within this constraint the specific laser design will impact its frequency agility. Two types of frequency tunability are available with NPRO lasers. The broadest tuning is accomplished by changing the temperature of the Nd:YAG crystal. Faster tuning is achieved by using a piezoelectric transducer bonded to the Nd:YAG crystal.

Broad thermal tuning is accomplished by thermoelectric control of the crystal temperature which allows either heating or cooling the NPRO. The inherent thermal tuning of the Nd:YAG gain curve (−1.2 GHz/°C, 1064 nm) as well as the temperature induced change in the laser cavity optical length (−3.1 GHz/°C, 1064 nm) enable tuning the frequency of the laser output. Continuous single-frequency tuning is possible over a range of 10 to 15 GHz, depending on the size of the laser crystal. This range is limited by the discontinuities ("mode hops") which occur when the cavity length changes sufficiently that a different longitudinal mode is favored. A longer tuning range in excess of 30 GHz is available if mode hops can be tolerated, as shown in Fig. 8.

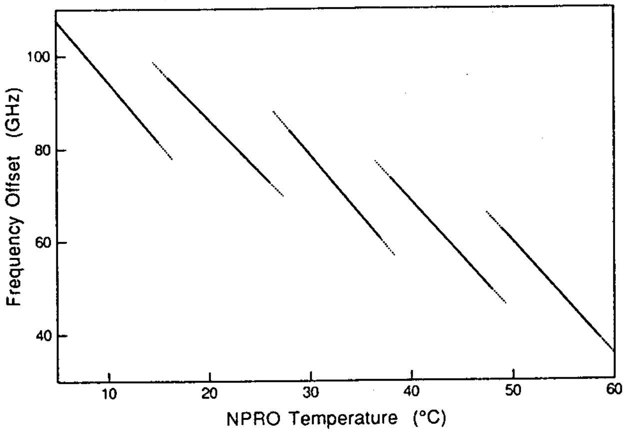

Fig. 8. Typical thermal tuning of the NPRO laser output frequency. The solid line segments represent regions of continuous single mode tuning, and the dashed lines indicate that the laser is near a mode hop where two frequencies may be present.

Although each NPRO laser has mode hops at different crystal temperatures, any two lasers can be frequency matched or frequency offset to any particular degree possible within the tuning limits of each laser. As an example, one laser could be used as a local oscillator, and the other as a transmitter in a coherent detection system.

Being thermal in nature, this tuning mechanism is slow. It has a time constant of 0.1 – 1.0 sec, so that it is limited to low modulation frequencies (< 10 Hz), and it may take as long as one minute for the laser to stabilize at a new temperature setting. For faster tuning, a small piezoelectric transducer is bonded to the Nd:YAG crystal which allows the output frequency to be changed in a few microseconds. When a voltage is applied to this piezoelectric element, it applies a force to the NPRO crystal, slightly changing its dimensions, shape, and index of refraction. This results in tuning of the output frequency of the laser. The tuning range is in excess of 30 MHz, and a constant tuning coefficient of > 1 MHz/V is obtained for modulation rates up to ~100 kHz. Above 100 kHz the response is no longer flat; it becomes larger and varies strongly with frequency due to excitation of mechanical resonances in the crystal. However this still allows useful modulation of the NPRO at fixed frequencies up to about 1 MHz.

The combined capabilities of piezoelectric and thermal tuning make the NPRO a highly versatile device. For instance two NPRO lasers can be phase or frequency locked together, or a single laser can be locked to an external reference.

Ultra-Low Intensity Noise

Small intensity fluctuations are always present in the output of a laser. This intensity noise is also very low in the NPRO, again due to the monolithic structure which eliminates the acoustic noise found in discrete component conventional lasers. Furthermore, diode laser pumping eliminates many of the noise features due to flashlamps and arc lamps. There are two principal ways of describing the intensity noise content. The first method integrates the noise over a certain frequency range. This is known as rms noise. The second method looks at the spectral distribution of the noise and is called relative intensity noise (RIN). A minimum noise level is desired and often essential in many applications such as wide-bandwidth analog communication or interferometric fiber-optic sensing.

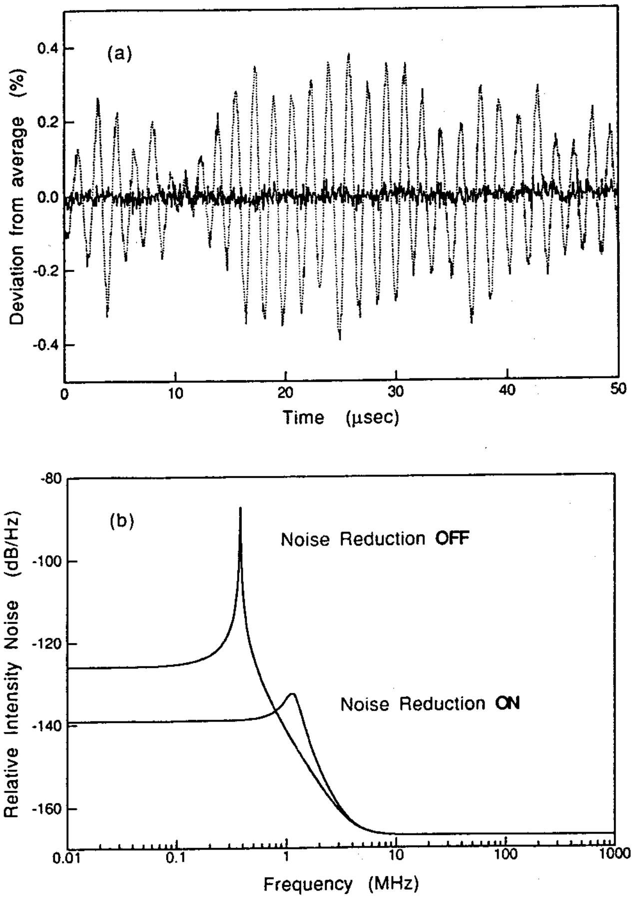

Fig. 9. (a) Typical intensity fluctuations for an NPRO laser without (dashed line) and with (solid line) active noise reduction. (b) The corresponding RIN spectra.

All solid-state lasers, including NPROs, exhibit a behavior known as relaxation oscillations which produces a noise spike in the ten's to hundred's of kilohertz range. The frequency of this relaxation oscillation depends on several factors such as the upper state lifetime of the laser material, output coupling transmission, and cavity length. In

LIGHTWAVE's NPRO lasers an opto-electronic noise reduction system is used to essentially eliminate the noise due to relaxation oscillations. A small portion of the laser output is monitored with a photodiode and a circuit provides feedback to the pump laser diode to minimize fluctuations in the output signal. Without any noise reduction system the NPRO laser has a low rms noise value of less than 1% over the range 5 Hz to 1 MHz. With active noise reduction, this value typically is reduced to 0.02 – 0.03%. The intensity fluctuations as a function of time for a typical NPRO are shown in Fig. 9(a). While the noise due to the relaxation oscillations is clearly evident when the noise reduction circuit is off, it is greatly reduced when the circuit is active. The RIN spectrum of the NPRO laser with and without active noise reduction is shown in Fig. 9(b). Most of the noise occurs between 100 and 900 kHz and is virtually eliminated with active noise reduction. However, the noise reduction system does lead to a small increase in the noise around 1 MHz At frequencies above 20 MHz, the noise of the NPRO laser is below the shot noise limit of most practical photodiodes.

Applications of NPRO Lasers

While NPRO lasers are useful for any cw application that falls within their power and wavelength range, their unique, ultranarrow linewidth, single-frequency output is finding utility in a broad range of applications. Their ultralow frequency and intensity noise, and frequency tunability make them the laser of choice for a number of applications. These include: interferometric sensing in free-space or optical fibers, optical difference frequency generation, velocimetry measurements, wide-bandwidth analog communication, coherent optical communication, antenna remoting, phased-array radar, coherent optical radar, optical time domain reflectometry, general fiber-optic studies, resonant frequency doubling, injection locking and seeding, holography, and interferometry.

The ultralow phase noise of the NPRO is crucial for many interferometric sensing applications, especially fiber-optic sensors. The phase noise of the NPRO laser is several orders of magnitude below that of laser diodes often used in these applications. This increases sensitivity and simplifies sensor construction. For instance, the extremely long coherence length, corresponding to the ultranarrow linewidth, allows interferometry with large path length differences to be performed.

Injection seeding

This is the process of inducing single-frequency operation of a Q-switched pulsed laser by injecting the output of a cw single-frequency (seed) laser into the pulsed laser cavity during the time when the Q-switch opens. When the seed laser frequency is within the bandwidth of the pulsed laser cavity, the Q-switched pulse develops at the frequency of the longitudinal mode which is closest to that of the seed beam more rapidly than it would from the broader band spontaneous noise emission. This causes the energy stored in the gain element of the pulsed laser to be extracted at a single frequency. This results in an output pulse that is temporally smoother with lower intensity noise and less timing jitter, as shown in Fig. 10. The LIGHTWAVE Series 100 injection seeding system is designed specifically for this application. It utilizes a low power NPRO laser as the seeding source, and includes the power supply and accessories for obtaining seeded operation of common commercial high-power lamp-pumped Q-switched Nd:YAG lasers.

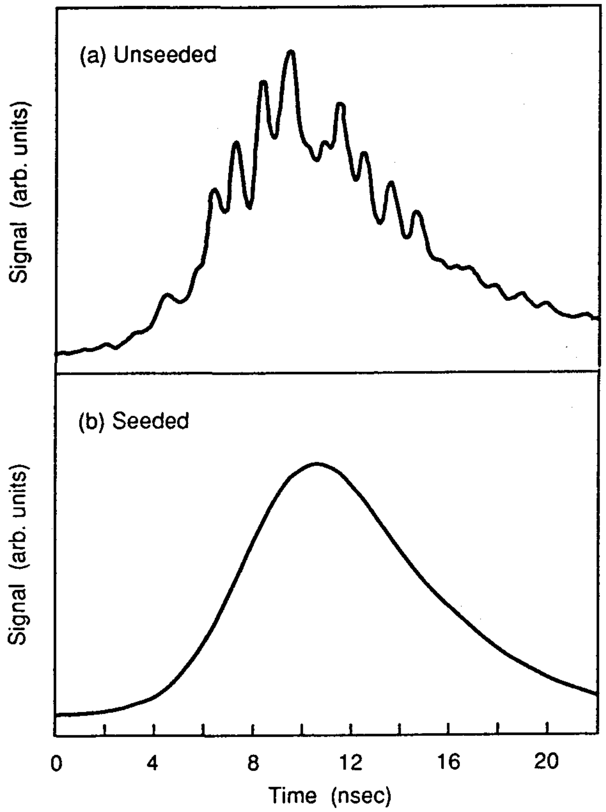

Fig. 10. Output pulse shape of a high power flash-lamp-pumped Q-switched Nd:YAG laser (a) without injection-seeding and (b) with injection-seeding.

Laser Offset Locking

By overlapping the outputs of two NPRO lasers, a beam of light amplitude-modulated at the frequency difference (beat note) between the two lasers is generated. This frequency difference can be as high as 60 GHz and controlled with a precision of 1 Hz or less. One use of this output is for testing the response of high-speed optical detectors. Others include optical delivery of radio frequency (RF) signals for radar, heterodyne detection of weak signals, Doppler lidar, precision directional velocimetry, MMIC testing, and optical communications research. The LIGHTWAVE Series 2000 Laser Offset Locking Accessory (LOLA) provides locking electronics for two NPRO lasers, and can power two Series 123 or 124 lasers. This device allows precise offset locking of two Series 12X lasers to be achieved easily, and its numerous features facilitate operation for these applications. Figure 11 shows the key components of such a system.

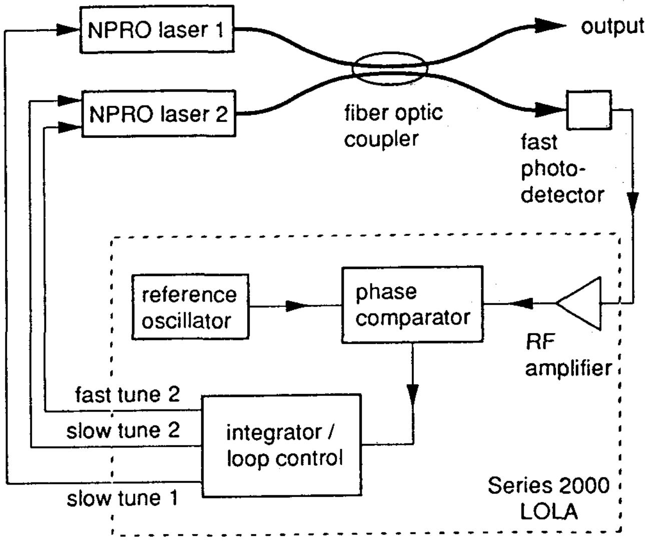

Fig. 11. The configuration required for optical generation of microwave frequencies.

Ultralow Noise Visible CW Lasers:

Frequency-Doubled NPRO Laser

Since high power GaAlAs diode lasers emit in the near infrared, diode-pumped lasers can only produce longer wavelengths, also in the infrared (except for upconversion lasers that are under development). The best approach for obtaining visible output with a solid-state laser is to frequency-double this infrared output. This second harmonic generation process yields an output wavelength exactly one-half that of the incident light. It simply requires appropriate focusing of the incident light into a suitable nonlinear crystal which is correctly oriented to allow phase matching between the incident fundamental frequency and the second harmonic frequency. The high peak power (> 10's of kilowatts) of a pulsed laser can be efficiently frequency-doubled in a single pass through a nonlinear crystal. However efficient doubling of low power cw sources (milliwatts or watts) requires resonant enhancement techniques. This entails operating the frequency-doubling crystal in a resonant optical cavity, which has a high internal circulating power, to greatly increase the power incident on the nonlinear crystal. Even for low power cw sources this technique can achieve doubling efficiencies as high as 80%.

There are two ways to perform resonant doubling. In intracavity doubling the nonlinear crystal is placed inside the laser cavity to make direct use of the high circulating power in the cavity. Although simple to implement, it is difficult to realize good performance with this approach since the cavity must be simultaneously optimized for maximizing the infrared power and the second harmonic output. The alternative is external resonant doubling, in which the infrared beam is coupled into a second cavity in which the doubling crystal is located. While this requires extra components, it allows for the generation of the infrared and the second harmonic to be individually optimized. It does however require a single-frequency laser as the input source. Of course, when the infrared power is generated in a monolithic resonator (e.g. a diode laser or an NPRO) an external resonant doubler must be used.

Typically the external resonant cavity is built from discrete elements. However to avoid degrading the quality of the highly stable output from the monolithic NPRO laser requires the use of a monolithic frequency doubler. By mode matching the output of an NPRO laser into a monolithic doubling ring, frequency-doubled output with the same low noise characteristics as the NPRO can be obtained. Also, this architecture is very compact and it minimizes intracavity losses in the doubler, which greatly improves the doubling efficiency. This is the basis for the LIGHTWAVE Series 140 laser: the output of an NPRO is frequency doubled in a monolithic ring doubler. The geometry of this device is shown in Fig. 12. This resonator has a simple, planar optical path; no special mechanism is required to maintain unidirectional output since the output beam direction is determined by the input beam.

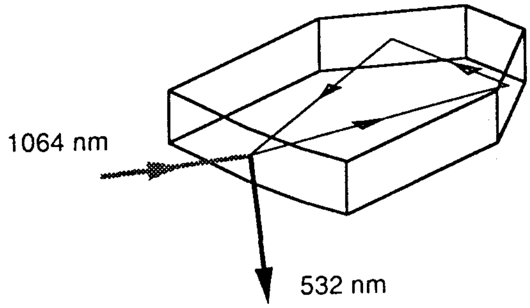

Fig. 12. Monolithic resonant ring doubler geometry. The arrows indicate the direction of propagation of the infrared beam coupled into the resonator, and the generated second harmonic beams.

While many nonlinear materials have been discovered, relatively few have the suitable combination of properties that allows them to be used in practical devices. The Series 140 utilizes MgO-doped Lithium Niobate as the nonlinear material. It has been demonstrated to have the requisite durability and lifetime. The photorefractive damage that plagues undoped lithium niobate has not been observed with this material at the power levels at which the Series 140 is operated. The doubler is fabricated so that one leg of the triangular optical path is aligned with the crystal axis for phase matching to occur. This design has yielded useful conversion efficiencies from 1064 nm to 532 nm of over 70%. Conversion of diode pump power to 532 nm output is as high as 25%.

In order to maximize the conversion efficiency, the doubling crystal must be held at the correct phase-matching temperature (~110 °C). To maintain stable 532 nm output, the NPRO output is frequency-locked to the resonant doubler so as to match the laser frequency to a resonance of the doubler. Once this is achieved, the 532 nm output has all the desirable characteristics of the NPRO input: the output is single-frequency, has extremely narrow linewidth, excellent frequency stability, and very low intensity noise. The only noticeable change in performance is the addition of a small noise component in the intensity noise at the locking frequency of 54 MHz. But it is quite small, being 60 dB lower than the DC level.

Broad frequency tuning of the 532 nm output can be achieved by varying the temperature of the monolithic doubler. The tuning rate is typically – 8 GHz/°C; due to its thermal nature it is fairly slow, around 250 MHz/min. Of course, since the phase matching has a narrow temperature bandwidth, the output power will vary strongly during tuning, as shown in Fig. 13. The asymmetry of the tuning curve arises from additional heating of the doubler material due to absorption of the resonant fundamental power. As the temperature is increased and the doubling efficiency improves, the input infrared power is better impedance matched to the doubler, resulting in higher circulating infrared power and increased heating. For the Series 140, the output power as a function of temperature has a half-power width (FWHM) of 1.6 °C which corresponds to a 12 GHz tuning range of the 532 nm output. The available range covers a number of molecular iodine absorption lines (Fig. 13), providing a potential means for absolute frequency stabilization of the output of this type of device.

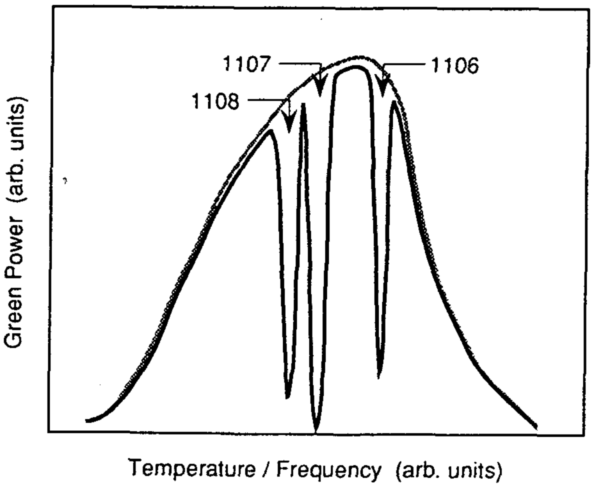

Fig. 13. The output power of the Series 140 laser as the temperature of the monolithic doubler ring is increased. The overall tuning curve is shown in gray, while the black curve is obtained when the beam is passed through an iodine cell. The narrow dips correspond to absorption lines of molecular iodine. These lines are numbers 1106, 1107 and 1108 at 18787.13, 18787.28 and 18787.34 cm^{-1} respectively.

Despite the two step process required to generate the green output power, the Series 140 laser achieves 100 mW of output with a wall plug efficiency of 1%, without much effort expended to optimize this parameter. This is in contrast with the poor efficiency of ion lasers. For instance, an air-cooled Argon-ion laser generating 100 mW of optical output consumes 2 kW of electrical power, corresponding to a conversion efficiency of only 0.005%.

Applications of the Series 140 Laser

This device can replace Argon-ion lasers with output in the region of 500 nm. The Series 140 embodies the advantages of a diode-pumped architecture over these gas lasers: most notably it has improved lifetime and much higher efficiency. It also has better frequency stability and is very compact. The high efficiency results in lower utility requirements, and reduced cooling requirements. The Series 140 is cooled through passive conductive cooling simply by mounting it to a heatsink. In addition, it provides tunable, single-frequency output, so that it can address applications with more stringent requirements. These include: holography, velocimetry, precision interferometry, nonlinear optics experiments, and frequency locking.

Pulsed Nanosecond Lasers:

Q-switched Operation

A major advantage of solid-state laser materials over other laser media is their energy storage capability. This allows solid-state lasers to produce very short, energetic pulses with high peak power. Typically this is achieved with a technique known as Q-switching: an optical switch ("Q-switch") is inserted into the cavity, which prevents operation of the laser for a period of time during which pump energy is stored in the upper laser level. When the Q-switch is altered rapidly so as to maximize the quality (Q) of the cavity, the circulating power in the cavity builds up rapidly so that the stored energy is extracted from the laser material and emitted as a short pulse of high peak power.

The switching mechanism can be either electro-optic (E/O) or acousto-optic (A/O). An E/O Q-switch acts like a waveplate, preventing the laser from operating until a high voltage is applied to change its state rapidly so that it transmits the desired polarization state. They have the advantages of fast switching, which allows short pulses to be produced, and good holdoff (ability to prevent the laser from lasing) as required in lasers with high gain. However they are operationally unwieldy: they require a high voltage supply, which makes high repetition rate operation difficult, and have tight alignment tolerances, high insertion loss and materials limitations (hygroscopic or susceptible to optical damage). An A/O Q-switch consists of a transducer bonded to an optical substrate which is traversed by the laser beam. RF power is applied to the transducer to establish an acoustic traveling wave within the device. This prevents the laser from operating by diffracting any optical signal out of the cavity until the RF drive is turned off momentarily, allowing a pulse to be emitted. By making the switch from materials such as fused silica, a very low insertion loss and a very high damage threshold are achieved. They also have the advantage of looser alignment tolerances. The down side to these switches are that they require an RF source, are somewhat more complex, and have less holdoff capability. They are also generally believed to have slower switching speed and larger timing jitter. However, as described below, LIGHTWAVE has developed A/O Q-switched lasers which produce very short pulses with very low timing jitter that were previously believed unachievable using A/O switching.

Acousto-Optically Q-switched Lasers

LIGHTWAVE's Series 11X lasers generally are optimized for producing pulses with maximum energy and minimal pulse width, i.e. maximum peak power. The cavity design used in these lasers is shown in Fig. 14. The minimal number of components are used: a Nd-doped laser crystal, an A/O Q-switch and an output coupler mirror. The diode pump light is imaged directly into the laser crystal through the dichroic HR coating. This end-pumped geometry ensures only the TEM_{00} spatial mode is excited, giving a high quality, diffraction limited output beam. The materials used for the end mirror and Q-switch are the same or similar, and are chosen so as to have indices of refraction close to that of the laser crystal; thus the optical paths in all three components are nearly parallel, and beam astigmatism is minimized.

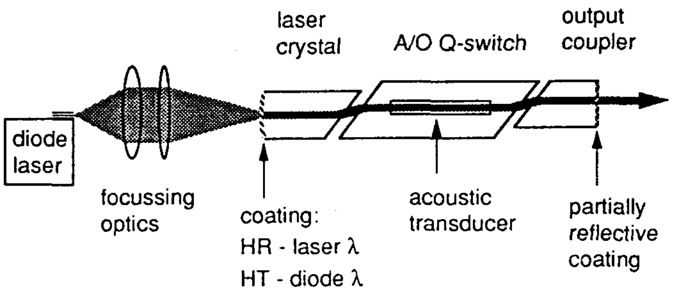

Fig. 14. Cavity design for LIGHTWAVE Series 11X A/O Q-switched lasers.

These lasers incorporate several key features that result in short pulse operation. The most important of these is high gain, which causes the leading edge of the laser pulse to rise steeply. Also, minimizing the cavity ring down time results in the tail of the pulse falling off rapidly. In combination, these two effects lead to very short pulses. In Series 11X lasers high gain is generated through the use of a small laser mode diameter into which the pump light is very tightly focused. The cavity ring down time is minimized by using a high output mirror transmission and by making the cavity length as short as possible. A very short cavity is achieved by minimizing the length of the cavity components and allowing only slight air gaps between them. End-pumping with a high intensity pump source facilitates generating the high gain and allows the cavity to be kept short. Additionally, a slow switching time for the Q-switch can limit the achievable pulse lengths and reduce the output energy. The switching time is minimized by careful Q-switch design and by having a small beam diameter in the Q-switch. Brewster surfaces on all internal optical elements reduce extraneous losses as far as possible, enhancing the laser efficiency. They also eliminate the use of intracavity optical coatings, which are sensitive to damage when subjected to the very high power densities present in a Q-switched laser cavity. Combining these properties results in output pulses among the shortest ever achieved using acousto-optic Q-switches. They are substantially shorter than from lamp-pumped or other diode-pumped solid-state lasers, yet have high peak power and excellent, TEM_{00} spatial mode quality. By lengthening the cavity, longer pulse versions can be produced easily.

The use of a cw pump diode allows the repetition rate to be continuously variable up to very high rates (0 – 100 kHz). At low repetition rates the pulse energy is constant with frequency. However, when the interval between pulses is reduced to about 3 times the upper state lifetime of the solid-state laser material, the pulse energy begins to decrease with frequency. This occurs since there is then insufficient time for the material to be fully "recharged" with stored energy between pulses. The highest pulse energies are achieved with the Series 110 laser based on Nd:YLF as the laser crystal, operating at 1047 nm, due to its high gain and longer upper state lifetime. The variation in pulse energy and pulse length with repetition rate for this laser is shown in Fig. 15. The output remains constant at > 50 μJ and ~ 6 ns up to 800 Hz. Peak power as high as 15 kW is achieved. For higher repetition rates the pulse energy decreases while the pulse length increases as shown.

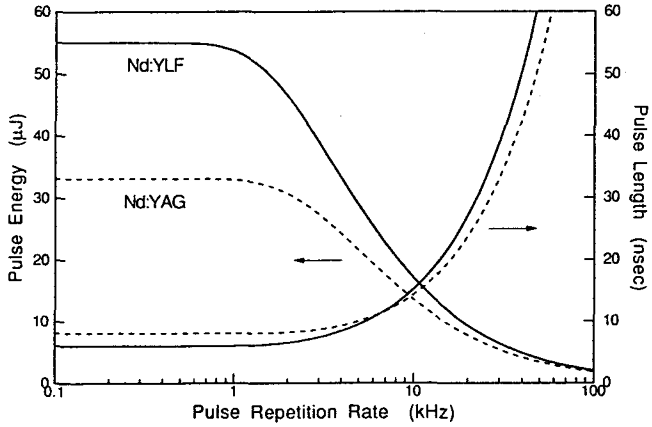

Fig. 15. Performance of the Series 110 laser based on Nd:YLF (1047 nm), compared with Nd:YAG (1064 nm). The pulse energy and pulse length are shown as a function of pulse repetition rate.

Alternatively the laser can be based on Nd:YAG with output at 1064 nm. Since it has a shorter upper state lifetime, higher pulse repetition rates can be achieved before the energy per pulse decreases. Typical performance for the Nd:YAG version is 33 µJ, 8 ns pulses at repetition rates below 1500 Hz. This laser can also be built to produce other wavelengths such as 1053 nm or 1321 nm from Nd:YLF. Versions with higher energy, or shorter or longer pulse lengths are also available.

The shortest pulse durations are achieved with the Series 111 laser using Nd:Vanadate (Nd:YVO_4) as the laser crystal. This laser produces shorter pulses than the Series 110 due to the high gain of this material, cooling of the laser crystal, and further reduction of the cavity length by minimizing the lengths of all three components. Strong absorption in Nd:Vanadate allows the crystal length to be reduced while maintaining good absorption of the pump light. This laser produces sub-nanosecond pulses as shown in Fig. 16. Pulses as short at 0.7 nsec with 5 kW of peak power at 1064 nm are achieved. In addition, the pulse width remains short at repetition rates up to 10 kHz and beyond. Also, the pulse energy can be held relatively constant over this same range by appropriate reduction of the diode current at lower repetition rates. The longer wavelength of 1342 nm also is available from Nd:Vanadate. This laser can also be based on Nd:YLF, for operation at 1047, 1313 nm or 1321 nm. The typical pulse width of the 1047 nm version is < 1 ns at a 1 kHz repetition rate and it remains < 3 ns at 10 kHz. The pulse width of the 1321 nm laser is < 10 ns at 1 kHz and is still < 15 ns at 10 kHz.

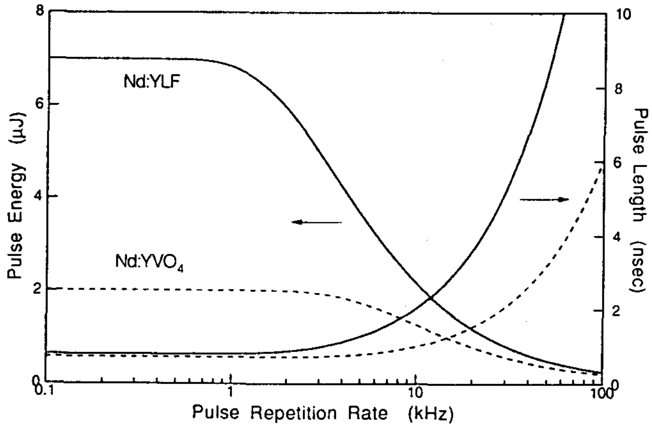

Fig. 16. Performance of the Series 111 laser based on Nd:YLF (1047 nm), compared with Nd:YVO_4 (1064 nm). The pulse energy and pulse length are shown as a function of pulse repetition rate.

Output Stability

Additional innovative design features of the Series 11X lasers allow excellent pulse-to-pulse stability in timing, energy, and pulse length (peak power) to be achieved. Firstly, instead of turning off the RF drive signal at random, it is always turned off at a zero crossing of the RF cycle. Thus, the acoustic power decays identically at each triggering. This ensures that small residual optical losses in the switch during laser pulse build-up will be identical from pulse to pulse so that very good pulse uniformity is obtained. Secondly, instabilities can occur when only a few longitudinal modes are present in the laser, due to intermode modulation, in which the different longitudinal modes interfere with each other causing amplitude spiking. The Series 11X lasers are operated many times above lasing threshold so that many longitudinal modes are present for all output pulses. With many modes present, significant averaging occurs and the resultant amplitude modulation is greatly reduced. Since Nd:YLF has a broader emission spectrum which supports more lasing modes than Nd:YAG, more averaging takes place in a Nd:YLF laser so that it provides better stability than an Nd:YAG laser. Thirdly, by utilizing manufacturing techniques that bond all cavity components permanently in place, a one-piece, solid laser assembly is achieved. This opto-mechanical construction ensures that the stability of the output pulses is maintained both in the short- and long-term. The pulse energy stability for a Series 110 Nd:YLF laser is shown in Fig. 17.

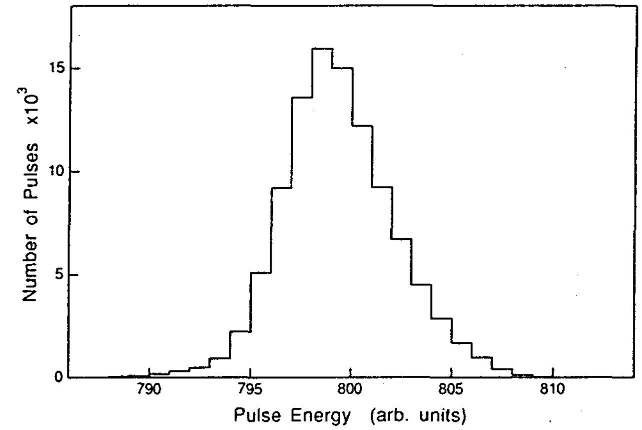

Fig. 17. Histogram of pulse energies for a Series 110-04 Nd:YLF laser operating at 1 kHz. The sample includes over 100,000 pulses and demonstrates an rms energy stability of 0.32%.

Applications of Series 11X Lasers

These lasers are useful in applications that require short, high peak power pulses with excellent pulse-to-pulse stability. Typically they are used in original equipment manufacturer (OEM) applications. The compact size, minimal service requirements, and field-proven reliability of these lasers make them ideal for OEM usage. Short pulses are critical to many applications: they provide resolution for range measurements, localized heat for material vaporization, and high peak power for nonlinear optical effects. The higher peak power of the Series 110 finds use in optical ranging, optical time domain reflectometry, microelectronics processing such as resistor trimming, memory repair, and marking, optical damage testing, and nonlinear optical experiments. The short pulse, high repetition rate performance of the Series 111 laser makes it well-suited for optical ranging, fiber-optic sensing, seeding amplifiers and detector calibration. Both types of laser can also be used for general laboratory experimentation.

Ultrashort Pulse, Mode-Locked Lasers

Mode-locked Operation

It is possible to generate pulses shorter than can be produced with Q-switching by establishing mode-locked operation of a laser. This technique can generate extremely short pulses, as short as tens of femtoseconds! Mode-locking can be achieved either passively or actively. Passive mode locking requires that a non-linear element that favors mode-locked operation be incorporated in the cavity. This technique is simpler, in principle, and produces the shortest pulses. However, under normal operation these lasers are free-running so that additional external feedback is required to synchronize the output to an external oscillator. Active mode locking is an established technique in commercial laser systems and is well-suited for use in lower average power diode-pumped lasers. It requires inserting a device known as a mode locker in the laser cavity; while this results in somewhat longer pulses, they can be easily synchronized to an external oscillator.

Mode lockers typically are acousto-optic devices similar to A/O Q-switches. However in a mode locker the RF power applied to the transducer establishes a standing acoustic wave within the device. This results in the intracavity beam being diffracted at all times except when the acoustic standing wave passes through a zero crossing. Then light is able to travel freely through the mode locker. The mode locker basically acts as a gate, inducing the laser to pulse at short discrete intervals. Consequently, all the longitudinal cavity modes which are able to resonate can pass through the mode locker only when the gate is open. This forces the cavity modes to be locked together in phase, hence the name "mode-locked" (or "phase-locked"). The superposition of all the modes running in phase generates an extremely short laser pulse, in the same way that the sharply spiked mathematical delta function is composed of many Fourier components that are in phase at one point, but cancel out everywhere else. The result is a continuous train of ultrashort laser pulses with a repetition rate set by the cavity round trip time, i.e. by the cavity length. Since the speed of light is so great, a fairly long cavity is necessary to achieve a manageable repetition rate. Commercial mode-locked lasers typically run at repetition rates around 100 MHz, which requires a cavity length of 1.5 m. This presents the laser engineer with a challenge: how to build a very stable structure that will maintain stable operation of this long a cavity.

Like other LIGHTWAVE lasers, the Series 131 mode-locked laser relies on innovative design and robust assembly procedures to obtain highly stable mode-locked operation. A diagram of the Series 131 optical cavity is shown in Fig. 18. The laser crystal is located at one end of the cavity where it is end-pumped by a cw diode to generate a TEM_{00} mode, creating a diffraction-limited output beam. The other key components are the mode locker and the output coupler, which are both located at the other end of the cavity. The intracavity surfaces of the laser crystal and the mode locker are Brewster-angled to eliminate étalon effects (which would lengthen the pulse width) and provide a polarized output beam. To achieve the desired cavity length in a compact device, a series of highly reflective, low loss turning mirrors are used to obtain a multiply folded cavity. One of these fold mirrors is mounted on a piezoelectric actuator for precise cavity length control. All optical cavity components are aligned carefully, then soldered in place onto a rigid, stable baseplate. It maintains the precise optical alignment, eliminating the need for any gross cavity adjustments and providing passive thermal stability for the laser cavity length. A passive vibration damping system is included to reduce acoustic noise. Construction of this long a cavity provides the ultimate test of LIGHTWAVE's laser assembly techniques which prove to be a match to the challenge.

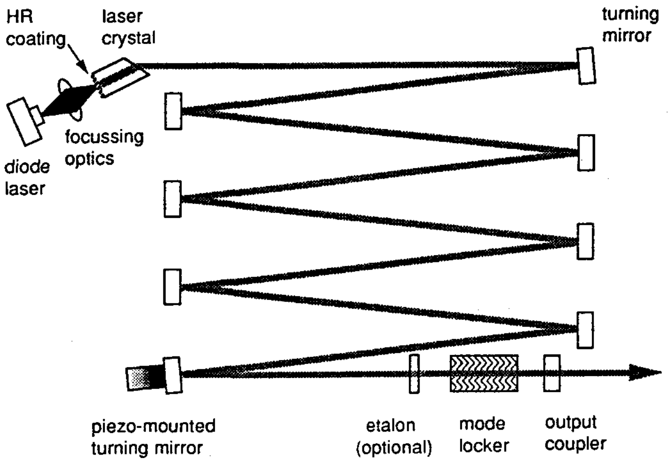

Fig. 18. Schematic layout of the Series 131 optical cavity.

The laser crystal can be either Nd:YLF or Nd:YAG. The shortest pulses are achieved with Nd:YLF operating at 1047 nm: pulses of < 10 ps are obtained with > 200 mW of average output power. This is the shortest pulse width available from any actively mode-locked laser system and is a 5 to 10-fold improvement over the performance of lamp-pumped lasers. The output pulses are very clean, as shown by the autocorrelation trace in Fig. 19. The laser also can be built to run at the alternative Nd:YLF wavelength of 1053 nm. With Nd:YAG an output power of > 100 mW is obtained at 1064 nm, with longer pulses (< 25 ps). Nd:YLF generates shorter pulses than Nd:YAG since it has a broader gain bandwidth which allows a larger number of longitudinal modes to resonate. To obtain longer pulse widths, an étalon can be inserted during assembly of the laser. This can lengthen the pulse duration to > 200 ps. The standard laser is built for a repetition rate of 100 MHz. However, due to the versatility of the folded cavity design, during assembly it can be configured to run at any rate in the range of 75 to 250 MHz, to precisions typical of electronic synthesizers (1 ppm). Once the laser is assembled the repetition rate is fixed and cannot be modified by the user.

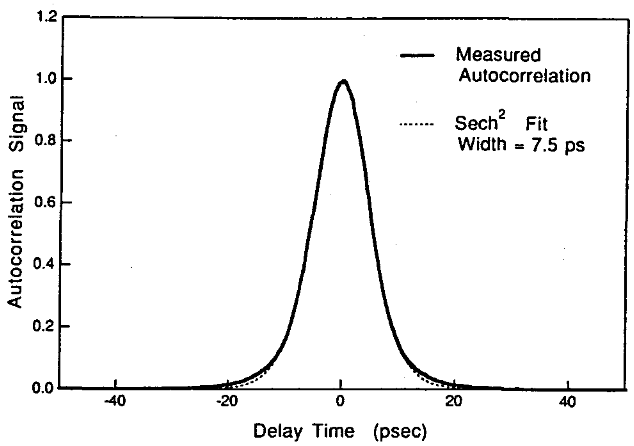

Fig. 19. Autocorrelation trace of the output pulse of a Series 131 mode-locked laser using Nd:YLF at 1047 nm.

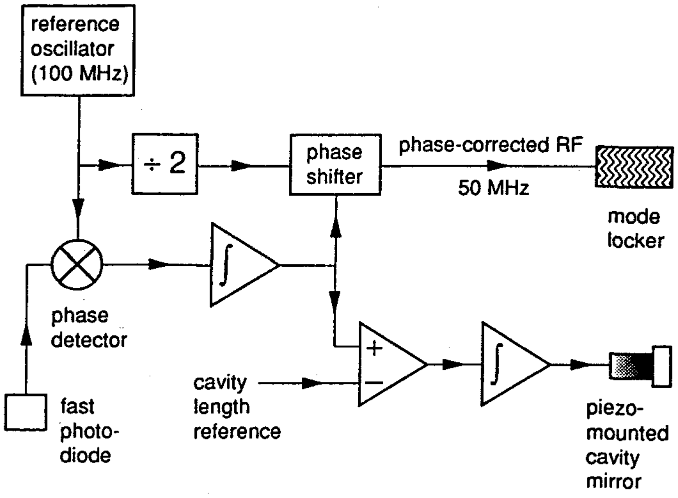

Fig. 20. Block diagram of the timing stabilizer electronics which minimizes the pulse timing jitter by providing feedback to the mode locker and controlling the cavity length.

Output Pulse Stability

In addition to the robust mechanical construction of the cavity, the Series 131 laser uses active control of key components to achieve pulse stability. The RF drive frequency, the acoustic resonance of the modulator, and the laser cavity length must remain constant, matched, and stable for proper mode-locked operation. A stable reference crystal oscillator supplies the RF signal for driving the mode locker. The mode locker temperature is controlled by a thermoelectric cooler to maintain the acoustic resonance matched to the RF frequency. Built-in timing stabilizer circuitry (Fig. 20) minimizes any pulse-to-pulse timing jitter: a photodiode monitors the laser output and its phase is compared to the reference oscillator frequency. This serves as input to control electronics which adjust the phase of the RF signal driving the mode locker to compensate for any detected jitter. They also drive the piezoelectrically-controlled fold mirror, keeping the cavity length locked to the correct value for best mode-locked performance, ensuring stable, ultrashort pulses. This active stabilization reduces the timing jitter to < 1 ps rms (1 Hz to 10 kHz) and amplitude noise to < 1% rms (1 Hz to 1 MHz). As an alternative to using the built-in crystal oscillator, the laser can be locked to a user-generated reference signal at the laser repetition rate. An optional phase-lock-loop allows for most repetition rates to be locked to a standard user-supplied 10 MHz reference.

The timing stabilization system incorporated in the Series 131 laser is also available as an independent electronic unit, the Series 1000 Timing Stabilizer. It serves to reduce timing jitter to 1 ps in selected commercial mode-locked laser experimental systems. There are two standard models: Model 1000-80 for operation at 80 ±5 MHz and Model 1000-100 for operation at 100 ±1 MHz. Other operating frequencies are available on a custom basis.

Comparison with lamp-pumped, mode-locked lasers

Compared to conventional (lamp-pumped) mode-locked lasers, the Series 131 provides shorter pulses, better stability, and significantly reduced timing jitter. For instance, the Nd:YLF version yields ~ 8 psec long pulses with subpicosecond timing jitter, whereas a large lamp-pumped Nd:YLF laser typically yields > 30 psec pulses with a few psec of timing jitter. Of course the Series 131 produces significantly less average power than lamp-pumped lasers, but this is not a concern for many applications such as seeding amplifiers. Diode pumping results in the Series 131 laser being more compact and efficient. The laser head is passively cooled through convective cooling of a built-in heat sink; no cooling water or special utilities are required. Also the Series 131 is more reliable and much easier to use. When turned on, the laser automatically powers up and stabilizes the various active components. The dial on the controller allows the user to adjust the laser cavity length for optimum mode-locked performance. Once set, the feedback loop ensures the system stays optimized, providing a "hands-off" laser.

Applications of Series 131 Lasers

The very short, highly stable mode-locked pulses produced by these lasers make them useful for precision pulse applications. In particular, the extremely low timing jitter of the system allows optical-to-RF synchronization that is unmatched by any other laser system. Applications include: seeding regenerative amplifier systems (for instance for photocathode injector systems), synchronizing laser pulses either to an RF reference signal or to other laser systems (at different wavelengths, e.g. self-mode-locked Ti:sapphire lasers), impulse response testing of high-bandwidth photodetectors and other optoelectronic circuits, and optical testing of integrated circuits using electro-optic sampling.

Conclusion

The practical realization of diode-pumped lasers stands as a major advance in the evolution of lasers, allowing the development of very efficient, compact devices with greatly improved reliability. The advantages of diode-pumped lasers are not only leading to improvements in established laser applications, but also the special properties of these devices are opening up new applications that could not have been addressed with conventional lasers. While the technology of diode-pumped solid-state lasers has begun to mature, we can expect major advances in the near future, and look forward to new devices becoming available. Main areas that are bound to receive attention are higher powers, new wavelengths, and shorter pulsewidths.

Acknowledgment

LIGHTWAVE Electronics gratefully acknowledges the support that it has received from a number of U.S. Federal Government agencies under the Small Business Innovation Research (SBIR) Program. This funding has directly benefited a variety of research and development efforts which have lead to the introduction of the commercial products described above.

T. R. Steele
July 1993

Bibliography

Robert L. Byer, "Diode Laser-Pumped Solid-State Lasers", Science Vol. 239, pp. 742—747, (1988).

Tso-Yee Fan and Robert L. Byer, "Diode Pumped Solid-State Lasers", IEEE Journal of Quantum Electronics Vol. 24, pp. 895—912, (1988).

Walter Koechner, "Solid-State Laser Engineering", Springer-Verlag, 3rd Edition, 1992.

References

The articles listed below provide additional information on the design and performance of LIGHTWAVE Electronics' products. Copies are available from LIGHTWAVE.

CW Lasers:

T. J. Kane, R. L. Byer, "Monolithic, Unidirectional Single Mode Nd:YAG Ring Laser," Optics Letters **10**, 65 (1985).

T. J. Kane, A. C. Nilsson, R. L. Byer, "Frequency Stability and Offset Locking of a Laser Diode-Pumped Nd:YAG Monolithic Nonplanar Ring Oscillator," Optics Letters **12**, 175 (1987).

T. J. Kane, E. A. P. Cheng, "Fast Frequency Tuning and Phase Locking of Diode-Pumped Nd:YAG Ring Lasers," Optics Letters **13**, 970 (1988).

T. J. Kane, "Intensity Noise in Diode-Pumped Single Frequency Nd:YAG Lasers and its Control by Electronic Feedback," IEEE Photonics Tech. Letters **2**, 244 (1990).

T. J. Kane, T. S. Kubo, "Diode-Pumped Single Frequency Lasers and Q-Switched Lasers Using Tm:YAG and Tm,Ho:YAG," OSA Proceedings on Advanced Solid-State Lasers, Vol. 6, eds. H.P. Jenssen, G. Dubé, 136 (1990).

E. A. P. Cheng, T. J. Kane, "High-Power Single-Mode Diode-Pumped Nd:YAG Laser Using a Monolithic Nonplanar Ring Resonator," Optics Letters **16**, 478 (1991).

D. C. Gerstenberger, G. E. Tye, R. W. Wallace, "Efficient Second-Harmonic Conversion of CW Single-Frequency Nd:YAG Laser Light by Frequency Locking to a Monolithic Ring Frequency Doubler," Optics Letters **16**, 992 (1991).

Pulsed Lasers:

W. M. Grossman, M. Gifford, R. W. Wallace, "Short-Pulse Q-Switched 1.3- and 1-µm Diode-Pumped Lasers," Optics Letters **15**, 622 (1990).

H. Plaessmann, F. Stahr, W. M. Grossman, "Reducing Pulse Durations in Diode Pumped Q-Switched Solid-State Lasers," IEEE Photonics Tech. Letters **3**, 885 (1991).

M. J. W. Rodwell, D. M. Bloom, K. J. Weingarten, "Subpicosecond Laser Timing Stabilization," IEEE Journal of Quantum Electronics **25**, 817 (1989).

K. J. Weingarten, D. C. Shannon, R. W. Wallace, U. Keller, "Two Gigahertz Repetition Rate, Diode-pumped, Mode-locked, Nd:YLF Laser," Optics Letters **15**, 17 (1990).