Comparative study on self-pulsation effect in Erbium-Ytterbium co-doped fiber laser under bi-directional and unidirectional cladding-pumping regime

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Self-pulsation effects of cladding-pumped Erbium-Ytterbium co-doped fiber laser (EYDFL) at around the lasing threshold are investigated. It is demonstrated that laser output of the Erbium-Ytterbium co-doped fiber under the bi-directional pumping regime is more stable than that under the unidirectional pumping one due to the relatively uniform pumping of the fiber. Mechanisms of self-pulsations in the laser system are discussed and possible techniques to avoid self-pulsing and stabilize the laser are proposed.

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Self-pulsation effects, the periodic emission of optical pulses at a repetition rate corresponding to the relaxation oscillation frequency of the inversion and photon populations, have been variously reported in several rare-earth doped fibers under specific pumping and cavity conditions. There are several possible origins for this unstable output regime, including the presence of saturable absorption due to the clustering of the active ions[1,2] and reabsorption of the laser photons in the unpumped or underpumped fiber part[3,4]. It is worth noting that although the self-pulsations typically occur at around the lasing threshold, the average energy of the pulsations increases and may act as the seed and eventually be intensified into high intensity pulses through nonlinear effects like stimulated Brillouin[5], Raman scattering (SBS, SRS)[6], and the optical Kerr effect[7] as the pump power increases, which will cause catastrophic damage to the fiber ends. Thus investigations of this self-pulsing effect and techniques to stabilize the fiber laser output will be necessary and significant to scale up the output power of fiber lasers.

Much work has been done to investigate the self-pulsing behavior and new schemes have also been proposed to suppress the self-pulsations in Erbium-doped fiber lasers (EDFL)[1,8,9] and Ytterbium-doped fiber lasers[5,10,11]. However, to the best of our knowledge, self-pulsations in Erbium-Ytterbium co-doped high power fiber lasers, which is of great importance for power scaling of 1.5-μm fiber lasers, have not yet been investigated. In this letter, we investigate the output temporal behavior of a multi-mode Erbium-Ytterbium co-doped fiber laser (EYDFL) under different pumping and cavity conditions. We find that the bi-directionally pumped EYDFL tended to produce more stable laser output than the unidirectionally pumped one, which indicates that the double-end pumping regime can be used as a possible technique to stabilize the fiber laser in our current configuration. Besides, the magnitude of the dual-ended output fluctuations is

greatly reduced compared with that of the single-ended output temporal behavior. The thermo-induced lensing resulting from excited-state-absorption (ESA) at the lasing wavelength is considered to be possibly responsible for this observation. The repetition rate of the well-developed self-pulsations increases with the pump power while the pulse duration remains around 2.4 μs in this experiment.

The fiber employed in this study had an Erbium-Ytterbium co-doped phospho-silicate core of 30-μm diameter and $\sim$0.22 numerical aperture (NA), surrounded by a pure silica D-shaped inner cladding of 400-μm diameter and $\sim$0.49 NA, with a low refractive index ultraviolet (UV)-cured polymer out-cladding. The experimental schematic is shown in Fig. 1. The pump power was provided by a laser diode (LD, LIMO, Germany) at a center wavelength of 976 nm at maximum driving current with output power of 650 W. The pump light was split into two beams (1 and 2) of roughly equal power and then launched into the two fiber ends (A and B) through dichroic mirrors by using two plano-convex lenses of 25-mm focal length. The pump launch efficiency was estimated to be $\sim$80%. The two dichroic mirrors with high transmission at the pump wavelength ($>$96%) and high reflectivity over the 1 530$\sim$1 570-nm band ($>$99%) were positioned at 45° to steer the pump light from the laser beam, allowing efficient extraction of the EYDFL output. For the unidirectional pumping configuration, pump beam 2 was blocked and cavity of laser oscillation for the single-ended output regime was formed by the 3.6% Fresnel reflection from a perpendicularly-cleaved fiber end facet (A) and at the opposite end (B) by a simple external cavity comprising a plane mirror (M) with high reflectivity at 1 530$\sim$1 570 nm and a 50-mm focal length collimating lens. Removing the highly reflective plane mirror M from the external cavity resulted in the double-ended output of the EYDFL with the feedback of lasing being provided by the two perpendicularly-cleaved

fiber facets (A and B). Only ∼75% of the pump power launched into the inner-cladding was absorbed after a single pass in the 2.8-m gain fiber due to the low absorption at the pump wavelength. The temporal behavior of the laser output was measured using a fast InGaAs PIN photodiode with a rising time of approximately 10 ns, connected to a 1-GHz digital storage oscilloscope (LeCroy 104Xs, LeCroy, USA).

In the bi-directional pumping regime, both pump beams 1 and 2 were active and used to cladding-pump the gain fiber from its two ends A and B. With the external cavity comprising the highly reflective mirror M and the perpendicularly-cleaved facet A as the feedback for laser oscillation, a single-ended output from fiber end A with maximum output power of ∼30 W at 1 545 nm has been obtained for the absorbed pump power of 240 W with the slope efficiency of 25% with respect to the absorbed pump power. The lasing threshold is measured to be ∼2 W (launched). In this letter, we mainly focus on the research of the temporal output behavior around the lasing threshold of the EYDFL.

Figure 2 shows the temporal behavior of the single-ended output with different laser powers under the bi-directional pumping regime. It is apparent that there appear a few irregular fluctuations of the output when the pump power slightly exceeds the threshold. These
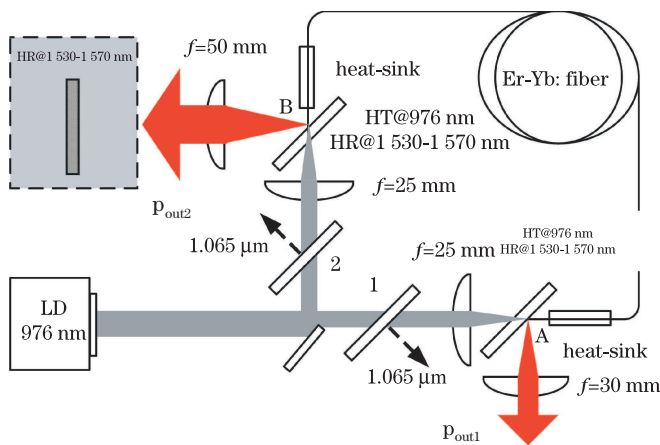

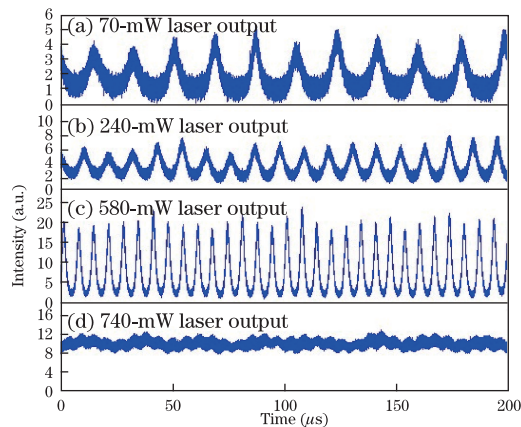Fig. 1. Experimental set-up for single-or -dual-ended output of EYDFL.

Fig. 2. Temporal behavior of single-ended output for the bi-directional pumping regime with the laser powers of (a) 70, (b) 240, (c) 580,and (d) 740 mW.

self-pulsations become a regular and well-developed pulse train with the repetition rate of 155 kHz and pulse duration of 2.2 μs when increasing the pump power up to generate a laser power of 580 mW, as seen in Fig. 2(c). The maximum room mean square (RMS) value of the self-pulsations was measured to be about ∼65%. A further increase in pump power resulted in a stable continuous wave (CW) operation with no obvious fluctuations when the produced laser power is 740 mW, which is shown in Fig. 2(d). The single-ended output for the bi-directional pumping regime remained the stable CW operation with the average laser power beyond 740 mW. Figure 3 shows the dependence of both pulse duration and repetition rate on the launched pump power. It is obvious that the well-developed pulse repetition rate increases with the launched pump power while the pulse width remains around 2.4 μs.

A 4%–4% linear cavity with double-ended laser output was formed by the two perpendicularly-cleaved facets (A and B) after removing the highly reflective mirror M. The temporal profile of the output from fiber facets A and B for different laser powers under the bi-directional pumping regime are shown in Figs. 4 and 5, respectively. We did not detect strong fluctuations from the output of these two fiber ends and the EYDFL operated in the quasi-CW mode. The maximum RMS value of the self-pulsations from these two fiber ends was measured to be below ∼35%, which is much smaller than that of the single-ended temporal output under the bidirectional pumping regime.

For comparison, we measured the laser temporal behavior for both single-ended and dual-ended output under the unidirectional pumping configuration. In the unidirectional pumping regime, only pump beam 1 was active and launched into the fiber end A while the other pump beam was blocked. Similar to the operation in the bidirectional pumping regime, a train of sustained remarkable self-pulsations was generated. The maximum RMS values of the self-pulsations for the single- and double-ended output regime are ∼80% and ∼40%, respectively. The fluctuations in the laser output were reduced under the bidirectional pumping regime compared with the unidirectional pumping one.

Self-pulsing behavior in Er-doped fiber lasers is mainly attributed to the saturable absorption effect due to Er-active ions' clustering or reabsorption of laser light at
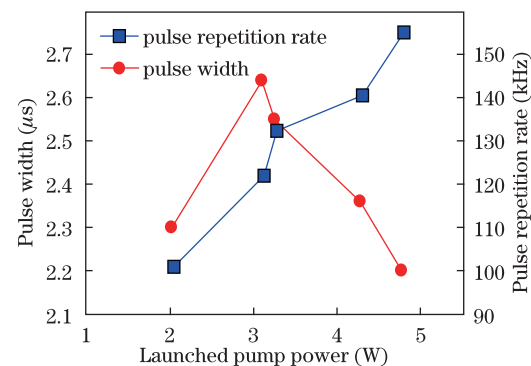

Fig. 3. (Color online) Dependencies of pulse width (red square) and pulse repetition rate (blue circle) for relatively regular self-pulsations upon the launched pump power under the bi-directional pumping and single-ended output regime.
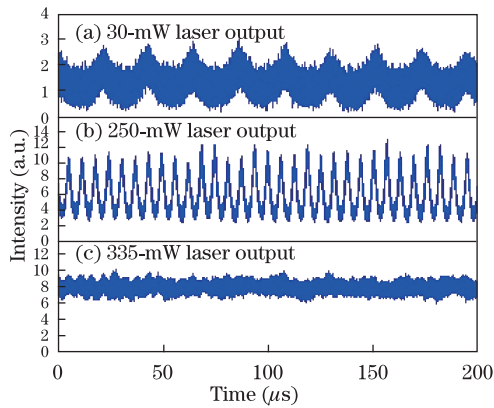
Fig. 4. Temporal behavior of output from fiber end A for the bi-directional pumping regime with laser powers of (a) 30, (b) 250, and (c) 335 mW.
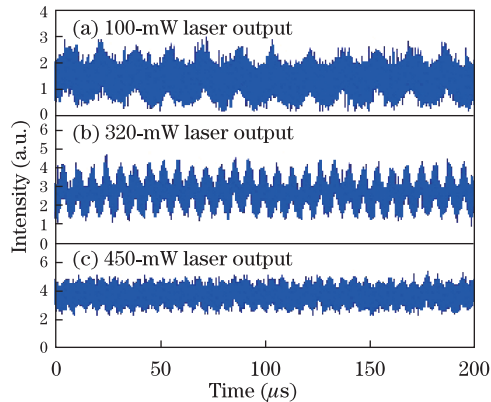

Fig. 5. Temporal behavior of output from fiber end B for the bi-directional pumping regime with laser powers of (a) 100, (b) 320, and (c) 450 mW.

the unpumped or lowly pumped fiber part. However, co-doping Er fiber with optimized concentration of Yb ions could avoid the formations of Er clusters, reducing the saturable absorption effects to some extent which can cause unstable operations[12]. In the experiment, the self-pulsations observed primarily originated from reabsorption of laser photons at the low-pumped fiber section in the typical EYDFL. The saturable absorption effect occurred when the excited state Erbium ions resulting from the reabsorption of laser photons rapidly drained back to the ground state. The much more stable laser output of the EYDFL operated under the bi-directional pumping regime relative to that under the unidirectional pumping one primarily originates from the much more uniform excitation across the fiber resulting from the simultaneous dual-end pumping, which greatly reduced the underpumped fiber part contributing to the saturable absorption effect. Thus, the self-pulsations were weakly suppressed to some extent. It is to be expected that this self-pulsing depression effect under the bidirectional pumping regime can be more evident with relatively longer fiber and much efficient pump absorption because the distinct pump absorption and excitation distribution across the fiber between these two different pump regimes can cause greatly different degrees of saturable absorption effect.

The measured pump absorption coefficient of the

Erbium-Ytterbium co-doped fiber in this experiment was about 0.5 m^{-1}, and the corresponding effective absorption fiber length was calculated to be about 2 m, which indicates that fiber parts longer than 2 m could possibly be acted as the saturable absorber in the EYDFL. Regarding to the optimum active fiber length (single-pass pump absorption ~90%), the saturable absorption will be more effective and the laser temporal output behavior will be greatly different between the bi-directional and unidirectional pumping configuration for the EYDFL. Therefore, the double-end pumping regime could be used to stabilize the high power EYDFL output.

Besides, it is worth noting that the magnitude of the dual-ended output fluctuations was generally much reduced compared with that of the single-ended output behavior. A possible explanation to this observation is the thermo-induced lensing resulting from ESA (from upper laser level $^4I_{13/2}$ to higher level $^4I_{9/2}$) at the laser wavelength. In Ref. [13], a theoretical model of the mechanism of self-Q-switching stemming from the ESA induced thermal lensing in an all-fiber Erbium laser has been developed. When the highly reflective mirror M was applied in the EYDFL to realize the single-ended output, the average intra cavity laser intensity was larger than that of the cavity without mirror M, causing a stronger ESA for the laser wavelength and therefore strong thermo-induced self-focusing effects in the active fiber, which will enhance the magnitude of the output self-pulsations. On the other hand, the larger average intracavity laser intensity when introducing the highly reflective mirror M simultaneously enhanced the third nonlinear effect like SBS, which has been identified as another factor responsible for the unstable output behavior[14].

Ultimately, the single-ended output pulses' width under the bi-directional pumping configuration depends on the pump power, however, not by the manner characteristic for the self-Q-switched operation. The pulse duration remained nearly the same around 2.4 μs rather than decreasing with the pump power as the Q-switched operation while the repetition of the pulse train increases along with the pump power. When the pump power was sufficient to indirectly saturate the level of absorption, the continuous train of pulses or oscillations could be dampened and then the CW or quasi-CW output occurred.

In conclusion, to avoid the possible high energy pulses evolving from the self-pulsations through nonlinear effects like SBS when scaling up the output power of EYDFL and understand its dynamic output behaviors, we characterize the output of self-pulsations for the EYDFL under the bi-directional pumping regime. A regular and well-developed pulse train with the repetition rate of ~155 kHz and pulse duration of ~2.2 μs is obtained. A further increase in pump power results in a stable CW or quasi-CW operation without obvious fluctuations as a result of reduced unpumped or low-pumped fiber part. For comparison, we also measure the temporal output of EYDFL under the unidirectional pumping regime and find that the output of the bi-directionally pumped EYDFL is more stable than that of the unidirectionally pumped one due to relatively uniform pumping of the fiber. Thus it is expected to be a possible ap-

proach to stabilize the output of the EYDFL using the bi-directionally pumping regime. In addition, it is worth noting that the magnitude of the dual-ended output fluctuations compared with that of the single-ended output behavior is greatly reduced. A possible interpretation is proposed to understand this observation based on the thermo-induced lensing resulting from ESA at the lasing wavelength.

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