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Developing thulium lasers for depth-selective scalpels

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New diode-pumped solid-state lasers doped with thulium can be wavelength-tuned around the local water absorption peak at 1.94μm, making them attractive as versatile laser scalpels.

Over the last several decades, diode-pumped solid-state lasers have become technologically mature and widely commercially available. They are used in industrial, scientific, military, and medical applications. One promising use for these lasers is as scalpels: absorbed laser radiation cuts tissue and, at the same time, welds microscopic blood vessels and thus stops bleeding. Because water is the main component of the majority of living cells and tissues, it makes sense to focus on lasers that emit wavelengths absorbed by water. The absorption of liquid water changes sharply from 11 to 124cm^{-1} between wavelengths of about 1.8 and 2μm, a feature that can be exploited to create a laser scalpel with a controllable cutting depth.

The most widely known and used solid-state laser is the neodymium-doped yttrium-aluminum-garnet (Nd:YAG) laser operating at 1.06μm. But water in tissue does not absorb this wavelength well, and consequently the radiation so produced can cause permanent thermally induced burns. Achieving the desired effect requires a laser with a wavelength more readily absorbed by water.

Thulium-ion-based lasers with emission wavelengths near 2μm are well suited to our purpose. They can be efficiently pumped using commercially available laser diodes at about 800nm and can operate with up to 50% efficiency.[1] We chose to develop thulium-doped yttrium aluminum perovskite (Tm:YAP) because it has a favorable wavelength of 1.94μm, which coincides with the local absorption peak of water. This laser material is mature, can be operated with high efficiency, and is readily available from Crytur (Turnov, Czech Republic). We also demonstrated another promising new laser material, thulium-doped gadolinium vanadate (Tm:GdVO$_4$), which was grown at Hokkaido University (Kita-ku, Sapporo, Japan). We added a new feature—wavelength tuning—to both laser systems to achieve variable cutting depth when the laser radiation interacts with tissue.

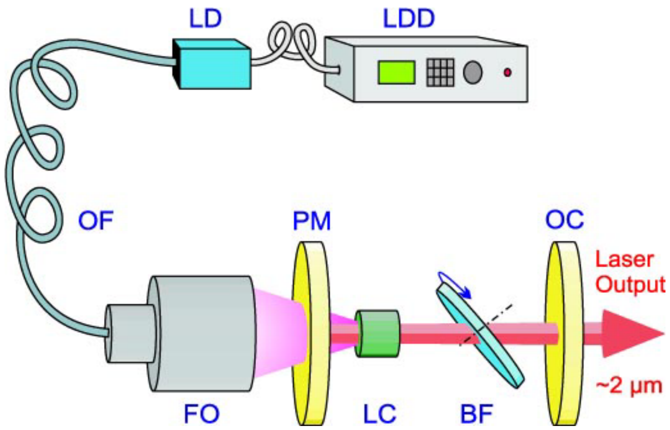

Figure 1. *A diode-pumped thulium laser uses a birefringent filter (BF) to provide wavelength tuning. The laser crystal (LC) can be either thulium-doped yttrium aluminum perovskite (Tm:YAP) or thulium-doped gadolinium vanadate (Tm:GdVO$_4$). LDD: Laser-diode driver. LD: Laser diode. OF: Optical fiber. FO: Focusing optics. PM: Flat resonator mirror. OC: Curved output coupler.*

Our tunable thulium laser system is shown schematically in Figure 1. We used a 3mm-long crystal of either Tm:YAP or Tm:GdVO$_4$ as the active laser medium. A fiber-coupled laser diode pumped the crystal with power as high as 17W. The pump beam waist had a diameter of about 360μm and was about 4mm long. The 80mm-long semi-hemispherical laser resonator consisted of a flat mirror through which the pump light entered and a curved output coupler with a reflectivity of 98%. A single quartz plate placed inside the optical resonator at the Brewster angle acted as a birefringent filter, which allowed us to change the laser emission wavelength by rotating the plate in its plane.[2,3]

When the Tm:YAP laser was pumped at 791nm, its tuning range extended from 1869nm up to 2036nm, with the maximum power output at 1985nm. We obtained output power as high as 3.85W with 44% slope efficiency for 8W of absorbed power (see Figure 2). In the case of the new Tm:GdVO$_4$ crystal,

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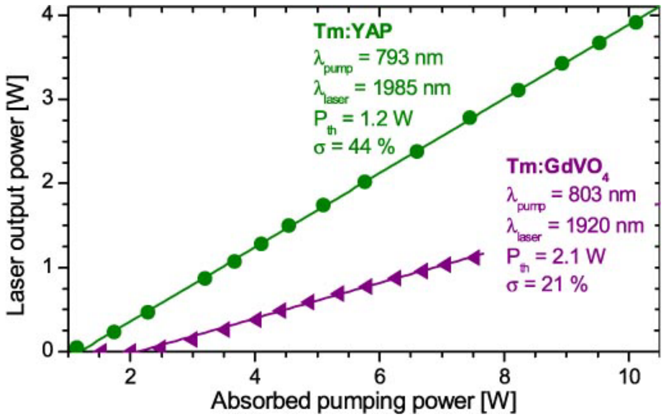

Figure 2. *Diode-pumped tunable thulium lasers show linear output power as a function of the absorbed pump power.* λ_{pump}*: Pumping wavelength.* λ_{laser}*: Laser emission wavelength.* P_{th}*: Threshold power. σ: Laser slope efficiency.*

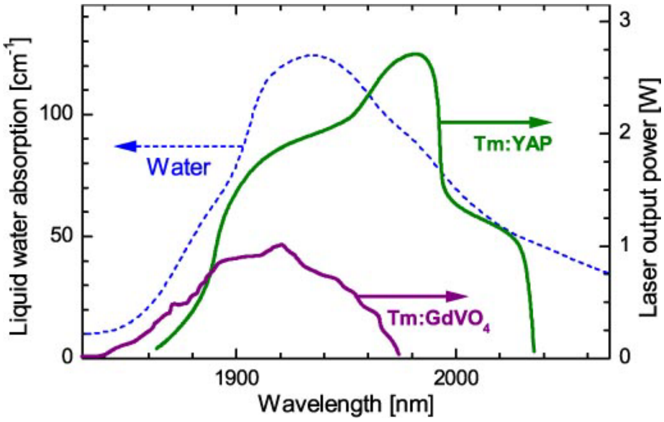

Figure 3. *Liquid water has an absorption coefficient peak at about 1.9μm.*[4] *Because the Tm:YAP and Tm:GdVO*$_4$ *laser tuning curves lie on the shoulders of the absorption curve, changing the laser wavelength varies the amount of absorption.*

pumping at 803nm gave a tuning range from 1840nm up to 2075nm, with the maximum at 1920nm. When pumped with 7.5W of absorbed power, we obtained 1.1W of output.

Tunable thulium lasers are also attractive for applications that use laser lines in the 1.8–2μm wavelength region. In our current arrangement, the emitted radiation is relatively broad—we estimate these lasers emit lines up to several nanometers wide—but there are straightforward ways to narrow the spectral line. For example, we can either insert more tuning elements with different free spectral ranges into the cavity, or we can use a narrow-band intracavity grating to select a wavelength.

The potential of these lasers for medical applications is evident when looking at Figure 3, which highlights the wavelength overlap between high-absorption wavelengths in water and the tuning ranges we achieved. In this wavelength range, the absorption depth in water changes from 100μm (for a laser wavelength of 1.94μm) to 400μm (for a wavelength of 1.87μm). Thus, such a system can potentially be used as a laser scalpel with a variable cutting depth in high-water-content tissues.

In summary, we have developed efficient diode-pumped Tm:YAP and Tm:GdVO$_4$ lasers with tunable emission from 1.84 to 2.04μm with multiwatt output power. We plan to further increase output power by optimizing the crystal length. We expect that we can achieve output power up to 10W without much variation in the current setup. The broad gain bandwidth of these lasers also makes them attractive for mode-locking experiments in the 2μm-wavelength region.

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Pavel Černý develops solid-state lasers for medical applications at the Czech Technical University in Prague. Previously he was at the Institute of Photonics at the University of Strathclyde in Glasgow, Scotland, where his research focused on stabilization techniques for passively mode-locked diode-pumped lasers. He was also involved in development of mid-infrared diode-pumped thulium- and chromium-based lasers. He received his PhD in physical engineering from the Czech Technical University in 2002 for his work on solid-state Raman lasers.

Helena Jelínková is a professor of applied physics at the Czech Technical University. She has more than 30 years' experience in researching and developing solid-state lasers. Additional research interests include short-pulse generation, interactions of laser radiation with tissue, and delivery of laser radiation. She is a member of SPIE, the Optical Society of America, the American Society for Laser Medicine and Surgery, and the New York Academy of Sciences.

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