Nonlinear Phenomena in Erbium-Doped Lasers

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Abstract. The nonlinear dynamics of an erbium-doped fiber laser is explained based on a simple model of the ion pairs present in heavily doped fibers. The single-mode laser dynamics is reductible to four coupled nonlinear differential equations. Depending on the ion-pair concentration, the pumping level and the photon lifetime in the laser cavity, numerical calculations predict cw, self-pulsing and sinusoidal dynamics. The regions of these dynamics in the space of the laser parameters are determined.

1 Introduction

In recent years much attention has been paid to the study of nonlinear effects in optical fibers [1, 2, 3, 4, 5, 6]. Erbium-doped fiber lasers (EDFLs) present numerous applications in telecommunications and laser engineering. In the same time, it is also a promising system for theoretical nonlinear studies [7, 8]. Self-pulsing and chaotic operation of the EDFLs has been reported in various experimental conditions [3, 4], including the case of pumping near the laser threshold. We present a model for the single-mode laser taking into account the presence of the erbium ion pairs that act as a saturable absorber.

2 The Basic Model

The erbium-doped laser emitting around 1.55 μm ($^4I_{13/2} \to {}^4I_{15/2}$ transition) is a three-level system (Fig. 1). Er^{3+}-ions at a concentration N_0 are pumped with the rate Λ from level 1 ($^4I_{15/2}$) to level 3 (for example $^4I_{11/2}$, 980 nm above the ground state). The level 3 is fastly depopulated through a non-radiative transition on the upper laser level 2 ($^4I_{13/2}$) which is metastable with the lifetime $\tau_2 = 1/\gamma_2 = 10\,\mathrm{ms}$. The letter σ in Fig. 1 denotes the absorption cross section in the laser transition. In the rate equation approximation, the laser dynamics is described based on two coupled differential equations, one for the population inversion and the other for the laser intensity:

$$\frac{\mathrm{d}n}{\mathrm{d}t} = 2\Lambda - \gamma_2(1+n) - 2in \ , \tag{1}$$

$$\frac{\mathrm{d}i}{\mathrm{d}t} = -i + Ain \ . \tag{2}$$

O. Gervasi et al. (Eds.): ICCSA 2005, LNCS 3482, pp. 643–650, 2005.

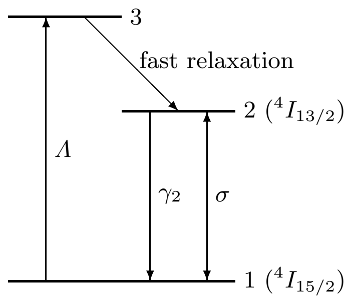

Fig. 1. Erbium-ion energy levels implied in the laser effect

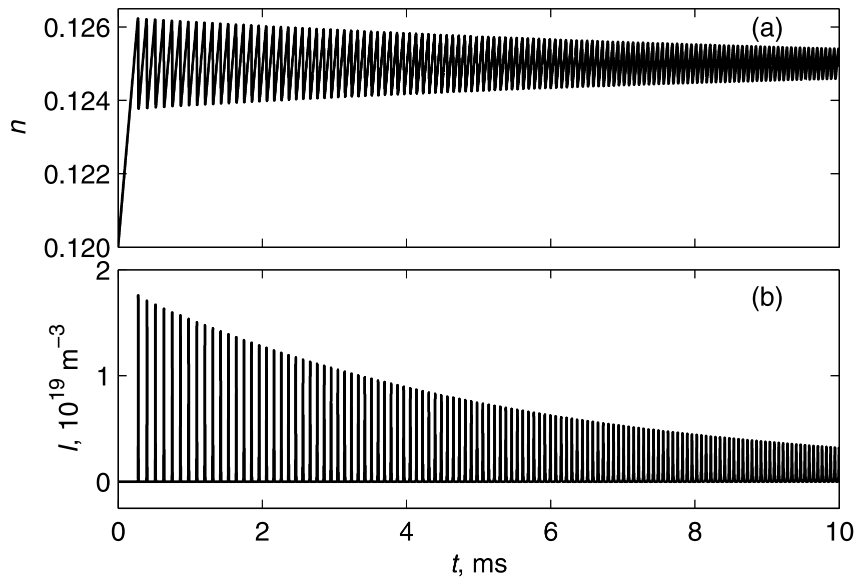

Fig. 2. Transient dynamics of the erbium laser. (a) Population inversion; (b) Laser intensity. Numerical values of the laser are given in text and photon lifetime is $\tau = 10^{-8}$ s. The plot starts at a point where the population inversion reaches a value close to the stationary one

Here, the time is expressed in units of the photon lifetime τ in the laser cavity, $n = n_2 - n_1$ is the difference of the occupation probability of level 1 and 2, respectively, and i stands for the dimensionless laser intensity; $i = \sigma I \tau$, where I denotes the photon density of the laser field. The parameter A in Eq. (2) is $A = \sigma N_0 \tau$; note that parameter γ_2 in Eq. (1) is dimensionless, i.e., the relaxation rate is expressed in $1/\tau$ units.

The determination of the steady-states furnishes the points

$$n = 2\Lambda/\gamma_2 - 1,\ i = 0 \quad \text{and} \quad n = 1/A,\ i = A(\Lambda - \Lambda_{\text{th}}) \ , \tag{3}$$