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Locking of self-oscillation frequency by pump modulation in an erbium-doped fiber laser

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Abstract

Frequency locking of self-oscillations in a diode-pumped erbium-doped fiber laser by external modulation of the diode current is studied experimentally. The coexistence of locking and unlocking regimes is detected. The condition for onset of the bistability and dependences of the frequency detuning on the modulation frequency and amplitude are established. Transitions to torus-chaos are also demonstrated.

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The self-modulation in a diode-pumped erbium-doped fiber laser (EDFL) is a well-known phenomenon [1,2] that recently attracts much attention due to exclusive advantages in utilization of this laser as a light source for optical communications, reflectometry, sensing, medicine, etc. [3,4]. Meanwhile the self-pulsations may restrict applications of this laser to areas where a stable operation is required. Different physical mechanisms have been considered to explain this phenomenon. In many works, it is attributed to the presence of a saturable absorber in the fiber resulting from the influence of ion pairs [1] or pump depletion [5]. Small quasi-sinusoidal modulation of the laser intensity with a broaden frequency of relaxation oscillations in the power spectrum can be explained by the presence of noise in a diode pump laser [6] and large self-pulsations by accounting for a thermo-lensing effect due to the excited state absorption at the pump wavelength [7].

Dynamics of the EDFL subjected to external modulation has been studied in several works

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[8–14]. In all these works, a high sensitivity to any external perturbation has been demonstrated, especially at the resonance laser frequency. In this paper, we study experimentally the frequency-locking phenomenon in a self-oscillating EDFL with harmonic modulation of the diode current of the pump laser. We demonstrate that the external modulation can lock the self-modulation frequency. Such a behavior of the pump-modulated EDFL has features that are generic to nonlinear systems characterized by the presence of two competing frequencies [15]. If the driving frequency is an integer multiple or submultiple of the intrinsic pulsation frequency the phenomenon of frequency locking can arise. The frequency locking is of practical importance in short pulse generation and in stabilization of oscillations (see, for example [16]). If the two frequencies are incommensurate, the resulting oscillations are usually quasiperiodic. A transition from quasiperiodicity to chaos can occur if the driving modulation amplitude is increased while the ratio between the two frequencies remains a fixed irrational value. The quasiperiodic route to chaos and generalized bistability have been also found in a dual-wavelength EDFL [17,18].

The influence of harmonic pump modulation to dynamics of a fiber laser was studied first by Bielawski et al. [19,20]. They demonstrated a period-doubling route chaos, generalized bistability, antiphase behavior and some polarization effects in an Nd-doped fiber laser. However, in their experiments the concentration of Nd^{3+} ions in the fiber was too small (300 m) to make the effect of ion pairs significant and thus self-pulsations were not observed. In that case, their laser acted as an ordinary class-B laser. In contrast to that work, here we study the EDFL with heavily doped erbium fiber (2300 ppm of Er^{3+} ions) which leads to the appearance of ion pairs and may provoke migration of excitation among the ions and hence induce the quenching effects. This results in self-modulation of 2–3% of the average laser power.

In the absence of the external modulation, the response of the EDFL exhibits a sharp peak in the power spectrum at the relaxation oscillation frequency f_0. This frequency characterizes the rate of energy exchange between photons in the cavity and excited ions in the active fiber. At a relatively low pump power, the self-sustained pulsations arise in the form of almost harmonic oscillations with frequency $f_s = f_0$. The second frequency f_m induced by external modulation of the pump interacts with f_0 resulting in detuning f_s from f_0 ($\delta = f_0 - f_s$) that depends on the amplitude of the external modulation. In this work we determine directly the range of f_m within which the external modulation can effectively entrain the self-pulsation frequency and evaluate the scaling relation ruled the dependence of δ on the amplitude of the external modulation.

In our experiments, the EDFL is pumped by a commercial laser diode (wavelength 977 nm, maximum pump power 300 mW) through a wavelength-division multiplexing coupler (WDM) (Fig. 1). The laser cavity of a 1.5-m length is formed by a piece of heavily doped erbium fiber of a 70-cm length and a core diameter of 2.7 μm, and two fiber Bragg gratings (FBG1 and FBG2) with a 1-nm full width on half-magnitude (FWHM) bandwidth and reflectivity of 91% and 95% at a 1560-nm wavelength. The powers of the pump diode and fiber lasers are recorded through WDM with photodetectors D1 and D2 and analyzed with an oscilloscope and a Fourier spectrum analyzer. The output power of the pump laser depends linearly on the laser diode current. The harmonic signal, $A\sin(2\pi f_m t)$ (A being the modulation amplitude), applied from a signal generator to the laser driver causes sinusoidal modulation of the diode current with frequency f_m. In our experiments, the signal with $A = 800$ mV provides a 100% modulation depth of the pump power, while the average diode current is fixed at 40 mA. In this

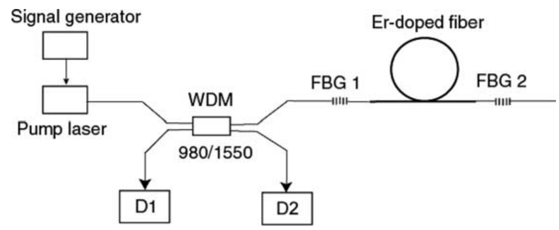

Fig. 1. Experimental setup. WDM is the wavelength-division multiplexing coupler, FBG1 and FBG2 are the Bragg gratings, and D1 and D2 are the photodetectors.