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Stable soliton-like train pulses in an active fiber laser system

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Stable soliton-like pattern formation in a compact erbium-doped all fiber laser system is reported. The windows where these bounded states can be achieved were founded varying the cavity losses actively with the help of an electro-optic modulator. The fiber laser worked with a slope efficiency of 24 percent and threshold of less than 16 mW allowing a maximum output power of 3.83 mW. This fiber laser system can be used to obtain non-distortion pulses for optical communication purposes.

Keywords: Fiber lasers; solitons; nonlinear optics; active cavity.

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1. Introduction

Nowadays, erbium-doped fiber lasers (EDFLs) are widely studied [1-6] due to their multiple properties (high gain and single-mode operation among others) and important applications in optical communication systems (erbium emission wavelength is 1550 nm) [3-6]. Solitons have also attracted a huge attention since years ago and they are considered one of the most promising techniques to improve the optical communication systems [7-10], unfortunately solitons are strongly reliant on nonlinear media to produce them, making them linearly unstable. Such optical patterns arise in defocusing Kerr nonlinear media [11-13], in dissipative optical systems [14,15] and, under certain conditions in quadratic nonlinear media [16-18]. In particular, some bounded states have been reported in ring cavities passively mode-locked through nonlinear polarization rotation and in figure-of-eight lasers with also a passive mode-locked achieved by mean of nonlinear amplifying loop mirror [19-21]. Accordingly to several authors, bounded states are intrinsic to fiber optics and can be considered as global dynamical behavior, being a reason why these kinds of dynamics can be predicted with some universal models which do not consider the exact physical mechanism behind their creation such as non-linear Schrödinger, Ginzburg- Landau, Balance equations, etc. [21-27]. In this article the formation of soliton patterns in a cw erbium- doped fiber laser, which is actively modulated, is reported. The founded patterns are linearly stable for long periods of time. The experimental results shown in this article are in agreement with the predicted by the authors in Refs. 7 and 27.

2. Experimental Setup

The implemented fiber laser has a Fabry-Perot structure whereby the light is reflected in the mirrors while a small part left the resonator. The gain media is provided by a section of excited rare-earth erbium-doped fiber. The experimental setup is shown in Fig. 1. The EDF section consists of a span of 84-cm, with an $\mathrm{Er_2O_3}$ concentration of 2300 ppm as the gain medium, which was constructed by the Institute of Photonic Technology (IPHT) in Germany, this fiber was pumped by a 980 nm laser diode (LD) through a 1550/980 nm wavelength division multiplexer coupler. In order to form the cavity, a fiber Bragg grating centered at 1550 nm with a 100 pm at FWHM and a Faraday rotator mirror (FRM) with 96 and

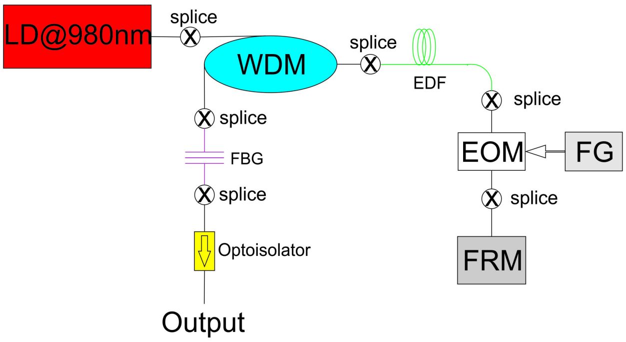

FIGURE 1. Experimental Setup, laser diode (LD), wavelength division multiplexer (WDM), fiber Bragg grating (FBG), erbium-doped fiber (EDF), electro- optic modulator (EOM), functions generator (FG), Faraday rotator mirror (FRM).

99.8 % reflectivities at the laser wavelength respectively were used; the FRM was used to avoid the polarization mode beating. An intracavity electro-optic modulator (EOM) driven by a functions generator was used. The splices were cut by fiber cleaver which kept the angles less than 1° and welded by a Fujikura optical fiber fusion splicer, the losses of every splices were smaller than 0.01 dB. To keep the all fiber structure, all the used devices were made by fiber except the LD, and all of the pigtails' clad diameters were 125 μm. One polarization independent opto-isolator was placed in the laser's output to prevent any feedback that could cause instabilities in the cavity. The total cavity length is around 3.5 m. The output intensity was detected using an InGaAs high-speed photodetector by Thorlabs (DET10N/M) and visualized with an 8 GHz oscilloscope (TDS6804B).

3. Results

The LD current was maintained at 65 mA and an input power to the fiber laser of 15.7 mW was obtained. The EOM works varying the amplitude linearly; this is achieved biasing the modulator at the 50 % transmission point applying a DC voltage to the modulator. The system posses a detuning through the control frequency, this detuning is given by $\mathrm{m}\Delta\mathrm{f}_{\mathrm{cav}}/n$, where $\Delta\mathrm{f}_{\mathrm{cav}}$ represents the fundamental cavity frequency and m and n are integers. This detuning has an impact on the repetition rate shifting it. When the driving frequency applied to the modulator is taken $\mathrm{f}_{\mathrm{m}} + \Delta\mathrm{f}_{\mathrm{cav}}/\mathrm{n}$ it's said that rational harmonic mode locking is being applied [28]. By varying the frequency applied to the EOM the laser output was modified as shown in Fig. 2; it can be noted that as the frequency increases, the pulses width (FHMW) decreases following a power law (solid circles), nevertheless, for the maximum power the dynamics is different, it start to grow with a close-to-a-Gaussian shape, it reaches a maximum of 3.63 mW at a control frequency of 440 kHz, it decays to 2.71 mW at 560 kHz, increasing again to a maximum of 3.83 mW with a control frequency of 630 kHz and after that, it decays following the Gaussian shape (solid squares); the dip in the power is due to the transition time related to the erbium ions, this phenomenon is observed when the system is working near this value (around 10 ms), especially in highly doped optical fibers. The output optical spectrum is centered in 1552.3 nm

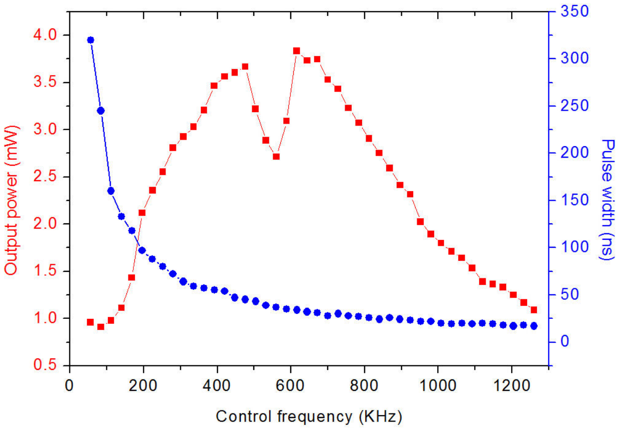

FIGURE 2. Frequency applied to the EOM as a function of output power in solid squares and pulses width (FHMW) in solid circles.

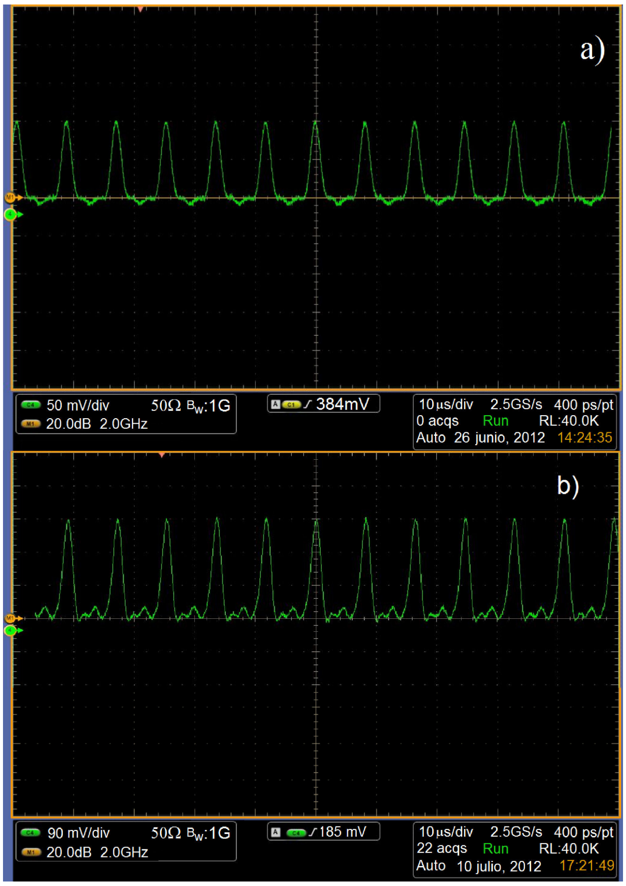

FIGURE 3. Experimental soliton-like trains for different control frequencies. a) 560 KHz. b) 616 KHz.

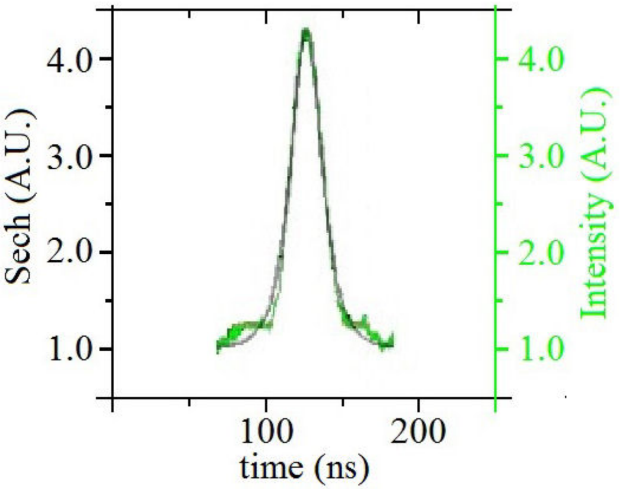

FIGURE 4. Experimental pulse (in green) compared with a numerical soliton pulse (in black). The observed difference between their areas and shapes is less than 2 percent.

and it remains without changes all time, the modulation applied to the cavity losses had no inference on it.

The maximum achieved power for a soliton-like train was 3.87 mW with a FHMW of 34 ns @ 616 kHz applied to the EOM; after this value, the maximum power is reduced because the system's recovery capacity is overpassed by the frequency applied to the EOM. The observed slope efficiency was between 6.4 and 24 % with a threshold below 16 mW. Figure 3 shows obtained pulses for the presented configuration using different control frequencies; Fig. 3(a) shows a maximum laser's output power of 2.71 mW with a repetition rate of 12.5 MHz and for Fig. 3(b) the maximum laser's output power achieved was 3.83 mW with almost the same repetition rate (12.2 MHz), this frequency variation is due to the system's detuning. The obtained repetition rate corresponds approximately to 8th harmonic of the fundamental cavity frequency of 1.54 MHz that is directly related to the cavity length, the applied modulation frequency through the EOM's aperture and response times and the doped fiber population inversion [27]. These pulses were generated when the EOM is operating at 560 and 616 kHz respectively; these values are multiple of the laser's relaxation frequency. The profile of the pulses achieved at the output was compared with a sech shape pulse (a soliton), giving a difference smaller than 2 percent between them, this confirms that the obtained pulses have a soliton shape as can be seen in Fig. 4.

4. Conclusions

In summary, it is shown that stable soliton-like patterns can be generated in an erbium-doped Fabry-Perot fiber laser cavity actively modulated through an Electro optic amplitude Modulator. The output pulses width and power dependence with the applied control frequency was experimentally explored. Furthermore, the proposed scheme is simple and can be used to generate soliton-like trains that can be applied in the optical communications field.

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