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The use of nonlinear dynamics of erbium-doped fiber laser at pump modulation for intra-cavity sensing

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ABSTRACT

We report the use of nonlinear dynamics of an erbium-doped fiber laser (EDFL) at pump modulation, namely the period-1 pulsed regime, for intra-cavity loss sensing and demonstrate noticeable sensitivity enhancement of an EDFL-based sensor, provided by this arrangement. Experimentally, we obtain a ten-fold increase of the sensor response, i.e. peak-to-peak pulse amplitude against loss variation, as compared with the standard sensing schemes using a low-power wide-spectrum light emitting diode (LED) or fiber laser without external modulation. This advantage originates from a strong dependence of pulse amplitude in the period-1 regime on intra-cavity loss variable that is, in turn, determined by the interrelation of relaxation frequency (an internal EDFL parameter) and frequency and depth of external (pump) modulation. A modeling of the EDFL-based sensor, presented for the case when the laser operates in the period-1 regime, allows an insight into the sensor operation details and opens the gate to its further optimization. The proposed sensing method seems to be a proper choice for the applications where an intra-cavity sensor's head has high internal loss (≥ 10 dB) while sensed loss is varied within a quite narrow range (a few dB).

1. Introduction

Erbium-doped fiber lasers (EDFLs) are coherent light sources emitting in a broad spectral range covering the S, C, and L communication bands [1,2]. A variety of EDFL regimes have been demonstrated: multi-wavelength operation [3,4], stable Q-switching and mode-locking [5,6], narrow-line [7] and even single-frequency [8,9] oscillation, wide-range wavelength tuning [1,10], and nonlinear dynamics regimes at external pump modulation [11,12]. The richness of operation regimes and generation wavelengths make EDFLs invaluable for applications, e.g. for gas spectroscopy [13,14], chemical sensing [15–17], mechanical strains and acoustics sensing [18–20], refractive index measurements in liquids [21], water flow sensing [22], etc.

Frequently, a fiber-optic sensor head has a high intrinsic loss when aiming on measurements of small loss variations. For instance, a common hydrogen sensor based on a Pd-coated fiber taper [23,24] is characterized by a background loss (in the absence of hydrogen) amounted to ~10 dB [16,17]. Another example is an intra-cavity EDFL-based sensor of refractive index with a ~30-dB factor of intrinsic loss [21].

In such or similar circumstances, a simple sensing scheme for direct measurements of a sensor head's transmittance, using a standard low power (~20,…,40 μW) LED as a light source, may encounter serious problems at sensing small loss variations. Thus, some special methods are required, among which the use of an EDFL for intra-cavity loss measurements is of interest. Intra-cavity sensing is usually performed using such fiber-optic components as fiber tapers, fiber Bragg gratings (FBGs), long-period fiber gratings, holey fibers, microscopic cells, etc. A variety of sensing techniques proposed to-date exploit the dependences of EDFL output power, transient regimes, or frequency of relaxation oscillations on intra-cavity loss [15–22].

In the present work, we propose a new method, the basic idea of which is intra-cavity loss sensing with an EDFL turned to one of its nonlinear dynamics regimes (namely, "period-1" operation) that arise at sinusoidal pump modulation [11,12]. The basic idea of the sensing originates here from a strong dependence of amplitude of laser pulses in the period-1 regime on the difference between the frequency of pump modulation (f_m) and natural relaxation frequency of the EDFL (F_r) that, in turn, is directly linked to the intra-cavity loss factor [21,25]. We demonstrate, both experimentally and theoretically, that a small loss variation on a background of high intra-cavity loss (≥ 10 dB) results in a strong change in amplitude of period-1 pulses and thereafter in effective sensing. The proposed method seems to be applicable when high-resolution real-time analysis is necessary, e.g. in gas

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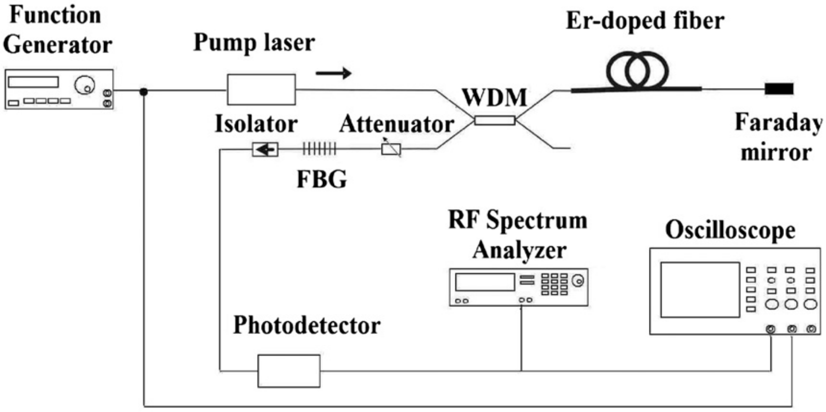

Fig. 1. Experimental setup.

sensing [15,17,23,24], refractive index measurements [21], and humidity detection [26,27].

2. Experimental

A schematic of an EDFL-based sensor is shown in Fig. 1. A fiber pigtailed diode laser, operating at a wavelength of 980 nm was used for pumping a low-doped erbium fiber (EDF) (*Thorlabs*, M5-980-125) through a wavelength division multiplexer (WDM). The pump light could be modulated by means of a sinusoidal signal (in the kHz range) applied to the diode laser driver from a function generator.

The laser cavity couplers were an FBG-mirror (with ~95% reflectivity on the peak wavelength 1550 nm) and inline Faraday rotator mirror (FRM), having a high reflectivity for the wavelengths ranged from 1520 to 1590 nm. A linear Fabry–Pérot, rather than ring, cavity was chose for experiments as a natural way to incorporate the FRM. In turn, the use of the latter was necessary for reduction of the laser instabilities when maintaining narrow-line lasing and diminishing the "modal noise" [7,28]. Another attractive advantage of using the FRM is its ability to prevent random polarization beatings in the laser output [29,30], allowing stabilization of the amplitude of the output pulses.

A fiber attenuator placed between the WDM and FBG allowed a controllable variation of the intra-cavity loss. This was used to simulate an intra-cavity sensor head. The attenuator was calibrated in advance to the main experiments; the interval of reliably measurable loss was found to be 0–14 dB.

The EDFL cavity had relatively high overall loss composed of (i) the attenuator loss, (ii) the loss owing to a number of splices, (iii) the loss in the WDM and FRM (~3.4 dB, one-pass), and (iv) the loss originated from Er^{3+} excited-state absorption (ESA) immanent to any silica EDF [31,32]. An EDF length was chosen to be ~6.3 m, providing gain sufficient to overcome the overall cavity loss and to allow lasing; for the same purpose, we used highly reflective FBG and FRM couplers in the EDFL scheme. A whole cavity length that comprised fiber tails of other elements (the WDM, FBG, FRM, and attenuator) was ~15.7 m.

The EDFL output was measured using a photo detector (PD), connected to an oscilloscope and a radio-frequency spectrum analyzer (RFSA). An optical spectrum analyzer (OSA) or a power meter could replace the PD when recording the EDFL optical spectrum or average output power, respectively.

Firstly, we have measured the dependence of F_r of the EDFL as a function of the attenuator loss (γ_A) at various pump powers (P_p) but with no modulation applied to the pump diode laser; see crossed symbols and dashed lines in Fig. 2. F_r was measured using the RFSA; notice that occurrence of lasing was reflected by the presence of an F_r peak on the RFSA screen [33].

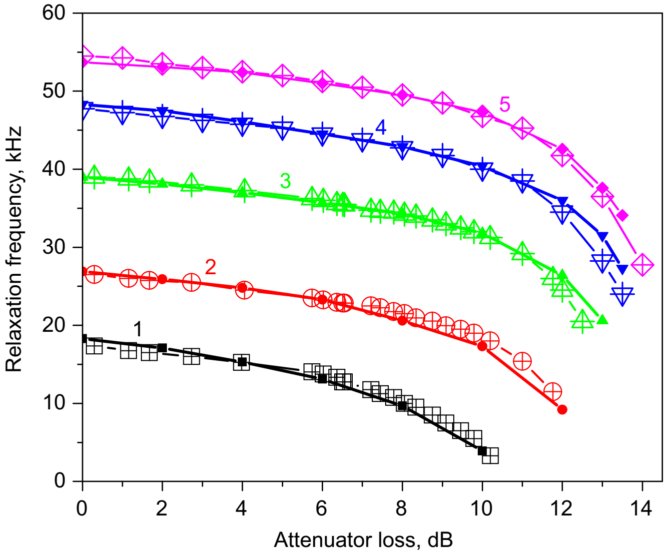

Fig. 2. Dependences of relaxation frequency on attenuator loss. Crossed and filled symbols correspond to the experiment and modeling, respectively. Pump power is 4.6 (curve 1), 7.2 (curve 2), 12.6 (curve 3), 17.3 (curve 4), and 23.5 (curve 5) mW.

It is seen that (i) the higher the pump power, the higher F_r value and that (ii) F_r decreases at increasing loss in the attenuator. At low pump powers (e.g. at P_p=4.6 mW, curve 1), lasing starts at less than γ_A~10.5 dB loss in the attenuator. At higher pump powers (e.g. at P_p=7.2 mW, curve 2), lasing appears once this loss becomes less than ~12 dB, and so on (see curves 3–5 for P_p=12.6, 17.3, 23.5 mW). Fig. 2 shows that the slope of the dependences of $F_r(\gamma_A)$ grows drastically at the highest loss values ($\gamma_A \geq 10$ dB). Notice that this feature provides a background for the remarkable enhancement of sensitivity of the EDFL-based sensor at pump modulation. Also note that the results of modeling of the dependences F_r (P_p, γ_A) (shown in Fig. 2 by filled symbols and plane curves) fit well with the experimental data; see Section 3.

A sinusoidal modulation was then applied to the pump laser. As the result, the EDFL operated in a pulsed regime whose features are defined by the difference between the relaxation frequency (F_r) and frequency of external modulation (f_m). It is seen from Fig. 3(a), where we demonstrate characteristic traces recorded at varying the attenuator loss ("snapshots" 1–3). The correspondent snapshots representing the theoretical counterparts to the experimental data are shown in Fig. 3(b); see also Section 3.