Elimination of Self-Pulsations in Dual-Clad, Ytterbium-Doped Fiber Lasers

Introduction

High-power, high-beam-quality, stable continuous-wave (cw) fiber lasers are desired in sensing, ranging, telecommunications, and spectroscopy.[1,2] Although high-output powers have been achieved in many high-power fiber laser systems,[3] self-pulsing often occurs in cw fiber lasers under specific pumping and cavity conditions.[4] Generally, self-pulsing in fiber lasers can be classified as sustained self-pulsing (SSP) and self-mode-locking (SML). SSP is the periodic emission of optical pulses at a repetition rate corresponding to the relaxation oscillation frequency of the inversion and photon populations. SML is the periodic emission of optical pulses with a rate corresponding to the cavity-round-trip time.[5] Both of the regimes can be described by the interaction of the photon population and the population inversion.[6]

Although the self-pulsations typically occur at the lower end of the pump power range, the pulses caused by these instabilities carry sufficient optical energy to cause catastrophic damage to the fiber laser, particularly when they are allowed to occur for extended periods of time. For this reason, there have been intensive investigations on self-pulsation suppression in cw fiber lasers. Electronic feedback has been used on the pump laser to shift the gain and phase to minimize relaxation oscillations.[7] Auxiliary pumping near the lasing wavelength sustains the population inversion in the gain medium, thereby preventing rapid gain depletion and minimizing the relaxation oscillations.[8] The fast saturable gain of a semiconductor optical amplifier included within the fiber-laser cavity prevents large signal buildup in the fiber laser and suppresses the self-pulsing behavior.[9] The narrow passband of a $\lambda/4$-shifted fiber Bragg grating (FBG) structure in a ring cavity limits the number of longitudinal cavity modes and suppresses self-pulsations.[10] In this article, increasing the round-trip time in the cavity by inserting a long section of passive fiber is shown to change the relaxation oscillation dynamics and make it possible to completely eliminate self-pulsations at all pumping levels. This technique is much simpler to implement than the alternative methods described above.

Experimental Results

The experimental setup is shown in Fig. 115.42. The 25-W pump light at a wavelength of 915 nm is delivered by the pump coupling fiber, which has a 200-μm core diameter and 0.22 numerical aperture (N.A.) with aspheric lenses of focal lengths 27 mm and 13.5 mm. The overall pump coupling efficiency is 75%. The laser gain medium is a 20-m, dual-clad, ytterbium-doped, single-mode fiber with an absorption rate of 0.5 dB/m at 915 nm. This ytterbium-doped fiber has a 130-μm cladding diameter with an N.A. of 0.46. The fiber has a core diameter of 5 μm with an N.A. of 0.12. One end of the fiber is spliced into an FBG having a 3-dB bandwidth of 0.36 nm and >99% reflectivity at a center wavelength of 1080 nm. The other end of the active fiber is cleaved perpendicularly, providing a 4% reflection at the fiber–air interface. A dichroic mirror is inserted between the aspheric lenses to couple the laser output signal into a 2-GHz-bandwidth optical detector and a 600-MHz-bandwidth oscilloscope to measure laser dynamics. Three additional configurations are characterized in this experiment. In these alternate configurations, three long sections of passive fiber (329 m, 1329 m, and 2329 m) are spliced into the laser cavity between the active fiber and the FBG. The four lasers are designated as laser 1 (20-m cavity), laser 2 (349-m cavity), laser 3 (1349-m cavity), and laser 4 (2349-m cavity).

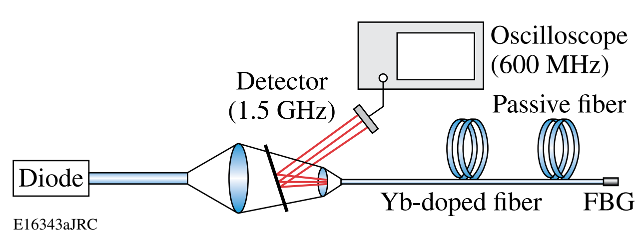

Figure 115.42
Schematic diagram of the ytterbium-doped fiber laser. FBG is the fiber Bragg grating.

The lasing properties of the four configurations have been characterized. The four lasers have about the same pump threshold of 0.75 W. At maximum pump power, the difference in output power between the four lasers is less than 9% due to the scattering loss of the passive fiber sections. Both SSP and SML have been observed in laser 1. A cw optical output is observed with low pump powers. As the injected pump power is increased beyond 2.0 W, quasi-periodic optical pulses, induced by undamped relaxation oscillations, are observed in the SSP regime. Figure 115.43 shows an example of such pulsations when the pump power is 3.2 W. The pulse period is around 20 μs, which agrees with the calculated relaxation oscillation frequency of the laser. As the pump power is tuned higher to 6.6 W, SML pulsing at a rate corresponding to a cavity-round-trip time is observed. This regime occurs because the gain medium is pumped hard enough to recover the population inversion in a single-cavity-round-trip time. Figure 115.44 shows an example of such pulsations when the pump power is 7.2 W. The measured pulse period of 290 ns corresponds to the round-trip time of the laser cavity. As the pump power is further increased beyond 7.5 W, the laser once again operates in the cw regime because the gain is replenished more rapidly than the time it takes for the pulse to complete a round-trip through the laser cavity.

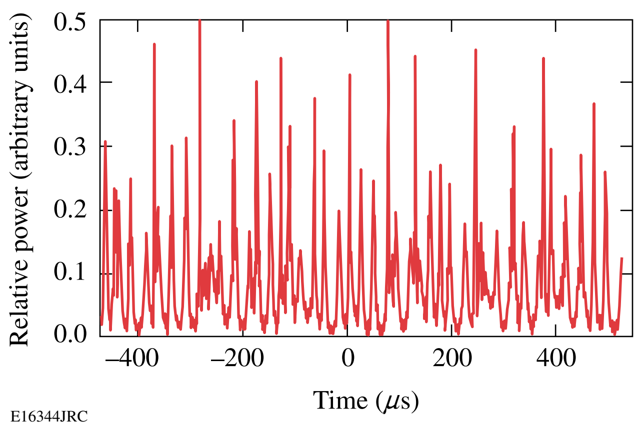

Figure 115.43
The self-pulsing dynamics of laser 1 when the pump power is 3.2 W.

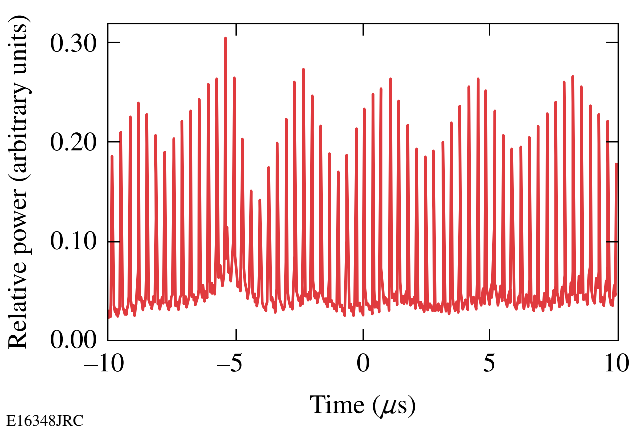

Figure 115.44
The self-pulsing dynamics of laser 1 when the pump power is 7.2 W.

Analysis

The physics underscored here implies that when the pumping rate is sufficiently fast compared to the relaxation oscillation dynamics, the gain will always be replenished before a pulse can build up in the cavity. The dynamics in the SSP regime are dependent on the cavity length such that the relaxation oscillation frequency becomes smaller with increasing cavity length, as governed by conventional laser theory. The dynamics in the SML regime are directly dependent on the cavity length since the laser mode locks to the cavity-round-trip time. Therefore, by sufficiently increasing the cavity length, all self-pulsation dynamics can be slowed down compared to the pumping rate and all self-pulsations will be eliminated.

The modulation depth of the pulsations, defined as the ratio of the peak-to-valley value of the modulation to the peak value, indicates the competition between self-pulsing and cw working regimes. Figure 115.45 shows the modulation depth as a function of pump power for the four laser cavities. As predicted by fiber-laser rate equations,[11] the modulation depth decreases as the fiber-laser cavity length is increased, indicating a stronger tendency toward cw operation. In addition, the pump range where self-pulsations occur also decreases drastically with increasing cavity length. Laser 2 has an instability range that is less than 19% of that of laser 1, while laser 3 has an instabil-

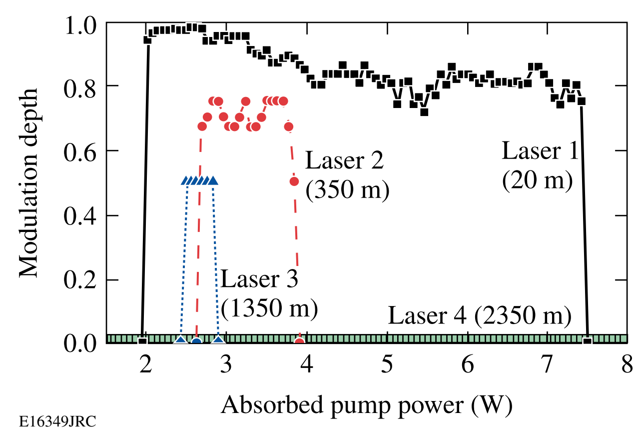

Figure 115.45
The self-pulsing characteristics of the fiber lasers with four different cavity lengths. The active fiber length is 20 m in all four cases

ity range that is less than 7% of that of laser 1. For laser 4, the instability range reduces to zero and no self-pulsations occur over the entire pump range.

For fiber lasers having long cavity lengths such as in laser 4, stimulated Raman scattering (SRS) can occur at high-power levels. In the experiments described above, no SRS spectra above the noise floor were observed, but SRS can be induced at higher pump levels. For example, a laser with a 1-km cavity length has an SRS threshold of about 5 W. SRS can be mitigated with appropriate filters, such as wavelength-division multiplexers, in-line short-pass filters, or hole-assisted single-polarization fibers.[12] Large-mode-area fiber can also be used to suppress SRS in long fiber lasers. For example, higher-order-mode (HOM) fiber with a mode-field diameter of 86 μm (Ref. 13) can increase the nonlinear threshold by a factor of 200 compared to normal single-mode fiber. By inserting a 1-km passive HOM delay fiber into the laser cavity, the effective fiber length that contributes to the nonlinearity is about 5 m, mitigating the SRS impairment of such a long-cavity fiber laser.

Using long lengths of passive fiber to suppress self-pulsing has many advantages over other methods. No active components or electronics are required, resulting in reduced system complexity. This method does not require free-space alignment and can be easily integrated into existing laser systems. Even though our demonstration was in an ytterbium-doped fiber laser, the technique can be applied to any rare-earth-doped fiber laser (e.g., erbium). Additionally, the laser output power degrades only a few percent due to the scattering loss so that high-efficiency performance can be maintained.

Conclusion

In conclusion, suppression and elimination of self-pulsing in a watt-level, dual-clad, ytterbium-doped fiber laser have been demonstrated. Self-pulsations are caused by the dynamic interaction between the photon population and the population inversion. The addition of a long section of passive fiber in the laser cavity makes the gain recovery faster than the self-pulsation dynamics, allowing only stable continuous-wave lasing. This scheme provides a simple and practical method requiring no active devices for eliminating self-pulsations in fiber lasers at all pumping levels.

ACKNOWLEDGMENT

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