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Passively Q-switched Nd:YAG microchip lasers and applications[☆]

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Abstract

Passively Q-switched Nd:YAG microchip lasers are robust, compact, economical, all-solid-state sources of coherent, subnanosecond, multikilowatt pulses at high repetition rates. When pumped with the cw output of commercially available infrared diode lasers, these diminutive, quasi-monolithic devices produce 1.064-μm pulses with a pulse width as short as 218 ps, pulse energy up to 250 μJ, and peak power up to 565 kW, without any switching electronics. The high output intensities of the microchip lasers enable the construction of extremely compact nonlinear optical systems capable of operating at any wavelength from 5000 to 190 nm. The short pulses are useful for high-precision ranging and 3-dimensional imaging using time-of-flight techniques. When focused, the output intensities are sufficient to photoablate materials, with applications in laser-induced breakdown spectroscopy and micromachining. The ultraviolet harmonics of the microchip laser have been used to perform fluorescence spectroscopy for a variety of applications, including environmental monitoring. Systems based on passively Q-switched microchip lasers, like the lasers themselves, are small, efficient, robust, and potentially low cost, making them ideally suited for field use.

Keywords: Solid-state laser; Diode-pumped laser; Q-switched laser; Nonlinear optics

1. Introduction

Many applications of lasers require subnanosecond optical pulses with peak powers of several kilowatts and pulse energies of several microjoules. The most common method of producing subnanosecond pulses is to modelock a laser, generating a periodic train of short pulses with an interpulse period equal to the round-trip time of light in the laser cavity, typically 10 ns. Because of the large number of pulses produced each second, even lasers with high average powers (10 W or greater) do not produce much energy per pulse. Energetic pulses can be produced by Q switching. However, the size of conventional Q-switched lasers, along with their physics, precludes producing subnanosecond pulses [1,2]. Extremely short, high-energy pulses can be obtained from Q-switched modelocked lasers or amplified modelocked lasers. Both of these approaches require complicated systems, typically several feet long and consuming several kilowatts of electrical power, and are therefore expensive.

The short cavity lengths of Q-switched microchip lasers allow them to produce pulses with a duration comparable to that obtained with modelocked systems. At the same time, they take full advantage of the gain medium's ability to store energy. Actively Q-switched microchip lasers, pumped with a 0.5-W diode laser, have produced pulses as short as 115 ps with peak powers of tens of kilowatts and pulse energies of several microjoules [3]. For proper Q switching, these lasers require high-speed, high-voltage electronics. A passively Q-switched microchip laser does not require any switching electronics [4], thereby reducing system size and complexity, and improving power efficiency. Pumped with a 1.2-W diode laser, passively Q-switched microchip lasers produce pulses as short as 218 ps with peak powers in excess of 25 kW at pulse repetition rates greater than 10 kHz. More recently, passively Q-switched microchip lasers have been pumped with high-brightness 10-W diode-laser arrays, and produced 380-ps pulses with peak powers in excess of 560 kW at pulse repetition rates up to 1 kHz. All of these devices oscillate in a single, transform-limited longitudinal mode, and produce a diffraction-limited, linearly polarized, circularly symmetric Gaussian beam.

Diode-pumped passively Q-switched microchip lasers are a new family of all-solid-state sources. The first half of this paper describes the characteristics of these devices, pointing out how their small size leads to rather remark-

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able and useful properties, including very short pulses, enormous peak powers, and ideal mode characteristics. The high peak powers make it easy to perform nonlinear frequency generation, greatly extending the wavelength coverage of these diminutive devices and their utility. The second half of this paper describes a few of the many applications for passively Q-switched microchip lasers. Three applications are discussed in detail: 3-dimensional imaging, laser-induced breakdown spectroscopy, and environmental monitoring using a cone penetrometer. Each of these applications is enabled by different characteristics of the laser.

2. Passively Q-switched Nd:YAG microchip lasers

2.1. Low-power systems

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. The onset of lasing, at that point, produces a high intracavity optical field that saturates the saturable component of the optical 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.

In their simplest embodiment, illustrated in Fig. 1, the passively Q-switched microchip lasers developed at MIT Lincoln Laboratory are constructed by diffusion bonding a thin, flat wafer of Nd^{3+}:YAG gain medium to a similar wafer of Cr^{4+}:YAG saturable absorber [4]. Alternative approaches include the use of a single material that acts as both the gain medium and the saturable absorber [5,6], the growth of one material on the other [7], and the use of semiconductor saturable absorbers [8,9]. The composite structure is 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 and to be highly reflecting at the oscillating wavelength. The output face is coated to be partially reflecting at the lasing wavelength and provides the optical output from the device. The IR laser is completed by dicing the wafer into small squares, typically 1–2 mm on a side. The YAG cavity is then mounted on an appropriate heatsink and pumped with the output of a fiber-coupled diode laser. Fig. 2 shows a photograph of a passively Q-switched microchip laser epoxied directly to the ferrule of the pump fiber, with the ferrule serving as the heatsink. The simplicity of the passively Q-switched microchip laser and its small amount of material give it the potential for inexpensive mass production; nearly monolithic construction results in robust devices.

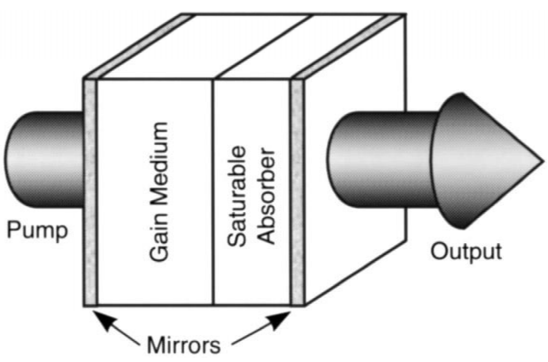

Fig. 1. Illustration of a passively Q-switched microchip laser.

The minimum pulse width that can be obtained from any Q-switched laser is given by [1,2,4]:

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

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. Since microchip lasers are physically very short, they have very short cavity round-trip times and can produce very short output pulses. As an example, a 0.75-mm-long Nd:YAG microchip laser has a round-trip time of 8.2 ps. Pumped with an incident power of 1 W from a diode laser, it is possible to achieve a round-trip gain of 1.4, resulting in a pulse width as short as 200 ps. To put this in perspective, before we started working 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 pulse widths in excess of 5 ns long.

The device shown in Fig. 2 produces an output pulse with a 218-ps pulse width. It operates at 10 kHz with a pulse energy of 4 μJ. The peak power of this device is in excess of 15 kW. High peak powers are another aspect of passively Q-switched microchip lasers that make them very interesting.

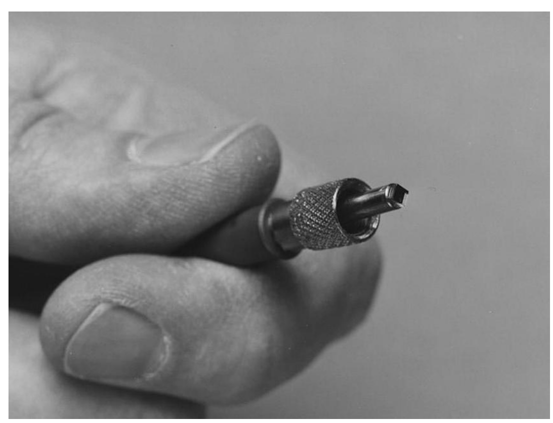

Fig. 2. Passively Q-switched microchip laser bonded to the end of a multimode pump fiber.

In addition to producing extremely short Q-switched pulses with high peak powers, the short length of the microchip cavity promotes single-frequency operation [10], so that the output pulses are free of mode beating. The flat cavity mirrors strongly favor fundamental-transverse-mode operation [10]. The result is an output beam with nearly ideal temporal and spatial mode properties.

We have built several variations of the 1-W-pumped passively Q-switched microchip laser, for applications including high-precision ranging, remote sensing, nonlinear frequency generation, material characterization, micromachining, and spectroscopy. These devices typically have a cavity length between 0.75 and 1.5 mm. Specifications and performance parameters for several of these devices are given elsewhere [11]. Using a 1-W pump, we have obtained output pulses as short as 218 ps, pulse energies as high as 14 μJ, and peak powers up to 30 kW [4,11,12]. Devices using semiconductor saturable absorbers have demonstrated 62-nJ pulses with pulse durations as short as 56 ps [9]. Time-averaged powers up to 120 mW have been demonstrated. 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 of Nd:YAG lasers at 946 nm using Cr^{4+}:YAG as the passive Q switch [13]. 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 [14].

2.2. Nonlinear frequency conversion

The high peak intensities of the passively Q-switched microchip lasers allow for efficient nonlinear frequency generation. By simply placing a 5-mm-long piece of KTP near the output facet of the laser, with no intervening optics, we have obtained doubling efficiencies as high as 70%, although more typical numbers are between 45 and 60% [4]. Since we still have 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, as shown in Fig. 3 [12,13,15–17]. In all cases, the crystals are polished flat on the faces normal to the optic axis and butt coupled to each other without any intervening optics, allowing for very simple, and potentially inexpensive, fabrication.

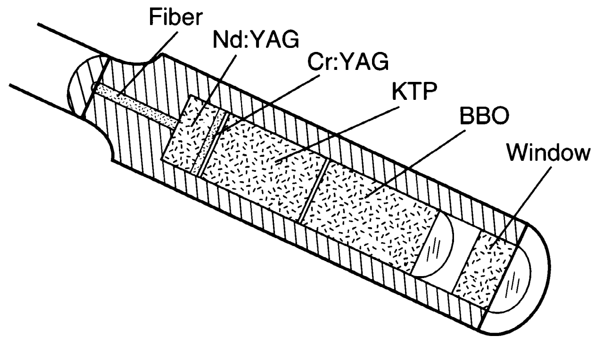

Fig. 3. Schematic of a UV harmonically converted passively Q-switched microchip laser.

By placing the appropriate nonlinear optical crystals near the output facet of the lasers, we have generated up to 7 μJ of green, 1.5 μJ of third-harmonic, 1.5 μJ of fourth-harmonic, and 50 nJ of 213-nm (fifth-harmonic) light, at a typical pulse repetition rate of 10 kHz [12,13,15–17]. In each case, the optical head of the device, including the passively Q-switched microchip laser and the nonlinear crystals, has been packaged in a 1-cm-diameter×2.5-cm-long stainless steel can, as shown in Fig. 4. The electronics required to operate the system fit in an 11 cm×17 cm×4 cm box that consumes ~8 W of power at room temperature. The wavelength diversity offered by harmonic conversion opens up numerous applications. In particular, the UV wavelengths are extremely useful for laser-induced fluorescence spectroscopy and flow cytometry.

Since the output of the microchip laser is diffraction limited, 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. This leads to very efficient stimulated Raman scattering. The input wavelength efficiently generates the first Stokes line, which is red shifted 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. Four-wave mixing broadens the spectrum beyond what is expected from Raman shifting alone [13,18,19]. By pumping a 100-m length of 10-μm-core fiber with 1.064-μm

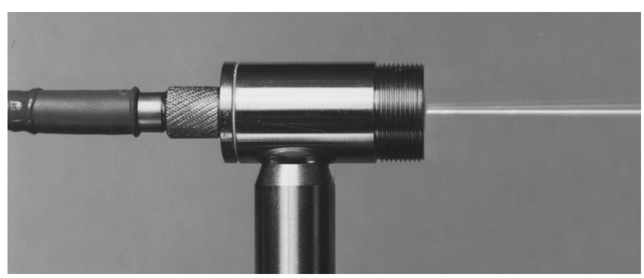

Fig. 4. Optical head of a low-power UV passively Q-switched microchip-laser system packaged in a 1-cm-diameter×2.5-cm-long stainless steel can.

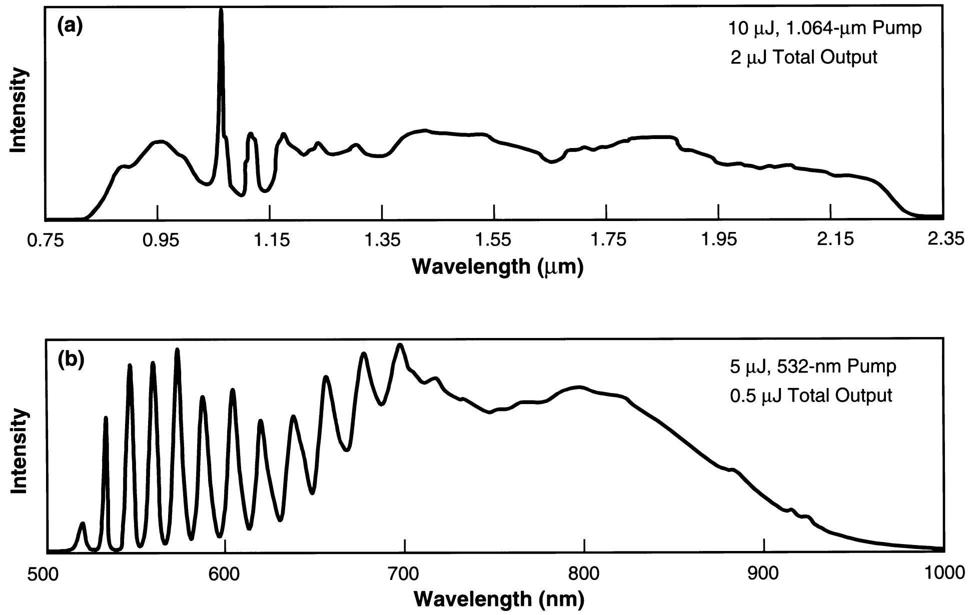

Fig. 5. Output spectra obtained through cascaded stimulated Raman scattering in: (a) a 100-m length of 10-μm-core fiber pumped with 1.064-μm light; (b) a 100-m length of 4.6-μm-core fiber pumped with 532-nm light.

light, we obtain a relatively featureless output spectrum extending from 850 nm to 2.25 μm, as shown in Fig. 5a. The long-wavelength end of the continuum is limited by absorption in the fiber. The spectrum obtained from a 100-m length of 4.6-μm-core fiber pumped with 532-nm light extends from the green to 950 nm in the near IR, as shown in Fig. 5b. Similar spectra can be generated in the near-UV-to-blue by starting with the third harmonic of the microchip-laser output. Potential applications for this technology include time-resolved reflection, transmission, and absorption spectroscopy; active hyperspectral imaging [19]; and white-light interferometry.

2.3. High-power systems

So far, all of the *Q*-switched microchip lasers discussed were pumped with ~1 W of optical power. We have also designed several devices to be pumped with the higher-power output of fiber-coupled diode-laser arrays [11,20–22]. In addition to the gain medium and the saturable absorber, the higher-power devices typically have undoped YAG endcaps, as shown in Fig. 6. The endcaps perform several functions. One thing they do is to lengthen the cavity. The higher-power devices typically have a cavity length of between 6 and 24 mm. Longer cavities produce oscillating modes with a larger diameter, which can more effectively use the power deposited by the pump diodes. Increasing the cavity length also increases the output pulse length, keeping the peak power of these higher-power devices below the damage threshold of the materials used. There are other reasons why it is sometimes desirable to lengthen the output pulses, such as when the device is to be used to pump optical parametric oscillators (OPOs) [13,20]. In this case, longer pulses result in a lower threshold for the OPO. The undoped YAG endcaps also increase the damage threshold of the lasers by reducing the thermal stress on the dielectric mirrors and by removing the active materials from the air interfaces.

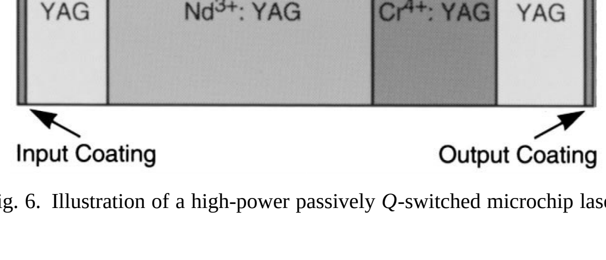

Fig. 6. Illustration of a high-power passively *Q*-switched microchip laser.

Pumping the high-power devices with high-brightness 10-W fiber-coupled diode-laser arrays, we are able to obtain pulse widths as short as 310 ps, pulse energies as high as 250 μJ, and peak powers up to 565 kW, at pulse repetition rates of several kilohertz [11,22]. Like the low-power devices, the high-power passively *Q*-switched microchip lasers have nearly ideal mode properties and excellent pulse-to-pulse stability.

The high-power devices can be harmonically converted to produce high-power UV output. Devices producing over 19 μJ of 355-nm output, or 12 μJ of 266-nm output, at 5 kHz, have been packaged in robust, 8-cm-long cans, as shown in Fig. 7 [11,22]. These diminutive systems have sufficient power to be useful for UV photo-ionization spectroscopy [23], UV matrix-assisted laser desorption and ionization (MALDI), and UV stereolithography for rapid prototyping.

Fig. 7. Optical head of a high-power UV microchip-laser system packaged in a 2.5-cm-diameter×8-cm-long (3-inch-long) stainless steel can.

Another thing we can do with these high-power devices is to pump optical parametric amplifiers and oscillators. We have used the unfocused 1.064-μm output of a high-power passively Q-switched microchip laser to drive several periodically poled lithium niobate optical parametric amplifiers (OPAs), covering the spectral range from 1.4 to 4.3 μm [13,21]. In these devices, we observe nearly 100% conversion of the pump radiation at the peak of the pulse.

We have also demonstrated bulk-KTP OPOs pumped with the first and second harmonics of a high-power microchip laser. The OPOs pumped at 1.064 μm were singly resonant devices oscillating at 1.6 μm. The OPOs pumped with the second harmonic of the microchip laser were doubly resonant, and oscillated at signal and idler wavelengths between 700 and 2000 nm [13,20].

The excellent mode quality and extremely high peak powers of the OPAs and OPOs allow for efficient harmonic conversion of their output. Optical parametric devices and their harmonics extend the spectral coverage of microchip-laser systems continuously from ~5 μm to 250 nm. By frequency summing the output of optical parametric devices with the harmonics of the microchip laser, we can extend the capabilities to about 190 nm, the absorption edge of BBO [13]. Potential applications for the deep UV include the alignment and calibration of optics for excimer lasers and excimer-laser systems.

3. Applications

As indicated throughout the first part of this paper, passively Q-switched microchip lasers are attractive devices for a wide range of applications. The short pulses are useful for high-precision ranging using time-of-flight techniques, with applications in 3-dimensional imaging, target identification, and robotics. The short pulse durations and ideal mode properties can also be used to advantage in the characterization of materials. The high peak powers of the microchip lasers can be used to photoablate materials, leading to applications in laser-induced breakdown spectroscopy and micromachining. As discussed above, the high peak powers also enable the construction of extremely compact nonlinear optical systems. The UV systems, in particular, have already been used to perform UV fluorescence spectroscopy for a variety of applications, including environmental monitoring and the detection of biological particles.

This paper will now discuss three of these applications in more detail, including: 3-dimensional imaging, where the short pulse width and good pulse stability are the key features of the laser; laser-induced breakdown spectroscopy, where the extremely high peak powers are the enabling laser characteristic; and environmental monitoring using a cone penetrometer, where the small size of the UV head and the ability to fiber pump it at IR wavelengths are essential. All of these applications use low-power, 1-W-pumped microchip lasers.

3.1. Ranging and imaging

Time-of-flight optical ranging is one application for the microchip laser. The resolution of such a system is one half of the speed of light multiplied by the pulse width. A 200-ps optical pulse can provide a range resolution (minimum separation between two resolvable objects) of 3 cm. When the shape of the optical pulse is repeatable, as is the case for the microchip laser, the accuracy of the system can be much better. At MIT Lincoln Laboratory, we have demonstrated a compact time-of-flight optical transceiver using a low-power frequency-doubled green microchip laser attenuated to the Class-II eye-safe level of 0.2 μJ per pulse. We were able to range to objects, including black felt, with a single-pulse range accuracy of 1 mm at distances up to 50 m. The system used a commercial 1-GHz detector and 5-cm-diameter collection optics. Coupled to a 2-dimensional scanning system, the high repetition rate of the laser makes it possible to obtain a high-resolution, 3-dimensional image in minutes. This system was developed in collaboration with Cyra Technologies, Inc. [24]. Cyra offers a commercial, tripod-mounted, battery-operated version of the system, Cyrax™, with software that can quickly convert the captured images to 3-dimensional CAD models [25]. Applications for such a system include automated production, civil engineering, construction, and architecture.

The system just described uses one of the least powerful of the microchip lasers discussed here, and attenuates its frequency-doubled output. Higher-power devices have the capability of ranging at much greater distances [26]. The unamplified output of the high-power devices is capable of performing earth-to-satellite ranging with centimeter accuracy [27,28]. The output of microchip-laser-pumped OPAs and OPOs can be used to perform ranging at eye-safe wavelengths.

3.2. Laser-induced breakdown spectroscopy

Passively *Q*-switched microchip lasers can be used to perform laser-induced breakdown spectroscopy (LIBS). Although the per pulse energy is relatively low compared to lasers conventionally used in this application, the diffraction-limited beam can be focused to a spot size as small as 1 μm in diameter. Even the low-power microchip lasers can be focused to intensities in excess of 1 TW/cm^2. This is sufficient to break down metals and many other solids [15,29,30]. In the resulting plasma, there are highly excited ions, atoms, and molecules — each emits a unique spectrum as it recombines. By examining the recombination spectra, it is possible to determine the composition of the material. We have demonstrated the detection of various metals in soil using a low-power microchip laser and a compact diode-array-based spectrometer [30]. Because the optical pulse length is short and the resulting plasma volume is small, the plasma continuum radiation decays rapidly (in ~15 ns). This has allowed us to measure sensitivities of up to 100 ppm without any of the standard temporal or spatial gating that conventional LIBS systems employ [31–33]. Potential applications include the identification of heavy-metal contaminants such as Pb, Hg, Cd, Cr, and Zn [34].

As the power of the microchip laser increases, so too do the sensitivity of the resulting LIBS system and the variety of materials that can be examined. Mid-power devices, pumped with 3-W diode-laser arrays, easily break down transparent media, including glasses and water; the focused output of the highest-power devices is sufficient to break down clean air [35], with potential applications in the monitoring of effluents and closed-loop process control.

3.3. Remote environmental monitoring

Laser-based techniques are highly sensitive methods for determining concentrations of chemical species, including pollutants. For many applications, the optimal measurement wavelengths lie in the UV. In recent years, remote detection has been performed with UV light delivered to the remote area with an optical fiber. Unfortunately, optical fibers transmit UV poorly. Thus, powerful lasers are required to provide sufficient energy at the fiber's distal end to ensure adequate detection sensitivity. In addition, sensitivity is critically dependent on the fiber length. These limitations can be overcome by using a multimode fiber to deliver easily transmitted near-IR diode-laser pump radiation to a remote head containing a UV frequency-converted passively *Q*-switched microchip laser [15,29,30].

We have constructed a sensor head that is 2.5 cm in diameter by approximately 7 cm long for use in a cone penetrometer [36–39] to characterize subsurface contamination at depths up to 50 m. The sensor head contains a frequency-quadrupled low-power passively *Q*-switched microchip laser and collection optics. The laser output is filtered to remove the IR and visible light before the UV light is focused outside through a sapphire window. Fluorescence from material contacting the window is collected and focused into a 500-μm-core return fiber for spectral analysis. The short duration of the excitation pulse facilitates accurate measurements of the decay times of even the short-lived benzene, toluene, ethylbenzene, and xylene (BTEX) compounds (decay times from 2 to 60 ns). Measurements of fluorescence decay times offer greater chemical selectivity than that of spectra alone [40].

This laser-probe technology has recently been field tested [30]. By examining the spectral and temporal fluorescence characteristics as the probe was pushed into the ground, we identified BTEX compounds as well as heavier aromatic hydrocarbons that resulted from contamination due to aviation and heating fuels. These tests demonstrated that the microchip-laser-based probe offers the potential for in situ, real-time characterization of soils and groundwater in a robust, compact, inexpensive package.

For compounds that do not fluoresce appreciably, such as chlorinated solvents, we have measured Raman spectra, using the time domain to distinguish the Raman lines from fluorescence due to interferents in the same spectral region [30]. Work is under way to develop a laser-based NO_x detector for the detection of energetic contaminants such as the explosives TNT, RDX, and HMX.

3.4. Other applications

Passively *Q*-switched microchip lasers are attractive devices for a wide range of applications, beyond those discussed in detail above. We have used UV laser-induced fluorescence spectroscopy for the detection of airborne biological particles [41]. In this application, the spectral characteristics of the fluorescence of tryptophan, NADH, and flavins can be used to distinguish biological particles from nonbiological particles, and even to do some classification of biological particles. In recent field tests, our battery-operated, portable bioaerosol-fluorescence sensor, built around a low-power frequency-quadrupled microchip laser, proved to be effective in the detection of biological-warfare simulants. Other potential applications of this technology include monitoring the air in hospitals and public buildings to help control the spread of airborne communicable diseases.

It is apparent from the above discussion of laser-induced breakdown spectroscopy that the *Q*-switched output of a microchip laser can photoablate most materials, including metals, semiconductors, glasses, and biological tissues. We have used a low-power microchip laser at both 1.064 μm and 532 nm to cut clean 5-μm-wide lines in the metallization on semiconductor wafers and to drill holes through the substrate. Higher-power devices have been used to bore holes in glass, scribe alumina, etc. Applications in microsurgery are being investigated.

Active Impulse Systems has developed the Impulse 300™, an instrument designed to measure the mechanical and thermal properties of thin films, around a low-power passively *Q*-switched microchip laser [42]. Using the technique of impulse-stimulated thermal scattering, the Impulse 300 can make nondestructive measurements of thin-film thickness to an accuracy of 5 nm, with a transverse resolution of 10 μm. It can also measure the anisotropic elastic moduli and thermal diffusivity, as well as determine whether or not there is delamination of the film, all at about 1000 measurements per second. In addition to semiconductor manufacturing, potential applications of this technology include checking for defects in painted or laminated surfaces, and monitoring the curing of epoxies and resins.

SPARTA, Inc. uses the green and UV output of a low-power microchip laser in their second-generation nanAlign™ interferometer system to remove measurement error that results from a turbulent air path [43]. This system improves the ability to position the stage used to hold semiconductor wafers during the lithography process.

The broad spectrum generated by microchip-laser-pumped cascaded stimulated Raman scattering in fibers has applications in absorption, reflection, and excitation spectroscopy; active 3-dimensional hyperspectral imaging [19]; and white-light interferometry. The high-power UV devices can be used for photo-ionization spectroscopy [24], matrix-assisted laser desorption and ionization (MALDI), and stereolithography. The list goes on, and new applications continue to emerge as this technology becomes more readily available.

4. Conclusions

Passively *Q*-switched microchip lasers are a new and important family of high-performance devices. These lasers, and the systems based on them, are small, efficient, robust, and low cost. They have the proven potential to take what were complicated laser-based experiments out of the laboratory and into the field, enabling applications in diverse areas.

This technology is still in its infancy; low-power microchip lasers are just now becoming commercially available [44–46]. Further work can be expected to lead to shorter pulses, higher peak powers, increased pulse energies, and new wavelengths of operation. With advances in the technology, and increased availability, the applications of passively *Q*-switched microchip lasers will continue to expand. At MIT Lincoln Laboratory, we are continuing to push the limits of this technology and to develop the unique systems that it enables.

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