Rare-earth-ion-doped continuous-wave 3-µm lasers

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Abstract

This paper reviews the progress on rare-earth-ion doped lasers in the wavelength range near 3 µm, with an emphasis on fiber-based devices. Er³⁺ and Ho³⁺ lasers are discussed.

Summary

For a number of years, there has been an increased interest in lasers emitting at 3 µm [1] mainly because of their potential applications in laser surgery. Due to the high absorption of 3-µm radiation in water, high-quality cutting or ablation is demonstrated in biological tissue using erbium-doped solidstate lasers. Erbium-doped fluoride fibers are promising candidates for the construction of compact and efficient all-solid-state laser sources that provide large flexibility and high laser intensity which is of relevance for surgical applications.

Based on a theoretical proposal [2], S.D. Jackson et al. reported the first 3-µm fiber laser of the 1-W class [3]. 1.7 W of output power and 17.3% slope efficiency (with respect to the launched pump power) at a wavelength of 2.71 µm were demonstrated from a double-clad erbium-doped ZBLAN fiber diode pumped at 790 nm. Energy transfer from the Er³⁺ lower laser level to a Pr³⁺ codopant decreased ground-state bleaching and excited-state absorption, thus avoiding output-power saturation. Advantages over current crystal-laser designs include nearly transverse-fundamental-mode operation, reduced thermal effects, and ease of use, e.g., in medical endoscopy. Based on the same idea, X.S. Zhu and R. Jain recently demonstrated more than 5 W of output power [4]. Also pulsed output near 3 µm with energies of 0.55 mJ and an average power of 3 W was demonstrated [5].

P.S. Golding et al. [6] presented a detailed characterization of energy transfer processes in Er³⁺-doped and Er³⁺,Pr³⁺-codoped ZBLAN bulk glasses. For several Er³⁺ (0.25–8.75 mol%) and Pr³⁺ (0.25–1.55 mol%) concentrations, energy transfer upconversion (ETU) and cross relaxation in Er³⁺ as well as energy transfer (ET) from Er³⁺ to the Pr³⁺ codopant were investigated. The measured parameters of ETU from the Er³⁺ 4I13/2 and 4I11/2 levels are comparable to those of LiYF4:Er³⁺. ETU from 4I13/2, in particular, possesses a factor of 3 larger probability than ETU from 4I11/2. The parameters of ET from the Er³⁺ 4I13/2 and 4I11/2 levels to the Pr³⁺ codopant are larger than the corresponding ETU parameters. ET effectively quenches the 4I13/2 intrinsic lifetime of 9 ms down to 20 ms for the highest Er³⁺ and Pr³⁺ concentrations investigated, and is more efficient than ET from 4I11/2, because the corresponding absorption transition in Pr³⁺ has a large oscillator strength and back transfer is inhibited by fast multiphonon relaxation from the corresponding Pr³⁺ level. In both cases, the ET parameters depend on Er³⁺ concentration in a similar way as the ETU parameters but depend only weakly on Pr³⁺ concentration. This shows that energy migration within the Er³⁺ 4I13/2 and 4I11/2 levels is fast.
Based on these spectroscopic measurements, a detailed analysis of the population mechanisms and the characteristics of the output from Er\(^{3+}\)-singly-doped and Er\(^{3+}\), Pr\(^{3+}\)-codoped ZBLAN fiber lasers operating at 3 µm, for various Er\(^{3+}\) concentrations and pump powers, was performed [7]. Whereas both approaches resulted in similar laser performance at Er\(^{3+}\) concentrations 4 mol.% and pump powers 10 W absorbed, it was theoretically shown that the Er\(^{3+}\)-singly-doped system can be advantageous for higher Er\(^{3+}\) concentrations and pump powers. In this case, energy recycling by energy-transfer upconversion from the lower to the upper laser level can increase the slope efficiency to values greater than the Stokes efficiency, as is associated with a number of Er\(^{3+}\)-doped crystal lasers.

On the other hand, the influence of energy-transfer upconversion (ETU) between neighboring ions in the upper and lower laser levels of erbium 3-µm continuous-wave lasers on heat generation and thermal lensing was investigated [8]. It was shown that the multiphonon relaxations following each ETU process generate significant heat dissipation in the crystal. This undesired effect is an unavoidable consequence of the efficient energy recycling by ETU in erbium 3-µm crystal lasers, but is further enhanced under nonlasing conditions. In a three-dimensional finite-element calculation, excitation densities, upconversion rates, heat generation, temperature profiles, and thermal lensing were calculated for a LiYF\(_4\):Er\(^{3+}\) 3-µm laser. In the chosen example, the fraction of the absorbed pump power converted to heat was 40% under lasing and 72% under nonlasing conditions. The heat generation in a LiYF\(_4\):Er\(^{3+}\) 3-µm laser is 1.7 and the thermal-lens power up to 2.2 times larger than in a LiYF\(_4\):Nd\(^{3+}\) 1-µm laser under equivalent pump conditions, thus, also putting a higher risk of rod fracture on the erbium system. Similar mechanisms may affect future erbium 3-µm fiber lasers.

By exploiting optical gain near 3 µm in another active rare-earth ion, Ho\(^{3+}\), a high-power tandem-pumped Ho\(^{3+}\), Pr\(^{3+}\)-doped ZBLAN fiber laser was demonstrated by S.D. Jackson [9]. Using the free-running 1100-nm output from a diode-cladding-pumped Yb\(^{3+}\)-doped silica fiber laser as the pump source, a maximum output power of 2.5 W was generated at a slope efficiency of 29% after the threshold of 30 mW was reached. Saturation of the output was avoided with Pr\(^{3+}\) codoping, which allowed single-transition output. The center wavelength of the output was 2.86 µm and the bandwidth at maximum power was 15 nm.

References