Heuristic estimation of the parameters for passively all-fiber Q-switched erbium- and samarium-doped laser

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*We present a parametric approach based on genetic algorithm (*GA*) techniques in the context of the estimation of the parameters of some specified model for passively Q-switched fiber laser. This method is applied on the experimental results given by a novel all-fiber configuration, where an Er-doped fiber laser, using Sm-doped fiber as a saturable absorber, oscillates in passive Q-switch operation by using a continuous-wave pumping. This heuristic methodology can be successfully employed and it turns out very useful when we want to determine the parameters values which cannot be directly or exactly measured because of limits imposed by the measurement equipment.*

Introduction

Q-switched fiber lasers operating at 1550 nm are of great interest for various applications in medicine, optical time domain reflectometry, distributed fiber-optical sensing and investigation of nonlinear phenomena. The development of completely all-fiber passively Q-switched lasers can be very useful because of their high reliability, device stability and the essential alignment of all the fibers [1,2]. To better control the behavior of the all-fiber passively Q-switched fiber laser, it is necessary to be able to know the values of its all parameters. For this purpose, the laser dynamics can be used to determine its characteristic parameters or to look for the best model fitting the laser behavior [3].
In this paper we are interested in the estimation of the parameters of passively Q-switched all-fiber laser with some specified model. The estimation is carried out by fitting parameters such that experimental and theoretical laser signal match as well as possible. The problem is reduced to a non-linear optimization one that we solve using genetic algorithms. This method is applied on our experimental results given by a novel all-fiber configuration. An Er fiber laser, using Sm-doped fiber with a relatively small core diameter as a saturable absorber, oscillates in passive Q-switch operation by using a continuous-wave pumping [4]. The laser produces very stable pulses trains, which are globally used by the GA to estimate the totality of the model parameters. A parameter which presents a great interest to be evaluated with high accuracy is the decay time of the absorption upper level of Sm-doped fiber. Its value has been experimentally evaluated in [5] to be less than 5 ns, but the precision of this value was limited by the resolution of the equipment used. The spontaneous emission factor represents an other critical parameter which plays an important role in the transient behavior of the passively Q-switched fiber laser.

Theoretical model

Let us consider the model which reproduces the experimental data is that proposed in [6]. This model is obtained, by adding a term for the saturable absorber, from the usual model used for the erbium-doped fiber laser. In order to obtain a more reasonable laser behavior, a term related to the spontaneous emission was added to the intensity evolution equation, as in [7]. We obtain the following model given by the nonlinear differential equations:

$$\begin{aligned} \frac{dI(t)}{dt} &= -\kappa I + \gamma(gD + g_A D_A)I + \beta D, \\ \frac{dD(t)}{dt} &= \gamma[I_p - 1 - (1 + I_p + I)D], \\ \frac{dD_A(t)}{dt} &= -(D_A + 1) - \gamma C_{AL} I D_A, \end{aligned} \tag{1}$$

where the time t is measured in units of decay time of the upper level of the saturable absorber $1/\gamma_a$. I(t) represents the laser intensity, D(t) is the population inversion of the active medium and $D_A(t)$ that of the absorber medium. Spontaneous emission is considered through the factor β. I_p represents the intensity of the pump laser. κ is cavity loss rate (κ_p) normalized to the decay rate of the upper level of the saturable absorber $\kappa = \kappa_p/\gamma_a$ and γ is the population inversion decay of the lasing medium ($\gamma_{||}$) normalized to the decay rate of the upper level of the saturable absorber $\gamma = \gamma_{||}/\gamma_a$. The parameters g and g_A are the unsaturated gain coefficients of the active medium and the unsaturated absorption coefficient of the absorber, respectively. C_{AL} is the ratio of the transition cross-section of the saturable absorber (σ_{AS}) to that of the lasing medium (σ_L). Based on pulses train from the laser, the genetic algorithm estimates the values of all these parameters. We detail this methodology in the following section.

Methodology and setup

Genetic algorithms [8] are stochastic optimization methods based on the mechanisms of the natural selection and genetics. Although using very simple techniques with manipulations of binary chains, they are very powerful and effective. They are used to solve optimization problems, in particular when a reliable model of the system is missing or for inverse problems.

In the present work, the GA is used to solve an inverse problem: we have got the experimental signals from the laser and we want to determine the values of characteristic parameters of this laser (see Fig. 1(a)). The optimization problem consists in finding

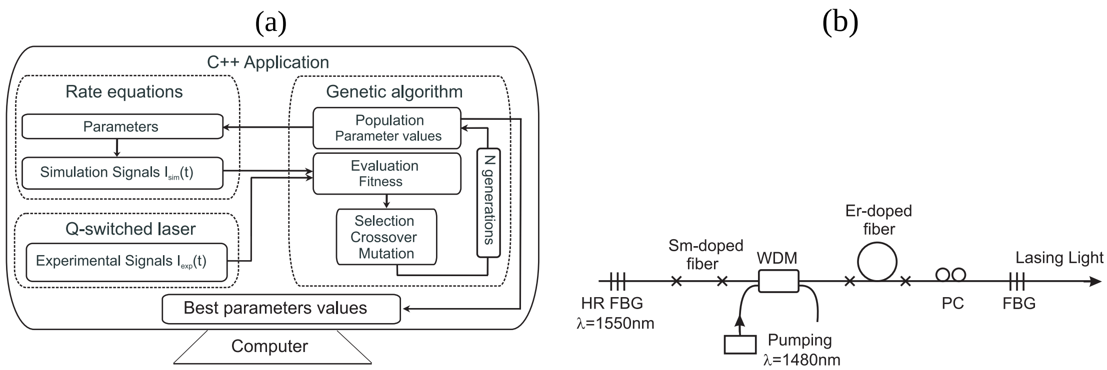

Fig. 1: (a) Diagram of the C++ application, including GA and the rate equations solving. (b) Self-Q-switched Er-doped fiber laser.

the optimal values of parameters included in the system (1) such that the simulation laser

intensity, $I_{sim}(t)$ provided by the model, fits as close as possible the experimental laser intensity, $I_{exp}(t)$ (see Fig. 1(a)). The seven parameters of the model described by (1) to estimate are: κ_p, $\gamma_{||}$, γ_a, β, g, g_A and I_p.
The experiments used by the GA have been realized on the same laser that has used for our previous passively Q-switched experiments [4]. Fig. 1(b) shows the experimental configuration of our all-fiber self Q-switched laser. A Raman laser emitting at 1480 nm pumps the laser through a WDM coupler (1480/1550 nm). The laser cavity is formed by two fiber Bragg gratings (FBGs), one with high reflectivity ($R > 99\%$) and the second one with a reflectivity about $R = 30\%$. The maximum reflectivity of both FBGs was at 1550 nm. The cavity, with the total length about 12 m, contains a 10 m long Er-doped fiber used as active medium and a 10 cm long Sm-doped fiber used as the saturable absorber.

Results

Through the evaluation procedure of the GA, as is shown in Fig. 1(a), the numerical integration of the rate equations and the use of experimental signals are coupled. We have realized the specific GA calculations by setting limits for the value of the κ_p, $\gamma_{||}$ and γ_a corresponding to reasonable guess. For κ_p we used a simple estimation of the cavity losses, whereas for the population inversion decays ($\gamma_{||}$ and γ_a) we considered the values provided by the literature as referred in [5, 9]. The spontaneous emission factor β is free between 10^{-8} and 10^{-5} [7] . The interval of the variation for the unsaturated gain coefficient of the active medium and the unsaturated absorption coefficient of the absorber medium, g and g_A were fixed by using the values given in literature for this type of fibers [6]. C_{AL} was free between 0.9 and 10. Due to the difficulty to localize with precision the threshold, the value of the pump intensity varies into a range chosen as 20% of the value indicated by the pump laser. These intervals are reduced after a first step considered successfully, when the overlapping of the theoretical and experimental signals is quite good. Convergence is usually obtained after 30 new generations.
On Fig. 2 we have shown three different stages of our laser dynamics which are used by GA to fit the laser parameters values. We observe an excellent agreement between

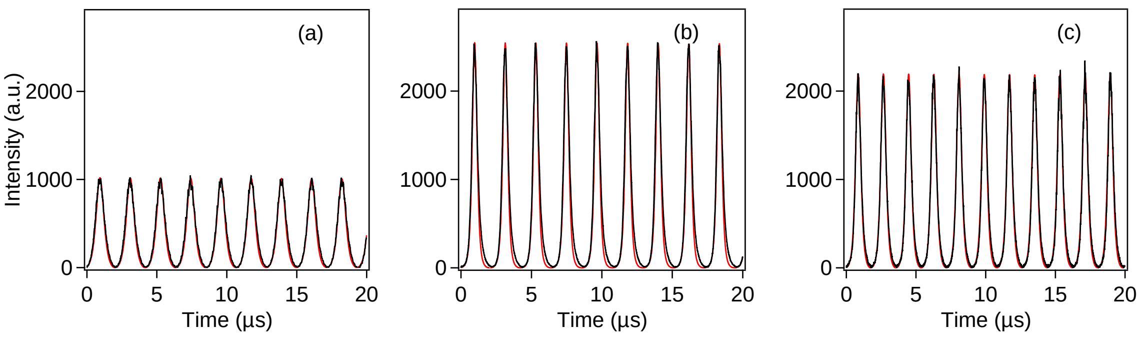

Fig. 2: Typical result of *GA* fit: the experimental pulse train (in black) and the calculated pulse train (in red) for three values of the pump power: (a) 2.86 W, (b) 3.7 W, and (c) 4.9 W.

experiments (the black signals) and simulations (the red signals) obtained for different values of the pump power. Despite of its simplicity, the model used provides a good description of the laser dynamics. More exactly, it reproduces the fact that the maximum intensity grows by increasing the pump power, while the period and the duration of the

Table 1: Parameter values given by GA for passively all-fiber Q-switched Er-and Sm-doped laser

Laser parameter	Value
Cavity loss ($10^5 s^{-1}$), κ_p	$53.77 \pm 0.87\%$
Population decay Er (s^{-1}), $\gamma_{\|\|}$	$99.84 \pm 1.53\%$
Population decay Sm ($10^8 s^{-1}$), γ_a	$2.05 \pm 5.50\%$
Spontaneous emission ($-\log_{10}\beta$), β	$6.48 \pm 14.13\%$
Unsaturated gain coefficient (10^7), g	$12.10 \pm 1.34\%$
Unsaturated absorption coefficient(10^6), g_a	$2.012 \pm 0.75\%$
Ratio of the transition cross-section, C_{AL}	$1.03 \pm 4.28\%$

pulses decrease. In Table 1 are shown the values obtained for the parameters of our laser. We have found for the decay time of the upper level of Sm-doped fiber a value about of 4.87 ns what is closely to value experimentally found by [5]. The GA fit gives a value of spontaneous emission factor β equal to $10^{-6.48 \pm 0.61}$. We can observe that a stable Q-switching regime is obtained, even for values of coefficient C_{AL} little upper to the unity.

Conclusions

We have proposed a heuristic methodology which allows, with little a priori knowledge of the laser parameters, to estimate all the parameters values of our passively Q-switched Er- and Sm-doped fiber laser. This method can be successfully employed and it turns out very useful when we want to determine, for multimode laser in more complex dynamic regimes, the parameters values which cannot be directly or exactly measured.

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