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Microchip lasers [1]

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Abstract

Microchip lasers are miniature diode-pumped solid-state devices formed by dielectrically coating thin platelets of gain media. Their simplicity and small size give them the potential for inexpensive mass production, while their cw output characteristics are comparable to those of the best conventional devices. By incorporating a thin platelet of a second material into the device, tunable cw lasers and picosecond *Q*-switched microchip lasers have been produced which outperform larger devices in many aspects. Electrooptically tuned devices have demonstrated a flat-band tuning response of 15 MHz/V at modulation rates from dc to 1.3 GHz. Pulses as short as 115 ps, with peak powers of 80 kW, have been generated by electrooptically *Q*-switched microchip lasers, and pulse repetition rates as high as 2.25 MHz have been demonstrated. Passively *Q*-switched devices generate pulses as short as 218 ps and produce peak powers in excess of 130 kW, without the need for switching electronics. A variety of miniature nonlinear optical devices, including harmonic generators, parametric amplifiers, parametric oscillators, and fiber-based Raman amplifiers, have been used to frequency convert the output of these lasers, accessing the entire spectrum from 5 μm to 190 nm in extremely compact optical systems.

Keywords: Solid-state laser; Diode-pumped laser; *Q*-switched laser; Nonlinear optics; Optical parametric amplifier; Optical parametric oscillator

1. Introduction

Microchip lasers are a rich family of devices with capabilities that exceed those of conventional lasers, while at the same time being extremely compact and potentially mass producible at low cost. This paper starts by presenting the basic concept of the microchip laser, followed by a brief discussion of its cw operation, including its single-frequency operation, transverse-mode definition, polarization, and line width. The paper then goes on to talk about frequency modulation of the device, using piezoelectric and electrooptic techniques. It continues with a discussion of what I feel is the most exciting aspect of microchip lasers, their pulsed capabilities, and covers both actively and passively *Q*-switched devices. Before concluding, it talks about nonlinear optical devices based on passively *Q*-switched microchip lasers.

This paper is presented with only one equation and focuses on work performed at MIT Lincoln Laboratory. For a more complete, quantitative treatment of the subject matter, the interested reader is referred to Ref. [1].

2. Basic concept

As shown in Fig. 1, a microchip laser, in its simplest embodiment, consists of a small piece of

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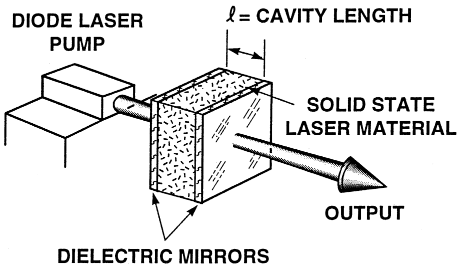

Fig. 1. Microchip laser.

solid-state gain material polished flat and parallel on two sides. The cavity mirrors are dielectrically deposited directly onto the polished surfaces. The laser is then longitudinally pumped with a semiconductor diode laser.

There are several aspects of the microchip laser that make it interesting. First, the cavity length can be made sufficiently short that only a single longitudinal mode falls under the gain profile, thereby ensuring single-frequency output. By using a flat–flat cavity and longitudinally pumping the microchip laser, the TEM_{00} mode is strongly favored and is the only transverse mode to oscillate. When only one spatial mode oscillates (both longitudinal and transverse), the two orthogonal polarization modes of the laser compete for exactly the same gain and the device operates in a single polarization.

Another extremely important aspect of microchip lasers is that all of their surfaces are flat. This allows large wafers of microchip lasers to be polished and coated before the wafers are cut into 1-mm-square pieces, with each piece being a complete device. As a result of their small size and simple fabrication, microchip lasers are potentially mass producible at low cost.

Other interesting aspects, for dynamic applications of microchip lasers, are their short cavity lifetimes and small mode volumes. These allow for rapid changes in the operating parameters of the lasers, leading to high rates of frequency modulation and short-pulsed operation.

Since the initial work on diode-pumped microchip lasers at MIT Lincoln Laboratory in 1987 [2], the microchip laser concept has been successfully applied to a large number of material systems. Although many of these are based on Nd oscillating at 1.06 or 1.32 μm [2–11], Cr:LiSAF has been used in the 0.8- to 1.0-μm spectral region [12], Yb:YAG has been used at 1.05 μm [13], Yb,Er: glass has been demonstrated at 1.5 μm for applications in fiber-optic communications [14], Tm and Ho devices operating near 2 μm have been built for remote sensing [15–18], and 3-μm microchip lasers have been investigated for medical applications [19].

Fabrication of microchip lasers starts with a large boule of gain material, such as Nd:YAG, which may cost several thousand dollars. The boule is sliced into wafers about 0.5 mm thick. The wafers are then polished and dielectrically coated before they are cut into 1-mm-square pieces, with each piece being a complete laser cavity. One 250-mm-long boule can produce up to 250 wafers, one 125-mm-diameter wafer can produce up to 6000 lasers, making the cost per device very small. And, throughout the fabrication process, the lasers never need to be handled independently – they are, in essence, always mass produced.

As an indication of their size, complete diode-pumped, piezoelectrically tuned Nd:YAG microchip laser systems have been packaged in industry-standard TO-3 cans [20]. The package also contains a thermoelectric cooler and thermistor for temperature control of the diode, and a photodetector. The microchip laser cavity itself typically occupies a volume of less than 1 mm^3.

3. CW operation

One of the basic ideas behind the microchip laser is that by making the laser cavity sufficiently short only a single cavity mode will oscillate. Real gain media are not as simple as this concept might infer. Real gain media, such as Nd:YAG, often have several gain peaks, and for efficient operation of the device it is usually necessary to make the cavity sufficiently long that several of thes cavity modes see gain [20]. For example, consider a 650-μm-long Nd:YAG cavity. This cavity length is shorter than the absorption length for the pump light; by making the cavity this short we are already starting to compromise the efficiency of the device. Still, there are potential second lasing modes that fall only halfway down the Nd:YAG gain profile. At high-enough pump powers these modes will oscillate, and we will no longer have a single-mode laser.

To find out how far above threshold a laser will oscillate in a single longitudinal mode we need to examine the gain distribution and the effects of mode competition, spatial hole burning, and energy diffusion [20–23]. A rigorous analysis shows that the number of times above threshold that a laser will oscillate in a single longitudinal mode is a strong function of its cavity length. For many gain media, including Nd:YAG, single-mode operation is easily maintained for cavity lengths below 0.5–1 mm. A 1.064-μm Nd:YAG microchip laser with a 730-μm-long cavity has been operated in a single mode at 22 times threshold [2]. In practice, a well-designed laser never needs to operate this far above threshold; these are single-frequency devices.

Microchip lasers have a flat–flat cavity. The eigenmodes of a passive flat–flat cavity are plane waves. A question that arises, therefore, is "What determines the transverse mode dimensions in microchip lasers?" As we optically pump the microchip laser we also deposit heat. If the refractive index increases with temperature, as it does in the case of Nd:YAG, this temperature profile results in a waveguide [24]. In addition, thermal expansion of the gain medium can result in end-face curvature [25]. (In materials with a refractive index that decreases with temperature, such as Tm, Ho:YLF, the end-face curvature can still result in a stable cavity mode [18].) When the length of the laser cavity is shorter than the confocal parameter of the oscillating mode, the end-face curvature can be modeled as contributing to the thermal waveguide [1]. At the pump powers commonly used for microchip lasers, the thermal waveguide formed is often a single-mode waveguide. The laser, therefore, operates in the fundamental transverse mode. Measurements of the beam quality of Nd:YAG microchip lasers indicate that it is typically between 1 and 1.3 times diffraction limited [3,20,26]. As can be seen from Fig. 2, these are ideal beams to work with.

As long as only one spatial mode of the microchip laser oscillates, the two possible polarization modes are perfectly correlated. The first polarization mode to lase depletes the gain for the second, and the second will never reach threshold [1]. The polarization of a microchip laser may be determined by the properties of the gain medium or by applied uniaxial stress. For isotropic gain media with no applied stress, the polarization may be determined by external feedback [27], or may wander with time.

In addition to being single-frequency, microchip lasers have a very narrow line width. To measure the line width of a microchip laser, the outputs of two similar devices are combined with a beam splitter and focused onto a photodetector. The resulting heterodyne spectrum of single-frequency Nd:YAG microchip lasers, shown in Fig. 3, typically has a line width of <7 kHz, with relaxation sidebands that are 30–40 dB down from the main peak [2,3,20]. These sidebands can be

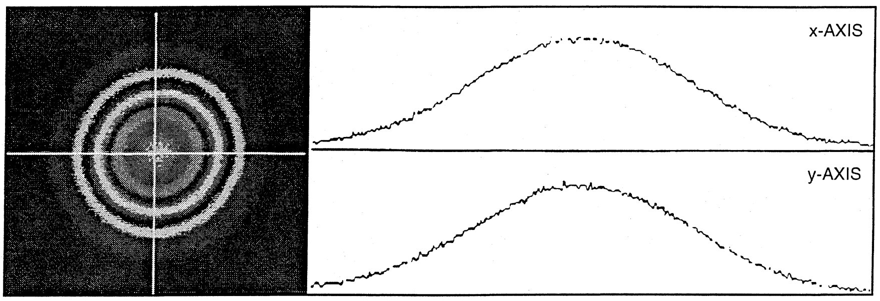

Fig. 2. Far-field intensity profile of a microchip laser. The left-hand portion of the figure shows the image obtained by mapping the two-dimensional field intensity into shades of gray. The right-hand portion shows an almost perfectly Gaussian intensity profile in two orthogonal directions.

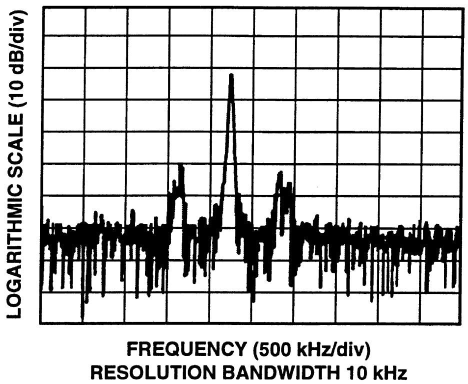

Fig. 3. Instrument-limited heterodyne spectrum of two cw Nd:YAG microchip lasers.

further suppressed using electronic sideband suppression techniques.

A 1.32-μm diode-pumped Nd:YAG microchip laser provides a good illustration of what can be expected from these devices [3]. (In the 1.32-μm laser, all of the other gain lines are suppressed by the spectral performance of the output coupler.) Pumped with a proximity-coupled semiconductor diode laser, the microchip laser oscillates in a single-frequency at output powers in excess of 50 mW. The transverse mode is TEM_{00} with a divergence of ~2 mrad. The slope optical conversion efficiency of the device is about 50%, with an overall wall-socket power efficiency of between 4% and 5%.

Although microchip lasers are small devices, they are capable of a fair amount of output power. Using a 5-W $Ti:Al_2O_3$ laser as a pump source, we obtained as much as 2 W of output from a cw Nd:YAG microchip laser. At this power level the laser was no longer single-frequency or TEM_{00}. However, we achieved 240 mW of single-frequency, TEM_{00} output with a $Nd:YVO_4$ microchip laser pumped with a 1-W diode.

4. Frequency tuning

Some applications of microchip lasers, such as fiber-optic gyros, require a modest amount of frequency tuning at low rates. Where the tuning requirements are not very demanding, a conservative approach can be used. A cw microchip laser can be tightly fitted into a U-shaped beryllium–copper holder next to a PZT piezoelectric transducer, as shown in Fig. 4. When a voltage is applied to the transducer, the transducer applies stress to the Nd:YAG, and the end faces of the laser bulge out, changing the cavity length. Using this technique, we have demonstrated lasers that tune at ~0.6 MHz/V for modulation rates from dc to 300 kHz [3,20,26]. Above 300 kHz the tuning response is determined by the acoustic resonances of the system.

An alternative way to tune a laser is to insert an electrooptic tuning element within the laser cavity, as illustrated in Fig. 5. This results in a much higher performance device. The electrooptically tuned microchip lasers that we built consist of a 0.5-mm-long piece of Nd:YAG bonded to a 1-mm-long piece of $LiTaO_3$ [28]. The pump-side face of the Nd:YAG was coated dielectrically to transmit the pump light (808 nm) and to be highly reflective at the oscillating wavelength (1.064 μm). The interface between the Nd:YAG and the $LiTaO_3$ was designed to be antireflecting at 1.064 μm and to reflect the pump light, allowing double-pass absorption of the pump in the gain medium. The opposite face of the $LiTaO_3$ was coated for 2% transmission of the laser light. The $LiTaO_3$ was oriented with its *c*-axis orthogonal to the cavity axis. Electrodes were deposited on the two faces of the $LiTaO_3$ normal to the *c*-axis, with an electrode spacing of ~1 mm.

In addition to being electrooptic, good electrooptic materials are piezoelectrically active. In or-

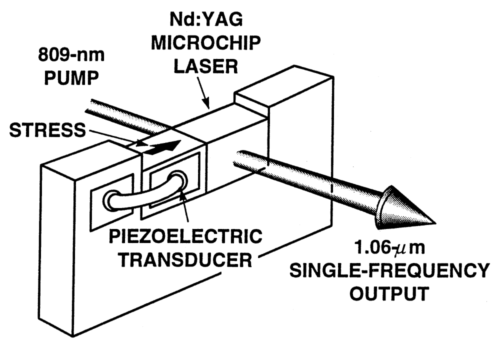

Fig. 4. Piezoelectrically tuned microchip laser.

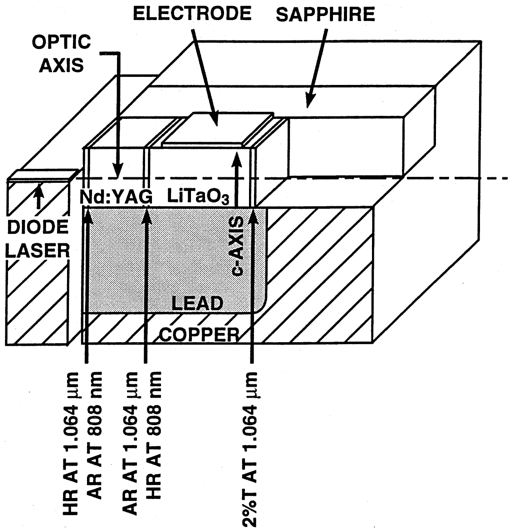

Fig. 5. Electrooptically tuned microchip laser. HR, highly reflecting; AR, antireflecting; T, transmitting.

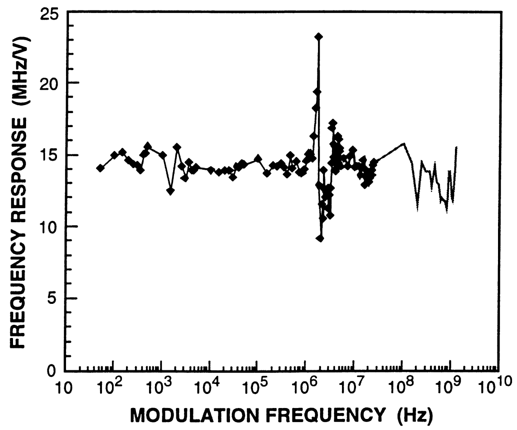

Fig. 6. Tuning response of an electrooptically tuned microchip laser.

der to obtain flat-band tuning of the laser, care must be taken to dampen the acoustic resonances [29]. Since the acoustic impedances along the *c* and *a* axes of $LiTaO_3$ are matched to lead and sapphire, respectively, these materials can be used to couple out the acoustic energy propagating in those directions. Lead also damps the acoustic excitations and provides the contact to the bottom electrode on the $LiTaO_3$. Sapphire provides the necessary electrical insulation along the sides of the device and transmits the acoustic excitations into the substrate.

As shown in Fig. 6, we have demonstrated an electrooptically tuned microchip laser with a flat tuning response from dc to 1.3 GHz, with the exception of a single resonance near 2 MHz. This resonance corresponds to the frequency of the fundamental longitudinal acoustic excitation along the cavity axis – the one direction that was not damped. This is an incredibly broad flat-band response, and 1.3 GHz is the highest rate of frequency modulation obtained with any solid-state laser. In principle, the tuning response should extend out to 25 GHz, although we have not done the experiments to confirm this. At low modulation rates, this device has been tuned by up to 30 GHz, limited by the free spectral range of the cavity. The high modulation rates and large depth of modulation are made possible by the short cavity length.

In addition to the methods discussed above, thermal tuning has also been used to frequency modulate the output of microchip lasers. The small size of microchip lasers allows them to be thermally tuned at higher rates than larger devices.

Frequency tuning via pump-power modulation is a variation of thermal tuning, since part of the pump power is converted to heat in the gain medium. The small dimensions of the microchip laser make it possible to obtain a usable amount of frequency tuning without significant amplitude modulation using this technique [30], and pump-power modulation has been used to phase lock microchip lasers [31]. Another important reason to understand the effects of pump-power modulation is that pump-power stability can limit the frequency stability of the microchip laser.

Potential applications of frequency-tuned microchip lasers include coherent lidar and the generation of tunable RF. By beating the output of a frequency-tuned laser with a fixed-frequency device it is possible to create a very broadly tunable microwave or RF source.

5. Pulsed operation

Since microchip lasers are physically very short, they have very short cavity lifetimes. This leads to the possibility of producing very short output pulses. The minimum pulse width that can be obtained from any Q-switched laser is given by [32,33]

$$t_w = 8.1 t_{rt} / \ln (G_{rt}),$$

where t_w is the full width at half-maximum of the output pulse, t_{rt} is the round-trip time of light within the laser cavity, and G_{rt} is the round-trip small-signal gain. As an indication of the capabilities of a Q-switched microchip laser, a 0.5-mm-long Nd:YAG device has a round-trip time of 5.5 ps. Pumped with an incident power of 1 W, it should be possible to achieve a round-trip gain of 1.8, resulting in a pulse width as short as 75 ps. To put this in perspective, before our work on pulsed microchip lasers, the shortest Q-switched pulse obtained from a solid-state laser was about 1 ns, and Q-switched Nd:YAG lasers typically produce pulses that are many nanoseconds long.

The short cavity length and monolithic construction of microchip lasers do not allow for the use of conventional intracavity Q switches. One approach we have taken, shown in Fig. 7, is the coupled-cavity Q switch, where the output coupler of a cw microchip laser is replaced by a tunable etalon, defined by two partially reflecting mirrors adjacent to a thin slice of $LiTaO_3$ [34,35]. The reflectivities of the pump-side mirror on the gain medium and the partial reflectors on the $LiTaO_3$ are chosen so that the resonant frequencies of the laser are determined primarily by the gain cavity

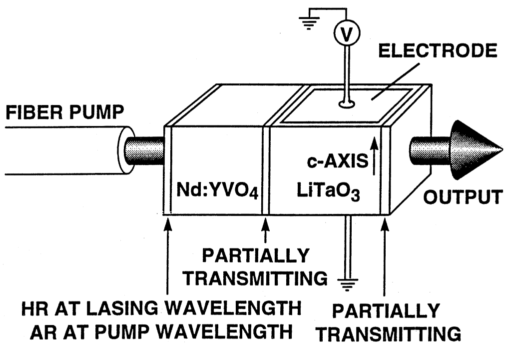

Fig. 7. Coupled-cavity electrooptically Q-switched microchip laser. HR, highly reflecting; AR, antireflecting.

(defined by the mirrors adjacent to the gain medium). The reflectivity of the etalon at the lasing wavelength is a strong function of the etalon's optical length. When the etalon is resonant at the lasing frequency, the gain cavity sees a low reflectivity, or high transmission loss, and oscillation is suppressed. In this state, very high inversion densities can be achieved. When we then make the etalon highly reflective at the lasing frequency, a short output pulse can be obtained.

In addition to Nd:YAG devices [34], we built two types of actively Q-switched $Nd{:}YVO_4$ microchip lasers [35]. The first was designed to produce short pulses at low repetition rates, and has low reflectivities for both of the partial reflectors adjacent to the $LiTaO_3$. At a pulse repetition rate of 1 kHz, this device produces a pulse width of 115 ps. This is the shortest output pulse ever obtained from an actively Q-switched solid-state laser. The energy of each pulse is 12 μJ, corresponding to peak powers in excess of 80 kW.

The second Q-switched $Nd{:}YVO_4$ microchip laser operates at repetition rates between 300 kHz and 2.25 MHz. The partial reflectors in this device have much higher reflectivities in order to reduce the threshold of the laser and make the higher repetition rates possible. The average output power of this laser is 360 mW, independent of the repetition rate. The pulse width is proportional to the repetition rate, varying from 1 ns at 300 kHz to 8.8 ns at 2.25 MHz. Even at the highest repetition rate, 2.25 MHz, the pulse width is shorter than that of most conventional Q-switched Nd:YAG lasers, which operate at repetition rates below 10 kHz. At 2.25 MHz, the pulse energy is 0.16 μJ, with a peak power of 16 W.

While the performance of the coupled-cavity Q-switched microchip laser is impressive, there is still room for improvement. In order to obtain proper Q switching of the coupled-cavity microchip laser, high-speed, high-voltage electronics are required. The size, performance, and power consumption of the electronics limit the size, performance, and power efficiency of the coupled-cavity Q-switched microchip laser system. In addition, the performance of the coupled-cavity laser relies on maintaining interferometric control of the relative lengths of the two constituent cavities, placing tight tolerances on the manufacture of the device and on its temperature control during use.

An alternative to the electrooptically Q-switched microchip laser is the passively Q-switched device [36–44]. The passively Q-switched microchip laser does not require switching electronics, thereby greatly reducing the size and complexity of the total system and improving the power efficiency. In addition, there is no need for interferometric control of cavity dimensions, simplifying production of the device and greatly relaxing the tolerance on temperature control during its use. The result is a potentially less expensive, smaller, more robust, and more reliable Q-switched system with performance comparable to that of the coupled-cavity Q-switched microchip lasers.

The principle behind the operation of a passively Q-switched laser is that an intracavity saturable absorber prevents the onset of lasing until the average inversion density within the cavity reaches a critical threshold value. The onset of lasing, at that point, produces a high intracavity optical field that saturates the saturable component of the loss, increasing the cavity Q and resulting in a Q-switched output pulse. Increasing the pump power above threshold changes the pulse repetition rate, but leaves the rest of the pulse parameters unchanged, and the pulse amplitude and pulse width are extremely stable.

The passively Q-switched microchip lasers used in the devices discussed here are constructed of a short piece of Nd^{3+}:YAG diffusion bonded to a Cr^{4+}:YAG saturable absorber, as shown in Fig. 8. Alternative approaches include the use of a single material that acts as both the gain medium and the saturable absorber [36,39], the growth of one material on the other [40], and the use of semiconductor saturable absorbers [41–43]. In the diffusion-bonded devices, both materials are polished flat and parallel on the two faces normal to the optic axis. The pump-side face of the gain medium is coated dielectrically to transmit the pump light (808 nm) and to be highly reflecting at the oscillating frequency (1.064 μm). The output face of the saturable absorber is coated to be partially reflecting at the lasing frequency and provides the optical output from the device.

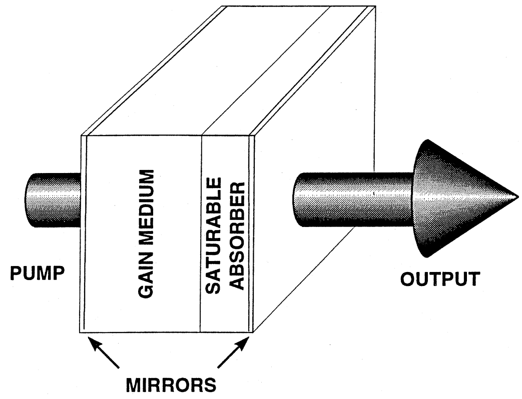

Fig. 8. Passively Q-switched microchip laser.

The passively Q-switched microchip laser has a typical cavity length of between 0.75 and 1.5 mm, and can be bonded directly to the ferrule of an SMA-connectorized multimode optical fiber. The pump diode is located at the opposite end of the fiber.

We have built several variations of Nd:YAG/Cr^{4+}:YAG passively Q-switched microchip lasers for applications including high-precision ranging and imaging, remote sensing, nonlinear frequency generation, material characterization, micromachining, laser-induced-breakdown spectroscopy, and UV-fluorescence spectroscopy. The shortest pulses we have obtained with these devices have a 218-ps full width at half-maximum and an energy of 4 μJ. Devices using semiconductor saturable absorbers have demonstrated 62-nJ pulses with pulse durations as short as 56 ps [42]. Using 1 W of optical pump power, we have obtained pulse energies as high as 14 μJ in 400-ps pulses, with peak powers of 30 kW [37,38]. We have demonstrated time-averaged powers up to 120 mW. Although we have produced devices with pulse repetition rates as high as 70 kHz, the high-performance lasers typically operate at repetition rates between 8 and 15 kHz. All of these lasers oscillate in a single longitudinal mode with transform-limited spectral performance, in the fundamental transverse mode with diffraction-limited divergence, and in a linear polarization. The pulse-to-pulse amplitude fluctuations of the high-performance devices have been measured to be <0.05%. Pulse-to-pulse timing jitter tracks fluctuations in the output of the pump diode.

In addition to 1.064-μm operation, we have demonstrated efficient operation at 946 nm using Cr^{4+}:YAG as the passive Q-switch [44]. Semiconductor saturable absorbers can be engineered for operation at many different wavelengths, and low-power passively Q-switched devices using semiconductor saturable absorbers have been demonstrated at 1.3 and 1.5 μm [43].

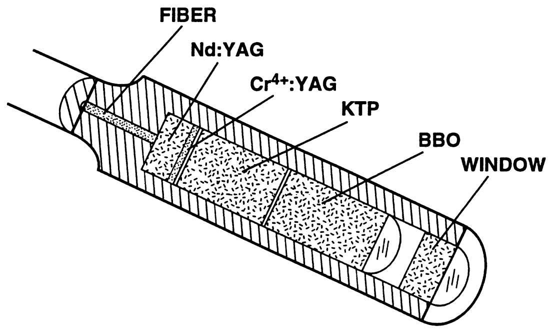

Fig. 9. Frequency-quadrupled microchip laser.

6. Nonlinear optical devices

Nonlinear frequency conversion of cw microchip lasers has been performed using self-frequency-doubling gain media [9,45] and intracavity harmonic generation to obtain green [46,47], blue [48,49], and red [50] output. Most of the nonlinear frequency conversion performed at MIT Lincoln Laboratory, however, has been based on passively Q-switched devices. The high peak intensities of the passively Q-switched microchip lasers allow for efficient nonlinear frequency generation in very simple and robust devices [37,38,51,52]. By simply placing a small piece of properly oriented KTP near the output facet of a passively Q-switched laser, with no intervening optics, we have obtained frequency-doubling efficiencies as high as 70% [37], although more typical numbers are between 30% and 55%.

Packaged versions of the passively Q-switched green device, pumped with 1 W of fiber-coupled optical power, produce up to 40 mW of green output in 300-ps pulses, with peak powers in excess of 10 kW. In addition, the output is single-frequency, transform limited, and TEM_{00}, diffraction limited.

Since we have such high peak powers and good mode quality in the green, it is possible to frequency convert the green radiation into the UV by simply placing the appropriate nonlinear material (BBO) adjacent to the output facet of the KTP [38,51,52], as shown in Fig. 9. All of the crystals in the device are polished flat on the faces normal to the optic axis, and proximity coupled to each other without any intervening optics.

A UV microchip laser head, containing the passively Q-switched IR microchip laser and the nonlinear crystals required for UV generation, fits in a 25-mm-long by 10-mm-diameter stainless steel can [38,51]. The only input to the device is a multimode fiber carrying the 808-nm diode pump light. Out of this device, we typically get over 5 mW of UV at a pulse repetition rate of 10 kHz, corresponding to pulse energies of 0.5 μJ, with peak powers of over 2 kW. The conversion efficiency from the green to the UV is greater than 13%; the total conversion efficiency from the IR to the UV is about 6%. Several of these devices have already operated for over 30 billion shots each. Since no degradation of any of these microchip laser heads has yet been observed, it is likely that the lifetime of the microchip laser system will be limited by the pump diode, not the microchip laser head. Additionally, without temperature control of the laser head, the devices produce in excess of 1 mW of time-averaged UV power over an ambient temperature range of >80°C. This is an enormous temperature window for fourth-harmonic generation, making them very "fieldable" devices.

We have generated the first five harmonics of the passively Q-switched microchip laser in a package similar to the one just described [51,52]. The maximum pulse energies we have obtained using 1 W of cw, fiber-coupled pump power are 14 μJ at 1.064 μm, 7 μJ at 532 nm, 1.5 μJ at 355 nm, 1.5 μJ at 266 nm, and 50 nJ at 213 nm. The pulse repetition rates of these devices are all between 8 and 14 kHz, depending on the spectral performance of the pump diode used.

Since the output of the microchip laser is TEM_{00}, it is possible to focus the beam into a single-mode optical fiber. The intensities in the fiber core can reach 100 GW/cm^2. Surprisingly, these intensities do not damage the fiber. They do, however, lead to very efficient stimulated Raman scattering [53]. In a 20-m length of single-mode silica fiber pumped with 2 μJ of 532-nm radiation from a frequency-doubled passively *Q*-switched microchip laser, the pump wavelength (532 nm) efficiently generates the first Stokes line, which is red shifted by ~14 nm and broadened. This line generates a second Stokes line, which is further shifted and further broadened. The second line generates a third, and so on, until we get an extremely broadband continuum going from the yellow, through the red, and into the near infrared. The long-wavelength end of the continuum is limited by the guiding properties of the fiber. Similar spectra can be generated in the mid-IR or near-UV-to-blue regions of the spectrum by starting with the fundamental or third harmonic of the microchip laser output, respectively.

7. High-power microchip laser systems

So far, all of the passively *Q*-switched microchip lasers discussed were pumped with ~1 W of optical power. We have also constructed devices to be pumped with the 12-W output of a fiber-coupled diode laser array [54]. These devices have cavity lengths of 6–24 mm, and are constructed of a diffusion-bonded Nd:YAG/Cr^{4+}:YAG/Nd:YAG sandwich, as shown in the left half of Fig. 10. The output facet of the pump fiber is imaged into the nearest piece of Nd:YAG. All of the useful pump light is absorbed within this crystal. The purpose of the other Nd:YAG piece is to increase the cavity length in a way that maintains the robustness of the device (undoped YAG would work as well as doped material). The increased cavity length results in a larger oscillating-mode diameter [24] and, therefore, more efficient use of the pump. The Cr^{4+}:YAG is positioned near the center of the cavity so that spatial hole burning within the saturable absorber has the largest possible effect on maintaining single-longitudinal-mode operation of the laser [1].

The diode-laser pump array is operated in a pulsed mode, with the output power at either its maximum value or zero. The length of the pump pulse is adjusted to provide a single output pulse from the passively *Q*-switched laser for each diode pulse. At pulse repetition rates below 2 kHz, we are able to obtain 160 μJ of single-frequency, TEM_{00} output in a subnanosecond pulse from a 12-mm-long cavity. (More recently, we have obtained 250 μJ of single-frequency, TEM_{00} output in a 380-ps pulse from a 10.5-mm-long device.) Pulse-to-pulse amplitude variations are <0.5%. At repetition rates above 2 kHz, it becomes difficult to maintain single-mode performance of the device. All of the experiments discussed below were performed at repetition rates below 2 kHz.

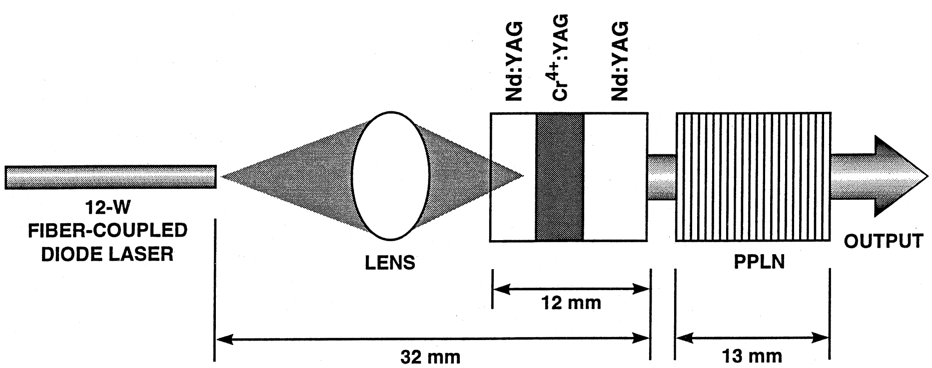

Fig. 10. Microchip-laser-pumped PPLN optical parametric amplifier.

The peak intensity of the unfocused output of the 12-mm-long microchip laser is 1 GW/cm^2; the confocal parameter is 5.2 cm. These parameters are ideal for nonlinear optics. By placing a properly oriented, antireflection-coated 5-mm-long piece of KTP in the output beam of the laser, without any intervening optics, a second-harmonic conversion efficiency of 55% was obtained, resulting in 86 μJ/pulse at 532 nm. Similarly, a properly oriented 5-mm-long piece of BBO placed in the 532-nm beam resulted in 44% conversion of the green to the UV, generating 38 μJ/pulse at 266 nm. Using a 1-mm-long piece of BBO results in 18 μJ/pulse of UV radiation.

The other thing we can do with these high-power devices is to pump optical parametric amplifiers (OPAs) and optical parametric oscillators (OPOs). The unfocused 1.064-μm output of a 12-mm-long passively Q-switched microchip laser has been used to drive single-pass periodically poled lithium niobate (PPLN) OPAs at wavelengths between 1.4 and 4.3 μm [54]. In each case, the PPLN was 13 mm in length and the experimental setup was as shown in Fig. 10. With a peak conversion efficiency of nearly 100%, these devices generate 100-kW, subnanosecond pulses in the mid IR, including the important spectral region near 1.5 μm, with a beam quality that is better than two times diffraction limited.

The frequency-doubled output of high-power passively Q-switched Nd:YAG microchip lasers has been used to pump monolithic KTP Fabry–Perot (microchip) OPOs. An initial demonstration used the same high-power microchip laser as the OPAs discussed above to pump a degenerate doubly resonant OPO [55]. The OPO cavity was 5 mm long and operated with 20% conversion efficiency, generating 8.4 μJ of 1.064-μm radiation in 600-ps pulses, with excellent mode quality and pulse-to-pulse stability. These are the shortest pulses reported for an OPO pumped with a Q-switched laser. The output of the OPO was subsequently frequency quadrupled into the ultraviolet with 3% efficiency.

A second KTP microchip doubly resonant OPO was built to operate at 820 and 1515 nm (signal and idler wavelength). This OPO has a cavity length of 1.2 mm and is pumped with the 1.7-ns frequency-doubled (green) output of a 24-mm-long passively Q-switched microchip laser. All of the crystals in the device are proximity coupled to each other, without intervening optics, as shown in Fig. 11. The OPO reaches threshold at a pump energy of ~35 μJ/pulse. By placing properly oriented crystals of KTP adjacent to the output face of the OPO, it is possible to sum the idler and signal frequencies with the remaining fundamental frequency of the microchip laser to generate red (625 nm) and blue (463 nm) outputs. The optical head of the resulting red–green–blue system can be packaged in a 75-mm-long can.

Optical parametric devices afford microchip laser systems enormous wavelength flexibility. Conservative calculations indicate that the fre-

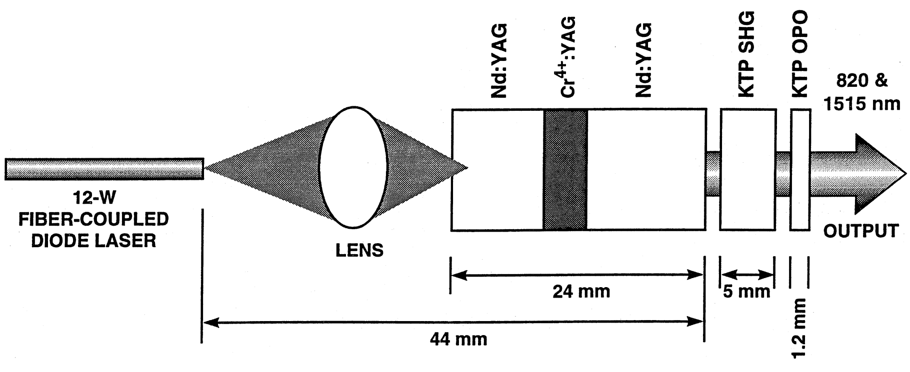

Fig. 11. Microchip-laser-pumped KTP optical parametric oscillator. SHG, second harmonic generator; OPO, optical parametric oscillator.

quency-doubled output of high-power passively Q-switched microchip lasers should be able to pump KTP OPOs operating at wavelengths (including both signal and idler) between 650 and 3000 nm [55]. Ongoing work in periodically poled materials [56–58] promises to extend this range and greatly reduce the threshold of the OPOs, making microchip-laser-pumped singly resonant devices possible. The output of the OPOs can be harmonically converted, or summed with harmonics of the microchip laser, to obtain visible and UV radiation, with wavelengths as short as 190 nm. PPLN OPAs, as mentioned earlier, have already demonstrated the ability to operate at wavelengths between 1.4 and 4.3 μm, and should work to wavelengths as long as 5 μm. The entire spectrum from the mid-IR through the deep-UV is accessible to these diminutive optical systems.

8. Summary

Microchip lasers are efficient, diode-pumped, single-frequency, fundamental-transverse-mode devices. They can be frequency tuned at high modulation rates and are capable of producing extremely short, high-peak-power pulses. A variety of miniature nonlinear optical devices, including harmonic generators, parametric amplifiers, parametric oscillators, and fiber-based Raman amplifiers, can be used to frequency convert the output of these lasers, accessing the entire spectrum from 5 μm to 190 nm in extremely compact optical systems.

Microchip lasers are a rich family of devices. The devices discussed above were designed to meet the requirements of specific systems, and should be viewed only as examples of what can be done.

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