Diode-Pumped 1.7-W Erbium 3-μm Fiber Laser

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In recent years, there have been enormous research efforts to improve the performance of lasers emitting at 3 μm 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 solid-state lasers.

The erbium-doped fluoride fiber is a promising candidate for the construction of a compact and efficient all-solid-state laser emitting on the transition at 2.7 μm (Fig. 1). Due to its geometry, the fiber provides significant flexibility and potentially high laser intensity without the drawbacks of thermal and thermo-optical effects. However, a high excitation density with the consequences of pump excited-state absorption (ESA) [1] and uncontrolled redistribution of the upconverted energy can lead to output-power saturation in the fiber laser.

In this paper, we follow a theoretical proposal to scale the output power of the erbium 3-μm fiber laser to the 1-W region [2]: Ground-state bleaching and consequent ESA losses are avoided by the combination of 1) a highly erbium-doped fiber and the relatively low pump intensity present in a cladding-pumped fiber with 2) an active reduction of the excitation density by energy transfer to a Pr^{3+} codopant [3]. Recently, the first investigation of the validity of this approach has led to 660 mW of output power at 2.7 μm under diode pumping [4]. By using a rectangular double-clad geometry of a design that was successful in scaling a Tm^{3+} silica-fiber laser to high output powers [5], we demonstrate 1.7 W of output power in a near transverse-fundamental mode and 17% slope efficiency at 2.71 μm from a diode-pumped Er^{3+},Pr^{3+}:ZBLAN laser.

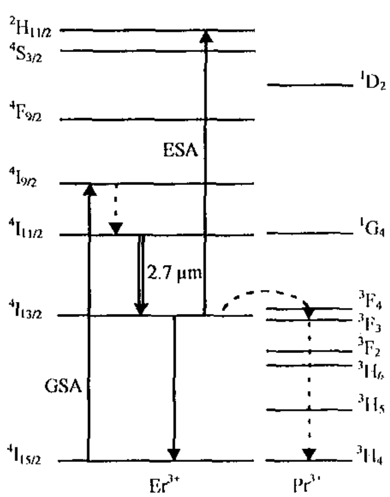

Fig. 1. Partial energy-level diagram of Er^{3+} and Pr^{3+} in ZBLAN glass indicating the processes which are relevant for the operation of the high-power diode-pumped Pr^{3+}-codoped Er^{3+} 2.7-μm fiber laser at the transition $^4I_{11/2} \rightarrow {}^4I_{13/2}$. The system is pumped by GSA at 790 nm into $^4I_{9/2}$. Fast multiphonon relaxation populates the $^4I_{11/2}$ upper laser level. The $^4I_{13/2}$ lower laser level is depopulated and pump ESA from this level is avoided by energy transfer to the Pr^{3+} codopant which then exhibits fast multiphonon relaxation to the ground state.

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The core of the double-clad fiber used in the experiments (KDD, Japan) contained a 35,000 ppm molar concentration of ErF_3 and 3,000 ppm molar concentration of PrF_3. The core had a diameter of 15 μm and a numerical aperture of 0.16 in order to provide near single-transverse-mode output at the laser wavelength of 2.71 μm. The nominal intrinsic loss was less than 50 dB/km at a wavelength of 2.7 μm. The pump cladding of the fiber had a 100 μm × 200 μm rectangular cross section. Surrounding the pump cladding was a transparent fluororesin second cladding layer which provided a numerical aperture of 0.55 for the pump cladding. The diode-laser pump source was a Diomed concentrator unit (Diomed Ltd., Cambridge, UK). This system optically multiplexes the output from sixteen 2-W-rated AlGaAs diodes each operating at a wavelength of 790 nm. The focus of the pump light had a spot size of 200 μm × 50 μm. 45-50% of the incident pump power of 22.4 W was launched into the pump cladding. The experimental set-up is shown in Fig. 2.

The fiber-laser output as a function of launched pump power for a 10.5-m fiber length is shown in Fig. 3. The threshold launched pump power was 0.47 W. The slope efficiency was determined to be 17% which represents ~60% of the Stokes' efficiency limit of 29%. The overall optical-to-optical efficiency was ~6%. The effective absorption coefficient for the fiber is approximately 0.15 m^{-1}. Taking into account the core-to-cladding area ratio, the effective absorption coefficient of the core is ~17 m^{-1} which translates to an overall absorption cross section with our pump source of 2.74×10^{-26} m^2. The ~6 nm-FWHM bandwidth of the pump source, therefore, has the effect of reducing the absolute absorption cross section at 790 nm of 4×10^{-26} m^2 [1] by ~30%.

Further power scaling seems possible by optimizing the resonator design and launch efficiency. Since ground-state bleaching and a high excitation density of the laser levels could be avoided by energy transfer to the Pr^{3+} codopant, pumping at 980 nm directly into the upper laser level is expected to further increase the quantum efficiency of this laser without introducing significant ESA losses from the upper laser level. At the present power level, we are able to perform laser-tissue interactions and investigate the potential of this laser in micro surgery.

References:

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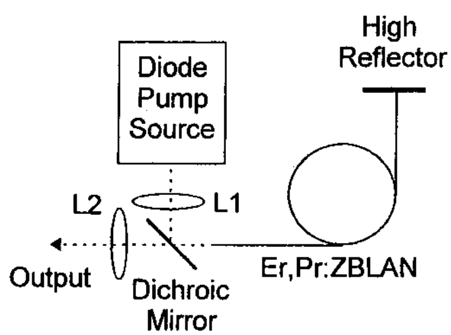

Fig. 2. Experimental set-up of the high-power diode-pumped 3-μm ZBLAN fiber laser.

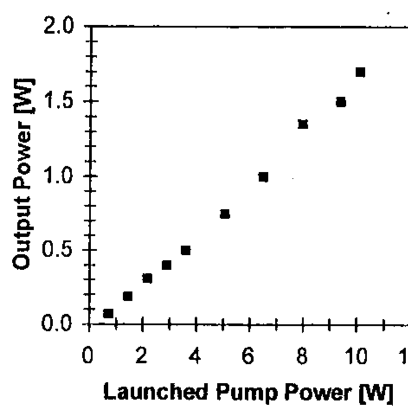

Fig. 3. Output power at 2.7 μm vs. launched pump power at 790 nm of the diode-pumped ZBLAN fiber laser.