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Theoretical study of energy evolution in ring cavity fiber lasers

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ABSTRACT

The theoretical study of the output energy evolution in ring fiber lasers is conducted. The analytical expression of the energy evolution in the laser cavity is proposed. It expands the theory developed previously by taking into account the saturable absorber losses. The results are verified by the mathematical modeling.

1. Introduction

Fiber lasers are used extensively in numerous industrial and research applications. In particular, due to the simplicity the lasers with the ring cavity are well-studied theoretically [1–3] and these lasers have been applied in various areas including metal processing, medicine and telecommunications [4–7].

The optimization of laser performance required massive numerical modeling (see, for example, recent papers [8–17] and references therein). However, certain optimization problems are difficult to solve by modeling due to its computationally expensive nature. In fiber lasers, typically, optimization should be performed in the multi-dimensional parameter space that makes global optimization over the whole parameter space impractical.

In general, the fiber laser output energy depends on both the type of laser cavity and the characteristics of intracavity devices such as the saturable absorber, active/passive fibers, and coupler. Consequently, detailed understanding of how these devices operate can aid in the prediction and consequent optimization of the quality of the output radiation. In [1] analytical theory of energy evolution in a fiber laser was developed that allows us to describe the intra-cavity energy evolution and to determine the energy at the fiber laser output. In this work we progress the theory developed in [1] further.

In combination with numerical modeling, the theory can significantly reduce the time required for laser optimization. In this paper, we present the theoretical formula describing the energy evolution in a ring cavity fiber laser with gain saturation, non-saturated losses, and a saturable absorber. The obtained results are verified using a numerical simulation. Moreover, we present the theoretical and numerical analysis of the dependence of the energy on the balance between the gain and losses. It is noteworthy that our approach can be further extended to laser cavities with more complex structures.

2. Mathematical analysis of ring fiber laser

To analytically describe the pulse evolution in modern fiber lasers, it is necessary to take into account several physical effects. These include the power amplification and losses, dispersion effects, and fiber nonlinearities. The dispersion effects and the nonlinear dynamics of the cavity radiation make the investigation of such laser systems more complex. The balance between saturated gain and non-saturated losses in the laser cavity defines the energy of the optical soliton; on the other hand, the dispersion and nonlinear effects define the pulse generation and the pulse shape [1,18]. Consequently, dispersion and nonlinear effects can be neglected for the analysis of the energy dynamics.

Recently, an analytical expression for the output energy/average power has been derived in terms of the cavity gain/loss

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parameters [1]. The theory proposed below generalizes the results obtained in [1] through including the non-saturated losses in the saturable absorber.

It is well known that the energy evolution in the gain medium can be described by the Schrödinger equation [3,2]

$$\frac{\partial A}{\partial z} = -\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} + i\gamma|A|^2 A + \frac{g_A}{2(1+E/E_{sat})}A - \frac{\alpha_A}{2}A, \tag{1}$$

where $A(z, t)$ denotes the envelope of the electromagnetic field, z is the spatial variable, t is the time variable, β_2 and β_3 are the dispersion coefficients, γ is the nonlinear coefficient. The input field is expressed as $A_{in}(t) = A(z = 0, t)$, and α_A denotes the fiber loss coefficient, g_A is the small signal gain and E_{sat} is the saturation energy.

It can be shown [3] that the energy evolution in an active fiber can be derived from Eq. (1) as follows:

$$\frac{\partial E}{\partial z} = E \times \left(\frac{g_A}{1+E/E_{sat}} - \alpha_A\right). \tag{2}$$

Let us consider Eq. (2). We define $s = \alpha_A/g_A$ as the ratio of the fiber losses to the fiber small signal gain, and further, L_A denotes the active fiber length. Our analysis below will follow the derivation given in [1]. Namely, the solution of Eq. (2) can be determined in a closed form. First, we transform the original equation into the following equation:

$$\left(\frac{1}{E} + \frac{1}{(1-s)E_{sat} - sE}\right)dE = (1-s)g_A\,dz.$$

For any gain medium, $g_A/(1 + E/E_{sat}) - \alpha_A > 0$. Consequently, the condition $(1 - s)E_{sat} - sE > 0$ is always satisfied. $E/E_{sat} < (1 - s)/s$, and in particular, $E/E_{sat} > 1$ in certain cases.

Integrating both sides of the equation, we can get the following:

$$E_0 = \frac{1-s}{s} \times E_{sat} \times \frac{1-\varphi_0^s \exp(s(s-1)g_A L_A)}{\varphi_0 - \varphi_0^s \exp(s(s-1)g_A L_A)}. \tag{3}$$

In order to derive the expression for the energy evolution, let us consider the laser cavity shown in Fig. 1. The cavity consists of the active fiber (AF) and passive fiber (PF) sections, the saturable absorber (SA), and the output coupler (OC). In [1], the cavity consisting of the active fiber and the output coupler was considered in the modeling.

We next estimate the steady-state energy balance between the fiber gain and losses in our configuration. The energy balance can be presented in the following form:

$$E_0 = RR_{SA}R_{PF}\varphi_0 E_0, \tag{4}$$

where E_0 denotes the energy at the input of the active fiber, R_{PF} and R_{SA} denote the output–input energy ratios (i.e., the ratio of the output energy to the input energy of the corresponding intracavity device) for the passive fiber and saturable absorber respectively, and R denotes the out-coupling parameter (i.e., the ratio of the energy that remains in the cavity to the input energy).

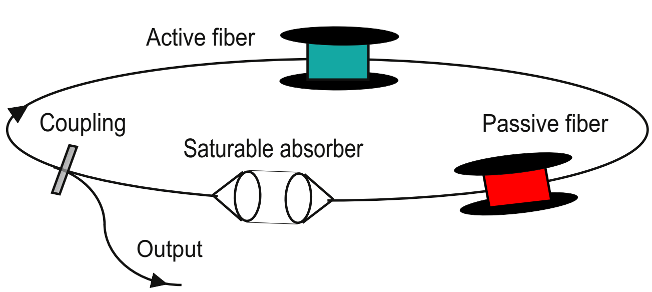

Fig. 1. Schematic of the ring laser cavity.

Consequently, we have

$$\varphi_0 = \frac{1}{R_{PF}R_{SA}R}. \tag{5}$$

We assume that initially $\tilde{\alpha}_A$, α_P, and $\tilde{g}_A$ are measured in dB/km, and hence, $R_{PF} = \exp(-\alpha_P L_P \cdot 0.1 \ln 10)$, $\alpha_A = \tilde{\alpha}_A \cdot 0.1 \ln 10$, and $g_A = \tilde{g}_A \cdot 0.1 \ln 10$. The losses at the output vary, and $R = \exp(-R_{dB} \cdot 0.1 \ln 10)$, where R_{dB} denotes the output losses expressed in dB and R_{SA} the losses in the saturable absorber. R_{SA} may vary and is limited by the modulation depth of the saturable absorber.

Eq. (5) can be rewritten as

$$\varphi_0 = \exp\left[(\alpha_P L_P + R_{SA,dB} + R_{dB}) \cdot 0.1 \ln 10\right], \tag{6}$$

where $R_{SA,dB}$ denotes the losses in the saturable absorber and is expressed in dB.

We define $S = \left(\tilde{\alpha}_A L_A + \alpha_P L_P + R_{SA,dB} + R_{dB}\right)/\left(\tilde{g}_A L_A\right)$ as the ratio of all losses to the full gain. Consequently, Eq. (6) can be transformed as

$$\varphi_0 = \exp\left[\left(\frac{\tilde{\alpha}_A L_A + \alpha_{PF} L_{PF} + R_{SA,dB} + R_{dB}}{\tilde{g}_A L_A} - \frac{\tilde{\alpha}_A L_A}{\tilde{g}_A L_A}\right) \cdot \tilde{g}_A L_A \cdot 0.1 \ln 10\right]$$

$$= \exp(G(S - s)), \tag{7}$$

where $G = \tilde{g}_A L_A \cdot 0.1 \ln 10 = g_A L_A$.

After substitution of φ_0 and G into Eq. (3), we have

$$E_0 = \frac{1-s}{s} E_{sat} \frac{1-\varphi_0^s \exp[s(s-1)G]}{\varphi_0 - \varphi_0^s \exp[s(s-1)G]}.$$

We can easily verify that $\varphi_0^s \exp[s(s-1)G] = \exp(sG(S-1))$.

After certain transformations, the following expression can be obtained for E_0:

$$E_0 = E_{sat}\frac{1-s}{s}\exp(0.5G(s-S)) \cdot \frac{\sinh(0.5G(1-S)s)}{\sinh(0.5G(1-s)S)}. \tag{8}$$

In particular, if we assume $R_{SA,dB} = 0$ and $\alpha_P = 0$, Eq. (8) can be reduced to the equation derived in [1] (see Eq. (5) therein). These assumptions correspond to the ring laser cavity consisting of the active fiber and output coupler. It should be noted that in order to estimate saturated SA losses theoretically it is necessary to make some assumptions about the pulse shape. For example, it can be assumed that the stable optical soliton saves the form of $\cosh^{-1}$ while propagating in the cavity. However, the interval estimation of the SA losses used below allows us to quickly estimate the output energy for each cavity parameter set. Thus it is not necessary to carry out the numerical simulation each time the cavity parameters are changed.

In general, E_{out} depends on the arrangement of the cavity devices. Let us consider the schematic shown in Fig. 1. Obviously, the output energy is

$$E_{out} = E_0 \cdot \frac{1-R}{R}. \tag{9}$$

Similarly, we can determine the output energy for any arrangement of cavity devices.

Let us consider the previously derived Eq. (9). It is useful to estimate the energy that can be obtained when the losses in the active fiber approach zero. To estimate this energy, it is necessary to calculate the following limit:

$$E_{s=0} = \lim_{s\to 0} E_{out}, \tag{10}$$

where s denotes the ratio of the active fiber losses to the full gain. Eq. (9) yields the following limit to be found: