Suppression of self-pulsing behavior in erbium-doped fiber lasers with resonant pumping: experimental results

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Experimental results are presented showing that resonant pumping can significantly improve the stability of erbium-doped fiber lasers. In particular, it is observed that an erbium fiber laser that exhibits sustained spiking behavior when pumped at 980 nm will revert to stable CW operation when pumped at 1510 nm.

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Sustained self-pulsing or spiking behavior is a phenomenon that has been commonly observed in erbium-doped fiber lasers, and in three-level solid-state lasers in general. Such characteristics are usually undesirable, and when they are encountered additional effort to stabilize the laser is typically needed. Evidence has been provided to suggest that the spiking behavior, at least in erbium fiber lasers, is linked to high ion concentration effects, which result in the formation of ion pairs and clusters acting as saturable absorbers. Because high ion concentrations are typically desired for the realization of short, robust single-frequency fiber lasers, the issue of suppressing spiking behavior is of substantial importance. Furthermore, even when they are operating in a CW state without spiking, erbium fiber lasers tend to be very noisy near the relaxation-oscillation frequency, and means to dampen the system are necessary. To this end, we recently suggested, based on a stability analysis, that resonant pumping directly into the metastable ion state can have a significant effect on the dynamics of erbium-doped fiber lasers. In particular, by simply selecting a pump wavelength sufficiently close to the lasing wavelength, we theoretically showed that spiking could be eliminated. In this Letter we report on experimental results to verify these conjectures.

The experimental configuration is shown in Fig. 1. An erbium-doped germanosilicate fiber was selected in which to fabricate the test fiber laser, which had an erbium-ion concentration of ~370 parts in 10⁶ and a measured small-signal absorption of 10 dB/m at 980 nm. The numerical aperture was 0.26, reflecting the high level of GeO₂ (17 mol %) in this fiber. With these levels of germania and erbium concentrations, ion clustering and laser spiking are expected. The single-mode cutoff wavelength was 1 µm. The test laser is a 1561-nm distributed-feedback (DFB) fiber laser, made simply by writing a 10-cm-long phase-shifted grating in the doped fiber.

The pump source to the DFB fiber laser is either a 980- or a 1510-nm diode, followed by an appropriate bulk isolator to prevent feedback to the diode, which might otherwise affect the stability of the pump and hence the fiber laser. For the case of the 980-nm diode, since the pump power required for this study is relatively low we also inserted a 10-dB optical attenuator to increase the isolation by an additional 20 dB. To couple the pump to the fiber laser, we used a 980/1550-nm wavelength-division multiplexer (WDM) (in the case of 980-nm pumping) or a 1510/1560-nm WDM (for 1510-nm pumping). Although both pump sources were stable, the stability of the 980-nm output, with intensity variations of <1%, was observed to be several times better than that for 1510 nm. Figure 2 shows the output of the fiber laser under 980- and 1510-nm pumping. For 980-nm pumping, the threshold is less than 1 mW, with an output power of 50 µW for a pump power of 20 mW. However, for output powers above 30 µW, the laser was unstable, exhibiting strong spiking behavior with self-pulsing frequencies of the order of ~100 kHz.

Under 1510-nm pumping, the threshold is higher at 2 mW, with an output power of 40 µW for the maximum pump power of 60 mW. Pumping at 1510 nm is thus less efficient than that at 980 nm; in return, however, in the former condition the laser was observed to be considerably more stable in intensity and lased in a CW condition without self-pulsations up to the maximum of 40 µW obtained. Under both pumping configurations, we observed, using a scanning Fabry–Perot interferometer, that single-frequency operation of the DFB fiber laser was maintained, even in the self-pulsing regime.

To investigate the dynamics of the laser under various pumping conditions, we introduced a mechanical chopper between the pump diode and the fiber WDM to observe the large signal transient response of the fiber laser. Figure 3 shows the corresponding transient response with 980-nm pumping for different laser output powers. It is seen that at 20-µW output power,
Fig. 2. Lasing characteristics for the erbium-doped fiber laser with different pump wavelengths.

Fig. 3. Transient response of the erbium fiber laser under 980-nm pumping and for average output powers of (a) 20 µW, (b) 30 µW, and (c) 40 µW.

Fig. 4. Transient response of the erbium fiber laser under 1510-nm pumping and for output powers of (a) 20 µW, (b) 30 µW, and (c) 40 µW.

time to settle to a stable cw state. Furthermore, the laser intensity is observed to be highly susceptible to external perturbations and prone to noise bursts. At 40-µW output power, the relaxation oscillations are undamped and the laser is clearly unstable, developing into a self-pulsing state.

By contrast, Fig. 4 shows the corresponding transient response of the fiber laser under 1510-nm pumping for the same laser output powers. It is seen that, although the damping time of the relaxation oscillations does increase slightly with output power from 20 to 40 µW, the laser is much better behaved and stable throughout its operating range.

The experimental results effectively confirm the theoretical predictions, which were based on a simple model involving a two-Stark-level ground state for resonant pumping and ion pairs as saturable absorbers for inducing spiking behavior. As mentioned in Ref. 8, the physical basis for the improved stability is believed to arise from the resonant pump's acting also as a gain limiter; hence the large excursions
in the inversion that typically accompany or contribute to sustained self-pulsations are damped out. In addition to eliminating spiking behavior, resonant pumping should also result in lower noise operation even when the laser is capable of operating in a stable cw condition. Figure 5 shows the relative intensity noise spectra of the fiber laser at the operating output power of 30 μW, which is stable for both pumping wavelengths. Under 980-nm pumping, the relative intensity noise spectrum exhibits a strong peak of −77 dB/Hz at the relaxation–oscillation frequency, which drops off to −113 dB/Hz at 1 MHz. With 1510-nm pumping, the noise peak is reduced by 13 dB, to −90 dB/Hz, without any worsening of the noise spectrum at higher frequencies. This is in contrast to the active noise-reduction technique involving negative feedback to the pump diode, whereby the relaxation–oscillation noise peak can be strongly suppressed but at the expense of increased noise at higher frequencies.5

In conclusion, we have experimentally demonstrated that the stability of erbium fiber lasers can be significantly improved by resonant pumping at 1510 nm instead of at 980 nm. In return for the higher-threshold pump power requirement, resonant pumping is able to suppress spiking behavior and yield lower noise operation. Although the research reported here relies on saturable absorber–based ion clustering as the cause of instability, the damping effects associated with resonant pumping should be applicable to other types of saturable absorber as well, e.g., in realizing quieter semiconductor mode-locked erbium-fiber lasers, which also tend to undergo a Q-switching or spiking regime at low pump powers.9

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