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Identifying the mechanisms of pulse formation and evolution in actively mode-locked Erbium fiber lasers with meters and kilometers-long

L.A.M. Saito *, E.A. Thoroh de Souza

MackGraphe - Graphene and Nanomaterials Research Center, Mackenzie Presbyterian University, Rua da Consolação 896, São Paulo/SP, 01302-907, Brazil

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ABSTRACT

We investigated the dynamics of pulse evolution in Erbium-doped fiber ring lasers with cavity lengths varying from 16.4 m to 100.8 km actively mode-locked at repetition rate of 1 GHz. The novelty of this work is to explore the limits of Kuizenga–Siegman theory in ultralong fiber laser and to demonstrate the dynamics of pulse generation and propagation separately. When we vary the length of the Erbium-doped fiber lasers from meters to kilometers long, three operation regimes were identified: mode-locking regime (for cavity lengths with 16.4 m to 1 km), nonlinearity-dominant regime (1 to 10 km) and dispersion and nonlinearity regime that locked the ratio between soliton period and cavity length: $Z_S/L_{cav} = 1.35$ for cavities with 10 to 100 km in a soliton intracavity condition. The variation of pulse widths and the peak powers are analyzed to define the propagation regimes inside the cavities, depending on the cavity length (L_{cav}), dispersion length (L_D) and nonlinear length (L_{NL}). When L_{cav} is shorter than L_D and L_{NL}, there is neither dispersive nor nonlinear effect during pulse evolution (pulse has duration of approximately 30 ps). In this regime, its final duration is determined by the standard theory of active mode-locking. For L_{cav} shorter than L_D but $\sim L_{NL}$, the pulse evolution is in nonlinearity-dominant regime where soliton propagation provides a sech^2 profile with a TBP transform limited of 0.315. In addition, for cavities longer than 10 km, $L_{cav} \sim L_D$ and longer (or much longer) than L_{NL}, the pulse evolution is in the dispersion and nonlinearity dominant regime with its duration depending on the accumulated dispersion. In this regime the soliton effect takes place and the final pulse duration is defined by the cavity length which is approximately the soliton period.

1. Introduction

Since the first demonstration of a cavity laser with 101 m long in 1982 by Nakazawa et al. [1], long fiber lasers have been exploited due to the facility to connect active and passive fiber components by fusion splicing, the reduction of the fiber loss and the possibility of a simple design. Mode-locked fiber lasers are capable of generating ultrashort stable pulses with ps and fs widths when longitudinal modes are forced to keep a phase relation between each other [2,3]. Recently, passively mode-locking regime was obtained by the use of a saturable absorber in which single-walled carbon nanotubes (SWCNT) were coated on the fiber connector end [4] and by the fabrication of thin films to put in the cavity [5,6]. By increasing the pump power, a SWCNT doped PVA film was employed as a fast saturable absorber to induce a high-order harmonic mode-locking Erbium-doped fiber laser [7], generating shorter pulses than double-walled carbon nanotubes (DWCNT) saturable absorber [8].

The actively mode-locking is another technique for the generation of pulses at high repetition rate by using an optical modulator driven by an RF source [9]. A stable operation can be obtained by a regenerative mode-locking that was achieved by feeding back the harmonic longitudinal beat signal which was detected with a high speed photodetector [10] and by a phase-locked loop (PLL) operation to lock the repetition-frequency of the cavity to an external signal [11]. Rational harmonic mode-locking is also to set up the pulse generation at high-repetition-rate that takes place in actively mode-locked fiber laser by using a low frequency RF synthesizer [12,13]. The pulse width is given by the Kuizenga–Siegman equation [14] that varies inversely as the modulation frequency which means that shorter pulses can be obtained with higher repetition rates.

Theory and modeling presented by Parvin et al. show concepts of coupled steady-state rate equations based on the energy band diagram for the lasing material that could approximate analytical expressions for gain coefficient, small signal gain and saturation power of rare-earth doped silica fibers which strongly depend on

* Corresponding author.
E-mail address: lucia.saito@mackenzie.br (L.A.M. Saito).

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the pumping power, dopant concentration and the active length [15,16]. The experimental results were obtained by adjusting only the pump power level.

Long and ultralong fiber lasers have attracted great interest in recent publications because they can generate pulses with low repetition rate and high energy [17]. Cavity length of 3.5 km long has been developed to generate a soliton-like pulse of 6.79 ps at a repetition rate of 58 kHz in an Erbium doped fiber laser mode-locked by SWCNT saturable absorbers [18]. Also, there is a secure key distribution over 200 km fiber ring laser which is based on establishing laser oscillation between the two communicating parties and each of the two end users places a randomly chosen spectrally selective mirror. [19–21]. These giant lasers can also set a quasi-lossless optical signal transmission up to 270 km by stimulated Raman scattering to overcome fiber loss and create an effective distributed gain medium [22,23]. Another important result was the ps pulses generation obtained in a 50 km ultralong Erbium-doped fiber laser installed around the city for the potential application of broadcast transmission at GHz repetition rate [24,25] and actively mode-locked Erbium doped fiber lasers with cavity length of 1 and 50 km that were used to demonstrate localization behavior in their frequency domain [26].

In this paper, we demonstrate ten different lasers with lengths varying by almost 4 orders of magnitude, from 16.4 m to 100.8 km by increasing the length of standard single mode fiber (SMF) in the cavity. We explore these long and ultralong cavity lasers to study the mechanisms responsible for the pulse evolution in the presence of intrinsic effects of propagation against the pulse generation by actively mode-locking. It allows us to observe three different behaviors that determine the physical mechanism responsible for the final pulse duration. Even though these results were obtained in an actively mode-locked Erbium-doped fiber laser structure, we believe that they can be applied to any ultralong mode-locked fiber laser system.

2. Experimental setup

Fig. 1 shows the experimental setup of all ten Erbium-doped fiber lasers. It consists of 2 m of Erbium-doped fiber (EDF) with single cladding, an absorption coefficient of 33.8 dB/m and dispersion coefficient of −57.0 ps/nm km, both of them at 1550 nm. A 980 nm laser source was pumped into the EDF and connected to an optical isolator with 50 dB of isolation at 1550 nm, a polarization controller, an electro-optic modulator driven by a RF source for amplitude modulation at frequency around 1 GHz, an output coupler of 15.3% and sections of standard single mode fiber. The 1st laser setup is a short cavity length with 16.4 m and intracavity loss of 3.7 dB. In the 2nd to 10th laser setup, 35.2 m to 100.8 km of SSMF between modulator and isolator was included.

Table 1 shows parameters such as cavity length, total intracavity loss, accumulated dispersion and fundamental repetition rate for all ten lasers. We considered the average attenuation of 0.19 dB/km and average intracavity dispersion balanced between 17 ps/nm km of the SMF and −57 ps/nm km of the Erbium-doped fiber.

The cavity length varies by almost 4 orders of magnitude and also all parameters linearly related to it, accumulated dispersion and the fundamental repetition rate. However the total intracavity loss varies much less, by almost 2 orders of magnitude. The fundamental repetition rate varies from 12.2 MHz in the shortest cavity with 16.4 m to 1.98 kHz in the 100.8 km ultralong fiber laser which is very low compared to conventional lasers.

3. Results and discussion

Fig. 2(a) shows the measured output pulse width as a function of cavity length and accumulated dispersion. The two curves are coincident except for short cavities or small accumulated dispersion values because the Erbium-doped fiber dispersion is compared to the dispersion of the whole cavity. In order to have a comparison between these lasers, all measurements were obtained at modulation frequency of 1 GHz. In addition, the pump power is adjusted from 75 to 220 mW (for 16.4 m to 100.8 km cavity length) to keep the average output power of 1.8 mW. The pump power level is sufficiently high to establish and keep the population inversion in the Erbium-doped fiber laser and because the higher attenuation at 980 nm, the residual pump power is

Table 1
Parameters of all Erbium-doped fiber lasers.

Setup	Cavity length	Total loss (dB)	Accumul. disp. (ps/nm)	Fundam. repet. rate
1	16.4 m	3.70	0.13	12.20 MHz
2	51.6 m	3.71	0.73	3.88 MHz
3	218.0 m	3.74	3.56	917.43 kHz
4	1.4 km	3.96	23.39	144.47 kHz
5	3.0 km	4.27	51.13	66.30 kHz
6	12.6 km	6.09	213.46	15.92 kHz
7	25.3 km	8.50	429.70	7.91 kHz
8	50.6 km	13.31	859.55	3.95 kHz
9	75.7 km	18.08	1286.21	2.64 kHz
10	100.8 km	22.85	1713.17	1.98 kHz

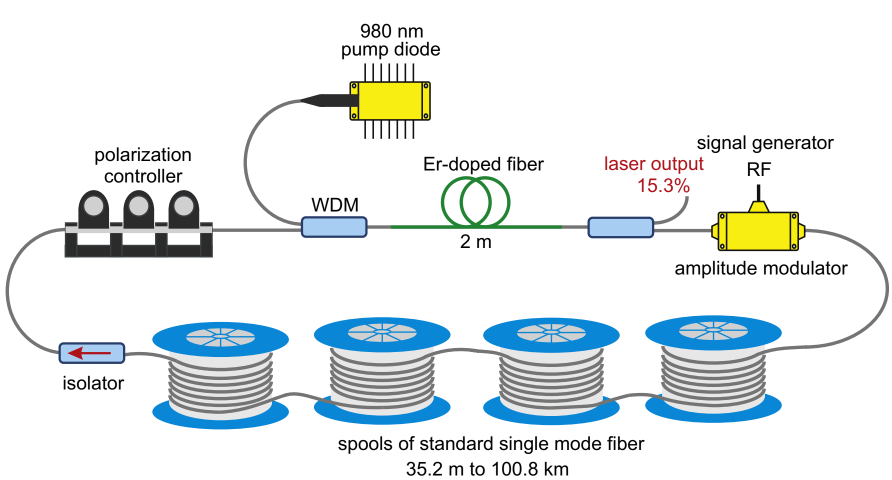

Fig. 1. Experimental setup of all Erbium-doped fiber lasers. The lengths of the cavities vary by almost four orders of magnitude, from 16.4 m to 100.8 km.