Thomas M Spinka
ECE 455
12/13/2004

Chromium-Doped Forsterite Lasers

1. Introduction

The discovery of the solid-state ruby laser by Theodore Maiman in 1960 opened the door to the now-flourishing field of laser research[9]. The chromium-doped sapphire crystal that forms the gain medium for the ruby laser provided a model for the discovery of the broadly tunable solid-state laser in alexandrite in 1979. The discovery of the emerald laser in the early 1980s led to a flurry of research focused on finding new laser crystals and new ions that would lase in commonly-used host crystals. These research efforts led to the discoveries of numerous laser systems, such as Cr:Nd:GSGG, Co:MgF_2, Cr:$ZnWO_4$, and many others. In early 1988, Petričević *et. al.* first reported lasing in chromium-doped forsterite (Cr:Mg_2SiO_4, hereafter Cr:forsterite)[11]. This fascinating laser system has tremendous potential for applications in near infrared imaging, communications, and semiconductor inspection.

In this paper, I will first review the forsterite crystal structure, properties and growth processes, and then move into the early history of the laser system, covering the discovery of the Cr:forsterite laser and the first demonstration of continuous-wave and mode-locked operation, as well as some important advances in Cr:forsterite laser output power and efficiency. I will then conduct a more in-depth study of lasing in continuous-wave (cw) mode, reviewing the laser system of Petričević *et. al.*[11], looking at the study done by Carrig *et. al.* in 1993, which tested several pump lasers[5], touching on the study done by Qian *et. al.* in 1997 of diode pumping[14], doing a short overview of the high-power record for cw Cr:forsterite lasers by Zhavaronkov *et. al.*[23], and concluding the cw section by investigating thermal effects on the laser output and ways that these effects can be minimized. In the following section, I will present an in-depth study of mode-locked operation of Cr:forsterite lasers by investigating several papers presented starting in 1991. This section will also proceed chronologically, including active mode-locking, synchronous pumping, additive-pulse mode-locking, and mode-locking with Semiconductor Saturable-Absorber Mirrors. I will close the paper by reviewing some applications that take advantage of some of the unique characteristics of Cr:forsterite lasers, including biological imaging, remote sensing, semiconductor inspection, and optical communications.

2. Forsterite Crystal Growth and Properties

Forsterite is a member of the olivine family of crystals[24]. Its empirical formula is Mg_2SiO_4, with the magnesium atoms forming a single bond with two oxygen atoms each of the silicate (SiO_4) tetrahedron. In its crystalline form, forsterite forms an orthorhombic dipyramidal structure of the space group *Pbnm*. In chromium-doped forsterite, the chromium ions (both Cr^{3+} and Cr^{4+} are generally present) replace the Mg^{2+} ions. Forsterite and its iron counterpart, fayalite (Fe_2SiO_4) almost always occur together in nature, so lasing crystals must be fabricated.

Synthetic forsterite can be grown from a seed crystal using the Czochralski method. This process for growing crystals is mainly used to produce high-quality low-impurity semiconductor wafers, but can be adapted to grow many types of laser crystals as well. Growing the laser crystal for the Cr:forsterite laser involves dipping a small forsterite seed crystal into a vat of liquefied magnesium and silicate with a small doping concentration of chromium and slowly removing the crystal from the vat while precisely controlling the temperature, pressure and rotation speed of the pulled crystal and its surroundings to form a very pure and low-impurity crystalline structure. Typical doping concentrations are on the order of 10^{18}-10^{19} ions/cm^3, and the crystals are typically cut to precise dimensions on the order of a few cm long and with a physical cross-section of around 25 mm^2 which is generally coated with a broadband anti-reflection coating to reduce photon loss at the boundaries of the crystal during lasing.

3. History

On March 28, 1988, Vladimir Petričević and his colleagues first reported lasing in a chromium-doped forsterite crystal[11]. In this historical article, Petričević *et. al.* laid the groundwork for all of the Cr:forsterite research to come. They provide an absorption spectrum and a fluorescence spectrum from 300 nm to 1500 nm, and report lasing at 1235 nm with a bandwidth of about 22 nm. However, due to the repetition rate of the Nd:YAG pump laser they used, the lasing they achieved was not true cw, but gain-switched lasing. However, soon thereafter, the same research group achieved true cw lasing in the Cr:forsterite at room temperature using a cw Nd:YAG pump laser[12]. Having obtained a new crystal, they were able to increase the tunable range of the Cr:forsterite laser to 1167-1345 nm with a full-width at half-max (FWHM) of 12 nm. They also estimated the effective emission cross section to be 1.1×10^{-19} cm^2.

Two years later, A. Seas and coworkers reported the first mode-locked operation of the Cr:forsterite laser, producing pulses of 260 ps and 31 ps with different mode-locking tactics[15]. These pulse-lengths were not spectacularly short, but the purpose of this first demonstration of mode-locking was not to break any pulse-length records. It was merely a demonstration that mode-locking in a Cr:forsterite laser is possible and effective. In fact, only a year later, Sennaroglu *et. al.* published their results on additive-pulse mode-locking (APM)[16]. With this technique, they narrowed the width of the pulse to 150 fs. By cryogenically cooling the Cr:forsterite laser, they were able to achieve average output powers of up to 2.8 W. Only months later, near the beginning of 1993, the length of the shortest pulse demonstrated on a Cr:forsterite laser dropped again, this time by a factor of 6. Yanovsky *et. al.* produced pulses of as short as 25 fs using self-mode-locking[21].

Back in the cw realm, Carrig *et. al.* did an extensive study on the most effective pump lasers[5], publishing their results in 1993. They tested lasing in Cr:forsterite with a krypton ion, Ti:sapphire and Nd:YAG laser as pumps, and showed that lasing was possible for all three pump sources. The natural next step towards making the solid-state Cr:forsterite laser an all-solid-state system was to show that diode pumping is effective, which is exactly what Qian *et. al.* did in 1997[14]. One obvious disadvantage to Cr:forsterite is its low thermal conductivity, which starts becoming an issue as the pump power increases to more than a few watts. This effect came under study in a paper by Zhaoronkov *et. al.* published in 1997[23], which addressed the thermal loading theoretically. They also obviously applied the theory in obtaining the highest room-temperature cw lasing in Cr:forsterite to date.

As the improvements to the Cr:forsterite laser system became more and more pronounced through the 10 years after its initial discovery, applications of the laser system became increasingly attractive. In 2000, Abraham *et. al.* published a paper on real-time two-dimensional biological imaging using a mode-locked Cr:forsterite laser at 1220 nm[1], and in early 2002, an extension of this group improved this application significantly to be competitive with a more standard technique of optical coherence tomography (OCT)[2]. But the real driver to application research will probably be the release, on November 9, 2004, of a complete, all-solid-state commercially available Cr:forsterite laser, from Del Mar Ventures[25]. With a commercially available complete laser system that provides 2 nJ pulses on the order of 65 fs long, scientists will be able to focus on applications. Del Mar Ventures also offers an amplification system which can produce similar length pulses with a peak power of 1 –2 TW. Possible applications of these extremely high power systems include condensed matter imaging and micromachining.

4. Continuous-Wave Operation

To understand the Cr:forsterite laser more fully, it is instructive to consider specific systems in more detail than we have so far. We will first examine the laser system employed by Petričević *et. al*. as they first demonstrated lasing in Cr:forsterite[11]. The experimental setup for this demonstration is, in fact, quite simple. The crystal, a 9 mm × 9 mm × 4.5 mm parallelepiped grown by Electronic Materials Research Laboratory of the Mitsui Mining and Smelting Co., Ltd., acts as the gain medium for the system. It is placed at the center of a stable resonator cavity formed by two spherical mirrors of radius 30 cm placed 20 cm apart. The high-reflectivity mirror was dielectric-coated to be 99.9% reflecting in the 1150 – 1250 nm range, while the output coupler was 98% reflective over this range. Both mirrors transmit the 532 nm pump wavelength. The laser system was pumped by a frequency-doubled Q-switched Nd:YAG laser operating at a 10 Hz repetition rate, providing pumping at 532 nm. The FWHM of the pump pulses was 10 ns and the observed threshold pump energy was 2.2 mJ. As the pump pulse energy increased beyond the threshold value, a single output pulse from the Cr:forsterite crystal was observed. The pulse energy increased smoothly with the pump pulse energy beyond the threshold value. Interestingly, the time delay between the pump pulse and the output pulse decreased with increasing pulse power. This is easily explained by noting that the cavity must have a very low single-pass gain, which means that it takes many round-trips through the cavity to build up the laser intensity to the lasing threshold level. This explanation is supported by noting that lasing was extremely sensitive to even a slight cavity misalignment or the insertion of a glass plate into the cavity, which introduces about an 8% loss. The measured slope efficiency is rather low, at 1.4%, which also supports the hypothesis of a high-loss cavity.

As the next step beyond the pulsed operation of the laser demonstrated in their 1988 article, Petričević and his research group attempted and attained true cw lasing with the Cr:forsterite laser[12]. As they pointed out in their article, cw operation is not assured based solely on obtaining pulsed operation, as evidenced by the Nd:Glass laser. The setup for this experiment was significantly different than that of the discovery paper. A new Cr:forsterite crystal (6 mm × 6 mm × 30 mm, Cr concentration $2.8\times10^{18}/cm^3$) was placed at the center of a nearly concentric laser cavity with spherical mirrors of radius 5 cm. The crystal was sandwiched between two copper plates to facilitate heat dissipation. The mirrors were coated to be mostly transmissive to the pump wavelength of 1064 nm, while maintaining high reflectivity for the Cr:forsterite lasing region. The output coupler for this experiment was 99% reflective, while the input mirror was 99.9% reflective over the entire lasing region from 1200 – 1400 nm. The pump was a cw-operated Nd:YAG, chopped to a duty cycle of 10%. When the pump laser was unchopped, the Cr:forsterite laser operated at 40% reduced output power due to thermal effects. The lasing threshold occurred at 1.25 W of input power, and the measured slope efficiency increased dramatically to 6.8%. In this paper, Petričević estimates the stimulated emission cross section to be 1.1×10^{-19} cm^2. However, the emission cross section obtained from the emission lifetime and line shape is 3.3×10^{-19} cm^2, which is a significant difference from the observed value. This difference is explained by realizing that there must be other small loss mechanisms at work. Vehicles for these losses include excited-state absorption and nonradiative relaxation, which implies that the fluorescence lifetime is not a good approximation for the radiative lifetime used to calculate the theoretical emission cross section. They also quote the lasing wavelength and FWHM at 1244 nm and 12 nm, respectively.

In the next several years, great strides were made in optimizing the Cr:forsterite laser. Once again, Petričević's group made significant contributions in optimizing the slope efficiency by testing multiple output couplers[13]. They achieved a massive increase in efficiency, raising it to 38%, which is one of the highest of any tunable solid-state laser system to that time. Another research group, Carrig and Pollock, demonstrated much higher output power at cryogenic temperatures than had been described in previous papers[4]. They obtained 1.8 W of output power at 77 K, tunable from 1200 – 1320 nm, fully 10 times higher than described in several previous papers. However, Carrig and Pollock mention that the output power decreases to about 35% of the cryogenic power level when the system is run at room temperature, which is much closer to that obtained previously.

To that point, the only pump laser used was a Nd:YAG laser. However, in 1993, Carrig and Pollock did a comprehensive study of three pump lasers for the Cr:forsterite laser system, including the Krypton Ion laser, the Ti:sapphire laser and the Nd:YAG laser[5]. Starting with the Nd:YAG laser at 1064 nm and 77 K, Carrig and Pollock obtained 2.8 W of cw power from the Cr:forsterite laser with a 13% output coupler. At this wavelength about 78% of the incident pump power was absorbed by the crystal. It would not have been unlikely to begin seeing saturation effects at these power levels, but no such output power leveling was observed for pump powers up to 12 W. Less input power was available from the other two pump lasers, and hence, the output power of the Cr:forsterite laser was also significantly lower than that for the Nd:YAG pump laser. For 4.4 W of incident power at around 750 nm from the Ti:sapphire laser, the output power was 0.64 W with a 10% output coupler, and for 4.4 W of incident power from a krypton ion laser at any of its dominant output wavelengths (676 nm, 647 nm, and others), the Cr:forsterite laser had an output power of 0.32 W with a 7% transmissive output coupler. As the temperature of operation was raised from 77 K to room temperature, thermal effects began to dominate the output power of the Cr:forsterite laser. For a Ti:sapphire pump, Carrig and Pollock could not obtain lasing at powers greater than 220 to 270 K, dependent on the pump wavelength and pump power. Similarly, they could not obtain Cr:forsterite lasing above 225 K for more than 6 – 7 seconds, after which the initial 40 mW of output power faded to zero. One of the major goals for this investigation was to determine the feasibility of diode-pumping. The conclusion they drew was that diode pumping is feasible, but some modifications to the chromium doping concentration of the laser crystal would be necessary, and the pumping may be inefficient due to weak absorption at diode-accessible wavelengths.

Several years later, in 1997, a group from Cornell University demonstrated a diode-pumped Cr:forsterite laser. Qian *et. al*. describe a Cr:forsterite laser system pumped by 4 AlGaInP semiconductor diode lasers which each emit about 400 mW of output power at around 680 nm[14]. This material and wavelength range was chosen because Cr:forsterite has a strong absorption band that peaks at 740 nm that exhibits absorbance of about 6 times that at the wavelength of a Nd:YAG pump at 1064 nm. Since there were no commercially available semiconductor diode lasers operating in this wavelength range, AlGaInP was chosen because it lases at 680 nm, where the absorbance is still 3 times that at 1064 nm. The maximum total power available at the forsterite crystal was about 1.2 W, and up to 65% of this was absorbed by the crystal. Because of the relatively small amount of available pump power, using an output coupler with a transmission coefficient of more than 2% dropped the gain in the laser cavity below the threshold value. However, lasing was achieved for both a 1% and 2% output coupler, exhibiting 1% and 2% efficiency, respectively. These extremely low efficiencies resulted in a maximum output power of the Cr:forsterite laser of only 5 mW. However, as was the goal of this project, Qian *et. al*. successfully demonstrated that diode-pumping of the Cr:forsterite laser was possible.

Later in 1997, Zhavoronkov *et. al*. published a brilliant paper detailing a method to significantly increase the room temperature cw output power of the Cr:forsterite laser[23]. In demonstrating this method, they achieved 1.1 W of unchopped cw output power at room temperature with a slope efficiency of 26%. By making a few useful assumptions, Zhavoronkov and his coworkers were able to model the distribution of thermal energy in the Cr:forsterite crystal, and optimize the laser cavity to match the thermal lensing properties of the crystal as a function of pump power. The assumptions they made in order to develop this theory are: 1) that heat flow in the laser crystal is radial, which is a reasonable assumption if the pump laser beam is centered on the crystal. 2) that the thermal conductivity of the material, the absorption coefficient at the pump wavelength and the amount of absorbed pump power per unit volume of material that leads to heating of the rod are all constants over the temperature and pump power ranges considered. 3) that the spatial intensity profile of the pump beam is a cylindrically symmetric Gaussian TEM_{00} mode. Making these assumptions and using several standard laser equations and the ABCD matrix formalism, they were able to derive a method for determining the optimal asymmetrical location of the laser crystal within the cavity. The reason that the optimal position is not the center of the cavity is that, due to the distribution of the absorbed heat energy in the forsterite crystal, the change in material index of refraction as a function of temperature acts as a focusing lens.

By 1998, thermal loading in the cw Cr:forsterite laser system was a topic of high interest. Alphan Sennaroglu made significant contributions in several papers published in February and March of 1998 and November of 2001[17,18,19]. His 1998 papers focused on improving the efficiency via improvements to the laser crystal properties, radiative cooling, and chopping of the pump laser. His 2001 publication focused not only on Cr:forsterite lasers, but on Cr^{4+}-doped solid state lasers in general, of which Cr:forsterite is one. It presents a highly detailed theoretical model of power performance of solid-state lasers subject to lifetime thermal loading. Another paper that was published in November of 2001 also focused on issue of thermal loading. Ivanov *et. al*. addressed the temperature dependence of the fluorescence lifetime of the upper laser state[7], which was shown to be a large factor leading to the decrease in output power of thermally constrained Cr:forsterite lasers. In fact, thermal effects in the laser crystal are still a major focus of current research today.

5. Mode-Locked Operation

Laser mode-locking is a group of techniques for producing extremely short pulses from a laser. Mode-locking is divided into two major categories: active mode-locking and passive mode-locking. Short pulses are useful in many application, including but not limited to optical coherence tomography (OCT) for biomedical imaging, high-speed communications, remote sensing applications, and others. The first demonstration of short pulses using a Cr:forsterite laser occurred in 1991 in a paper by Seas *et. al*.[15] Using the Ti:sapphire laser as a model for the Cr:forsterite due to the similarities between them, they achieve synchronous pumping mode-locking and active mode-locking. Synchronous pumping is the simplest way to achieve mode-locking in a laser system. In this technique, the active gain medium of the driven laser is modulated at a frequency that equals the round-trip time of the active laser cavity resonator as well as the frequency of the mode-locked pump source. In this case, the pump laser was a cw mode-locked Nd:YAG laser oscillating in a 1.8 m cavity, which corresponds to an 83 MHz repetition rate. When the Cr:forsterite laser cavity was length-matched to the Nd:YAG laser cavity to within ±5 µm, the Cr:forsterite output pulse length was less than 300 ps. The minimum pulse length of 260 ps was obtained for an exactly equal cavity size, while the pulse length was shown to decrease slightly for a very slight mismatch in cavity length of 1 µm. The output wavelength in this configuration is continuously tunable from 1195 – 1295 nm, limited by the spectral characteristics of the mirrors used in the experiment. The maximum output power observed for synchronous pumping was 175 mW at 1232 nm for 2.4 W of absorbed pump power, which corresponds to a slope efficiency of 12.5% with a threshold of 0.7 W of absorbed pump power. The other technique for mode-locking the Cr:forsterite laser demonstrated in this paper was acousto-optic modulation, which falls into the active mode-locking category. The authors placed a Brewster acousto-optic modulator and mode-locker driver from the Coherent Laser Products Group of Coherent, Inc. into the Cr:forsterite laser cavity near the output coupler. The pump laser was operated in cw mode (no mode-locking). By driving the modulator at ~76 MHz and adjusting the cavity length to ~1.97m (the round-trip distance for the light to travel in this amount of time), the pulse width can be decreased to 50 ps. With the cavity slightly misaligned, shorter pulses were observed, but with the addition of satellite pulses as well. The pulse width for the shortest observed pulses was approximately 20 ps. With this cavity configuration, the output was tunable from 1204 – 1277 nm, and produced 120 mW at 1227 nm for an absorbed pump power of 2.4 W. This represents a slope efficiency of 9.1% with a threshold of 0.9 W of absorbed pump power.

In 1992, another standard mode-locking technique was demonstrated by Sennaroglu *et. al.*[16] To that time, additive-pulse mode-locking (APM) had been demonstrated in Ti:sapphire, Nd:YAG, Nd:glass, Nd:YLF and other laser systems. APM is generally established by sending part of the laser output beam into an optical fiber. An intensity-dependent mirror returns the output to the cavity, but with slight modifications. The leading edge of the pulse is redshifted, while the trailing edge is blueshifted. If the cavity lengths are adjusted properly, the pulse is reinjected into the laser cavity such that the leading edge of the pulse adds in phase with the pulse propagating in the cavity, and the trailing edge destructively interferes, effectively decreasing the intensity of the pulse. As the pulse propagates in the cavity, this effect continues to shorten the pulse until the pulse-width is limited by the bandwidth of the gain medium[20]. Sennaroglu and his research team used this technique to obtain pulses 2 orders of magnitude shorter than the previous shortest pulse. They demonstrated a system that gave a stable train of 150 fs pulses with an average usable power of up to 63 mW at a repetition rate of 82 MHz. This corresponds to an instantaneous peak pulse power of about 5 kW. In this paper, they demonstrated the feasibility of producing femtosecond pulses with the Cr:forsterite laser in a convincing fashion. This opened the door to applications such as biological imaging via OCT and high-speed optical communications relays.

Another significant advance in the mode-locking field was the use of Semiconductor Saturable Absorber Mirrors (SESAMs). This type of mode-locking is sometimes also called colliding pulse mode-locking (CPM). The simplified version of how CPM produces short pulses is that two electromagnetic waves propagating in opposite directions interfere with each other within the saturable absorber. Where the two waves constructively interfere, the saturable absorber can saturate, producing a standing wave in the absorber. This, in turn, narrows, stabilizes and shortens the incident laser pulse, which can the be coupled to the output. Is a SESAM, the saturable absorber is constructed in the same device as the semiconductor mirror such that as the wave propagates through the saturable absorber and is reflected from the mirror, the returning beam interferes in the absorber. In 1997, Zhang *et. al*. published the first evidence of using SESAMs with a Cr:forsterite laser to produce femtosecond pulses[22]. Operated in cw mode, the Cr:forsterite crystal in the laser cavity had its peak intensity at 1290 nm, so Zhang and his colleagues attempted to fabricate a semiconductor mirror/quantum well (saturable absorber) combination at this wavelength. After determining that the absorption edge of an $In_{0.38}Ga_{0.62}As$ quantum well occurred around 1290 nm, they fabricated the semiconductor device using molecular beam epitaxy. By using this device as one of the laser cavity mirrors, Zhang obtained a pulse width of 36 fs with a bandwidth of 50 nm at 1295 nm. The maximum average output power with a 2% transmission output coupler was 150 mW. The pump laser for this setup was a diode-pumped $Nd:YVO_4$ laser operated at 1.06 μm.

Further research into mode-locking and optimization of existing techniques beyond 1997 has resulted in generation of pulses as short as 14 fs (Chudoba *et. al*., 2001[6]), which is only a factor of 3 longer than the shortest laser pulse ever created. Also, 54 fs pulses with a peak power of 1 GW have been demonstrated by stretching the pulse, amplifying it, and then compressing the pulse again (Jonusauskas *et. al*., 1998[8]). Finally, on November 9, 2004, Del Mar Ventures released a commercially available complete all-solid-state mode-locked Cr:forsterite laser system[25]. This system has a center wavelength of 1250 nm (tunable from 1230 – 1270 nm), produces pulses of about 60 fs and provides an average output power of 280 mW at a repetition rate from 76 – 120 MHz. It runs in the TEM_{00} mode and has a beam divergence angle of < 2 mrad. A complimentary system, the Jaws Terawatt System, runs at a repetition rate of 10 Hz and produces pulses 60 – 80 fs long with peak output powers of 1 – 2 TW. The applications of this type of system are rapidly expanding and developing.

6. Current Research and Applications

Current research is taking place mostly in two main areas. The goal of the first is to reduce the heating effects in the Cr:forsterite laser crystal when it is operated in cw mode. This is important for increasing the possible output power of this laser system at room temperature. The second main research topic is increasing the efficiency and attainable output power for mode-locked systems, as well as increasing the repetition rate for today's highest-power Cr:forsterite lasers. One highly studied aspect of this is reducing or compensating for the dispersion effects of the laser crystal. However, perhaps the most research relating to Cr:forsterite lasers is not into the laser system itself, but in applications of these lasers.

In late 1996, Bouma *et. al*. published a proof-of-principle study that applied a Kerr-Lens mode-locked Cr:forsterite laser system to optical coherence tomography[3]. Extremely short pulses are preferred over longer pulses because the available bandwidth of shorter pulses is far superior to that of long pulses. Also, Cr:forsterite is preferred over other laser systems because it lases at around 1.3 μm, which allows for much deeper penetration into a biological sample than does Ti:sapphire at 800 nm and other lasers systems at shorter or significantly longer wavelengths. The Ti:sapphire laser is limited by scattering while laser systems beyond 2 μm are quickly absorbed by water. Cr:forsterite sits neatly in the middle, and allows for the optimal balance between scattering and absorption. Abraham *et. al*. followed up with this idea in 2000 with the modification that instead of collecting the information one pixel at a time, the traditional OCT method, and obtaining resolution limited by the laser spot size, they increased the spot size of the laser beam and imaged with a 640×480 element CCD camera at speeds up to 30 frames/sec[1]. This video-speed image acquisition, even for significantly lower resolution could be invaluable in large-scale and real-time observations of biological samples. Continuing the trend, Bordenave *et. al*. improved upon the 2000 results and actually reconstructed a 3-dimensional section of a mouse ear using a wide-field mode-locked Cr:forsterite OCT system in 2002[2]. Continued research in this area is almost certain to bring major advances in resolution, speed and dynamic range.

Tremendous numbers of other possible applications exist. Müller *et. al*. demonstrated third-harmonic-generation microscopy in 1998[10]. The operational wavelength of Cr:forsterite lies near or at 1276 nm, a wavelength of zero material dispersion, allowing for the maximum information capacity of a fiber to be exploited. Interestingly, the extremely short pulses demonstrated in Cr:forsterite present possibilities for very high data transmission rates, as well. The wavelength of operation of the Cr:forsterite laser also allows for eye-safe ranging and small band-gap semiconductor inspection. One of the most-promising applications is micromachining. Extremely short (tens to hundreds of fs) high-power laser pulses transfer much of their energy to only a few particles, which immediately makes the phase transition to a high-temperature plasma without significantly disturbing the surrounding particles. The plasma material is then quickly ejected from the area, leaving very little residue. This is a significant improvement over high-power ns pulses, which tend to leave slag along the cut edge and, depending on the material being cut, can deposit detrimental amounts of heat in the material which can cause cracking or other unfavorable thermal effects. This technique would be useful from dentist drills to machining finer holes in automobile fuel injectors resulting in cleaner combustion and better fuel economy. Other possible applications include studying chemical reactions as they occur. The extremely rapid nature of chemical reactions has thus far defeated any attempts to study them in depth as they are occurring. However, with the extremely short pulses dipping to only a few femtoseconds, characterization of chemical reactions may be within reach. It is certain that the applications for Cr:forsterite and other maturing laser systems are only beginning to be realized. The future holds great promise for laser applications in our world and beyond.

7. References

1. E. Abraham, E. Bordenave, N. Tsurumachi, G. Jonusauskas, J. Oberlé, C. Rullière, and A. Mito. Real-Time Two-Dimensional Imaging in Scattering Media by Use of a Femtosecond Cr^{4+}:Forsterite Laser. Optics Letters. 25:929-931. 2000.

2. E. Bordenave, E. Abraham, G. Jonusauskas, N. Tsurumachi, J. Oberlé, C. Rullière, P. E. Minot, M. Lassègues, and J. E. Surlève Bazeille. Wide-Field Optical Coherence Tomography: Imaging of Biological Tissues. Applied Optics. 41:2059-2064. 2002.

3. B. E. Bouma, G. J. Tearney, I. P. Bilinsky, B. Golubovic, and J. G. Fujimoto. Self-Phase-Modulated Kerr-Lens Mode-Locked Cr:Forsterite Laser Source for Optical Coherence Tomography. Optics Letters. 21:1839-1841. 1996.

4. Timothy J. Carrig and Clifford R. Pollock. Tunable, CW Operation of a Multiwatt Forsterite Laser. Optics Letters. 16:1662-1664. 1991.

5. Timothy J. Carrig and Clifford R. Pollock. Performance of a Continuous-Wave Forsterite Laser with Krypton Ion, Ti:Sapphire and Nd:YAG Pump Lasers. IEEE Journal of Quantum Electronics. 29:2835-2844. 1993.

6. C. Chudoba, J. G. Fujimoto, E. P. Ippen, H. A. Haus, U. Morgner, F. X. Kärtner, V. Scheuer, G. Angelow, and T. Tschudi. All-Solid-State Cr:Forsterite Laser Generating 14-fs Pulses at 1.3 μm. Optics Letters. 26:292-294. 2001.

7. Anatoliy Ivanov, Vladislav Shcheslavskiy, Vladislav Yakovlev, Boris Minkov, and Alexander Vasiliev. High-Power Continuous-Wave Cr^{4+}:Forsterite Laser. Applied Optics. 40:6034-6037. 2001.

8. G. Jonusauskas, J. Oberlé, and C. Rullière. 54-fs, 1-GW, 1-kHz Pulse Amplification in Cr:Forsterite. Optics Letters. 23:1918-1920. 1998.

9. T. Maiman. Stimulated Optical Radiation in Ruby. Nature. 187:493-494. 1960.

10. M. Müller, J. Squier, K. R. Wilson, and G. Brakenhoff. 3D Microscopy of Transparent Objects Using Third-Harmonic Generation. Journal of Microscopy. 191:266-274. 1998.

11. V. Petričević, S. K. Gayen, R. R. Alfano, Kiyoshi Yamagishi, H. Anzal, and Y. Yamaguchi. Laser Action in Chromium-Doped Forsterite. Applied Physics Letters. 52:1040-1042. 1988.

12. V. Petričević, S. K. Gayen, and R. R. Alfano. Continuous-Wave Laser Operation of Chromium-Doped Forsterite. Optics Letters. 14:612-614. 1989.

13. V. Petričević, A. Seas, and R. R. Alfano. Slope Efficiency Measurements of a Chromium-Doped Forsterite Laser. Optics Letters. 16:811-813. 1991.

14. Leijia Qian, Xiang Liu, and Frank Wise. Cr:Forsterite Laser Pumped by Broad-Area Laser Diodes. Optics Letters. 22:1707-1709. 1997.

15. A. Seas, V. Petričević, and R. R. Alfano. Continuous-Wave Mode-Locked Operation of a Chromium-Doped Forsterite Laser. Optics Letters. 16:1668-1670. 1991.

16. Alphan Sennaroglu, Timothy J. Carrig, and Clifford R. Pollock. Femtosecond Pulse Generation by Using an Additive-Pulse Mode-Locked Chromium-Doped Forsterite Laser Operated at 77 K. Optics Letters. 17:1216-1218. 1992.

17. Alphan Sennaroglu. Efficient Continuous-Wave Radiatively Cooled Cr^{4+}:Forsterite Lasers at Room Temperature. Applied Optics. 37:1062-1067. 1998.

18. Alphan Sennaroglu. Comparative Experimental Investigation of Thermal Loading in Continuous-Wave Cr^{4+}:Forsterite Lasers. Applied Optics. 37:1627-1634. 1998.

19. Alphan Sennaroglu. Analysis and Optimization of Lifetime Thermal Loading in Continuous-Wave Cr^{4+}-Doped Solid-State Lasers. Journal of the Optical Society of America. 18:1578-1586. 2001.

20. William T. Silfvast (2004), *Laser Fundamentals*. Cambridge: Cambridge University Press.

21. V. Yanovsky, Y. Pang, F. Wise, and B. I. Minkov. Generation of 25-fs Pulses from a Self-Mode-Locked Cr:Forsterite Laser with Optimized Group-Delay Dispersion. Optics Letters. 18:1541-1543. 1993.

22. Zhigang Zhang, Kenji Torizuka, Taro Itatani, Katsuyuki Kobayashi, Takeyoshi Sugaya, and Tadashi Nakagawa. Self-Starting Mode-Locked Femtosecond Forsterite Laser With a Semiconductor Saturable-Absorber Mirror. Optics Letters. 22:1006-1008. 1997.

23. Nickolay Zhavoronkov, Aleksander Avtukh, and Victor Mikhailov. Chromium-Doped Forsterite Laser with 1.1 W of Continuous-Wave Output Power at Room Temperature. Applied Optics. 36:8601-8605. 1997.

24. http://webmineral.com/data/Forsterite.shtml

25. http://www.femtosecondsystems.com/products/Femtosecond_Lasers/CR-FORSTERITE_LASERS/CR-FORSTERITE_LASERS_main.php