Influence of Cavity Loss Upon Performance of Q-Switched Erbium-Doped Fiber Laser

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***Abstract*— Performance of an actively Q-switched erbium-doped fiber laser in function of intracavity loss is discussed. We show experimentally and theoretically (employing a distributed model that takes into account two contra-propagating laser waves) that the laser performance strongly depends on the intracavity loss of different kinds. We reveal in particular that the dominant source of smaller than expected pulse energy is the loss via excited-state absorption, inherent in erbium-doped fibers. We also discuss the other important processes involved in active Q-switching, such as passive losses and residual active fiber charge, the impact of which is clarified by a straightforward comparison of the modeling versus experiment.**

***Index Terms*— Erbium-doped fiber laser, active Q-switching, intracavity loss, excited-state absorption, pulse energy.**

I. Introduction

During the last two decades Q-switched fiber lasers (QS-FLs) based on erbium-doped fibers (EDF), emitting in the broad spectral range covering the S, C, and L communication bands, attracted great deal of attention as candidates for many practical needs such as optical time-domain reflectometry (OTDR) [1], super-continuum generation [2], differential absorption Lidars (DIALs) [3], Brillouin-effect-based sensors [4], [5], *etc*.

Active Q-switching (AQS) in FLs is usually implemented using bulk acousto-optic modulators (AOMs), switching rapidly ON/OFF Q-factor of laser cavity (a standard AOM's rise-time is of the order of 10…100 ns) [6], or by means of including into cavities all-fiber acoustical devices, modulating Q-factor much slower [5], [7]. A QS-FL with a bulk AOM is capable to release QS pulses with duration measured by few to hundreds nanoseconds [6]. However such QS pulses always demonstrate a multi-peak envelope when AOM's opening time is short while the cavity length is long enough, with an interval between the adjacent sub-peaks being approximately equal to the cavity round-trip time [8], [9]. In attempt to explain the multi-peak structure of QS pulses without arguing on any "mode-locking" mechanism, the traveling waves' model [10]–[14] was successfully applied. This model was shown to accurately account for the temporal and spatial dynamics of both the population inversion and intensities of the pump and laser waves in a FL's cavity. The idea of traveling waves was shown to be productive for seeking novel QS-EDFL regimes, *e.g.* lasing of (i) short pulses resembling the ones releasable at "true" QS / mode-locking; *(ii)* pulses with reduced (less than the photon round-trip in cavity) time gaps between the adjacent sub-pulses; *(iii)* very short lone and smooth in shape giant pulses [15]–[17].

In spite of a number of works dedicated to inspection of the clue properties of QS-EDFLs, some of them were aside of researchers' attention. In this letter, we present a study of influence of passive intracavity loss upon performance of an AQS EDFL having long-cavity Fabry-Pérot configuration in terms of releasable pulse energy, the point yet not visited in detail to the best of our knowledge. We make as it follows a direct comparison of an experiment *vs.* modeling using the mentioned traveling waves' approach. This allowed us to reveal the trends that such contributions as excited-state absorption (ESA) inherent in EDFs [18], [19], amplified spontaneous emission (ASE), residual active fiber's charge, and passive loss obey at the pulsed laser operation, when the passive loss itself is changed within a wide range. Notice that low-doped EDF was chosen as an active medium in experiments, which allowed us to facilitate the analysis by disregarding the loss originated from cooperative up-conversion (always observed in heavily-doped EDF [20]–[22]). The numerical results are shown to be in good agreement with the experimental data, which is demonstrated *e.g.* by explicit coincidence of the multi-peak structuration of QS pulses and their delays with respect to the AOM's opening moment; this also ensures the validity of our conclusions about the role of the mentioned contributions upon the AQS EDFL's performance.

The issue of a short pulse's characterization in function of cavity length [15], [16] is out of the current study's scope; nonetheless the principal ideas discussed thereafter are applicable to inspect such case, too.

II. Experimental Setup

An experimental configuration of the AQS EDFL is shown in Fig. 1. A fiber-coupled semiconductor laser (operation wavelength 976 nm) was used for in-core pumping a standard low-doped EDF (*Thorlabs*, M5-980-125) through a

Manuscript received February 6, 2013; revised March 21, 2013; accepted April 6, 2013. Date of publication April 15, 2013; date of current version May 7, 2013. This work was supported in part by the Ministerio de Educación y Ciencia under Project TEC2008-05490, in part by the Generalitat Valenciana under Project PROMETEO/2009/077, both from Spain, and in part by CONACyT under Project 167945, Mexico.

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Digital Object Identifier 10.1109/LPT.2013.2257725

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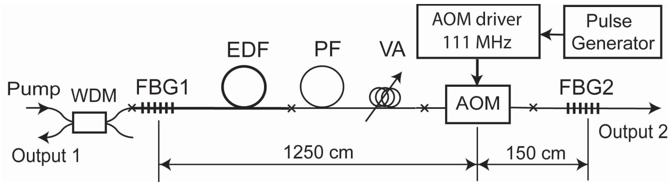

Fig. 1. Experimental setup: crosses indicate fiber splices.

980/1550-nm wavelength division multiplexer (WDM). The laser cavity consisted of 4 m of EDF, 7 m of a single-mode passive fiber (PF) (*Thorlabs*, 980HP) with the waveguide parameters similar to the EDF's ones, a fiber-coupled AOM (*Gooch & Housego*, M111-2J-F2S), and two fiber Bragg gratings (FBGs) as the cavity couplers. Since standard fiber-coupled AOMs are never free from internal reflections, the active fiber length was chosen to be short enough (4 m in our case) to prevent spurious lasing at the moments when AOM is in OFF state; this also provided complete "charging" of EDF (*i.e.* maximizing Er^{3+} population inversion) and reaching thereafter the maximal QS pulse energy.

A weakly-reflecting (30%) FBG1 was used as the laser Output 1 and a highly-reflecting (98%) FBG2 – as the laser auxiliary Output 2. Both FBGs were centered at 1550 nm, the laser wavelength. Notice that to diminish the overall cavity loss, FBG1 was written directly in the EDF after its preliminary hydrogenation.

A variable fiber attenuator (VA) consisted of a certain number of PF spooled over a 2-cm tube, permitted us to steeply increase the intracavity loss from ~7.4 dB (unavoidable loss inherent in our arrangement, given by the presence of AOM, ~4 dB, and fiber splices, ~3.5 dB) up to ~15 dB. In advance to main experiments, the attenuator was calibrated using a tunable semiconductor laser at the wavelength set to 1550 nm.

The total cavity length was rather long (~14 m), which allowed us to resolve the multi-peak structure of QS pulses.

AOM was driven by RF voltage with frequency of 111 MHz. When RF voltage at this frequency was applied to AOM, a collimated input beam was switched between the zero and the first diffraction orders (the latter being the AOM output). Thus, each reflection of the laser wave by FBG2-coupler followed by two consecutive, forward and backward, passes through AOM increased the laser frequency by 222 MHz (this shift is far from the mode beating frequency measured by 14.8 MHz). AOM's transparency gate in the experiments was 4 μs (fixed). The experiments were fulfilled at pump power of 200 mW and repetition rate of 100 Hz, also fixed.

The signal from the laser Output 1 was monitored by a 125-MHz photo-detector connected to a 2.5-GHz oscilloscope.

III. Numerical Model

The route of numerical calculations employed for modeling the experimental data was explicitly described in our recent papers; see Refs. [13], [14]. Briefly, it is based on calculating four contra-propagating laser and ASE waves and one pump wave, interacting in the laser cavity with EDF. In the model, we suppose that the Er^{3+} ion is described by a five-level scheme, with the transitions between the levels being: $^4I_{15/2} \rightarrow {}^4I_{11/2}$ and $^4I_{15/2} \rightarrow {}^4I_{13/2}$ for the ground-state absorptions at the pump (976 nm) and laser (1550 nm) wavelengths; $^4I_{11/2} \rightarrow {}^4I_{15/2}$ and $^4I_{13/2} \rightarrow {}^4I_{15/2}$ for the spontaneous and stimulated emissions (at 1550 nm); $^4I_{11/2} \rightarrow {}^4F_{7/2}$ and $^4I_{13/2} \rightarrow {}^4I_{9/2}$ for the ESA processes (at 976 and 1550 nm), respectively. The active fiber's parameters in calculations were the ones of EDF M5-980-125 we used in the experiments; see Table 1 in Ref. [13]. The concentration-related cooperative up-conversion was ignored in virtue of the low doping level of the EDF. Note that in the modeling we used a modulator's loss function, most closely adjusted to the experimentally found AOM ON/OFF switching law.

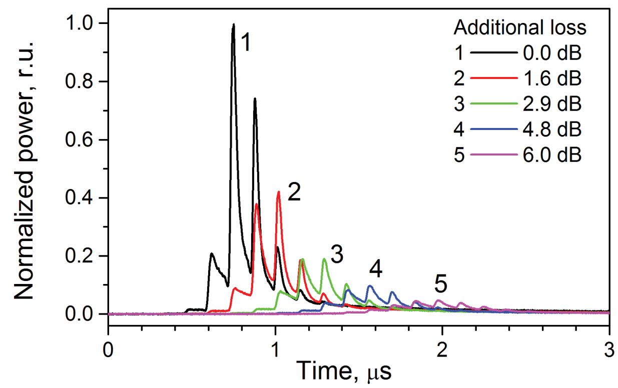

Fig. 2. Snapshots of QS pulses registered at varying the additional VA-loss from 0 to 6 dB. Pulse power is normalized to the maximum value (12 W) observed at the zero loss (curve 1).

IV. Results and Discussion

A few examples of the oscilloscope traces of QS pulses obtained for some values of additional loss produced by VA are shown in Fig. 2 (hereafter the zero-times correspond to the moments when AOM gets opened). The QS pulses captured at VA-induced loss in excess of 6.5 dB are not shown in the figure due to their small amplitude.

It is seen that, when the intracavity loss increases QS pulses dramatically decrease in amplitude and become delayed for a longer time with respect to the AOM's opening moment, whereas the number of sub-pulses grows. The interval between adjacent sub-pulses was measured to be 135 ns that equals to the photon round-trip in the cavity. At no additional loss (see curve 1 in Fig. 2), the first notable sub-pulse appears at 470 ns after the moment of AOM's opening, which corresponds to ~3.5 photon round-trips.

In order to verify correctness of the model, we have compared the simulated QS pulses with the ones obtained experimentally. Figure 3 exemplifies the experimental and simulated QS pulses for a couple of the VA-induced loss values, 1.6 and 2.9 dB. It is seen that the results of modeling for amplitude, shape, and delay of QS pulses precisely fit the experimental data. This reveals capacity of the model for predicting the AQS-EDFL performance within the loss range broader than it is attainable in our experiments, in particular for low losses (see below).

The dependence of the measured and simulated QS pulse energy upon the intracavity passive loss is shown in Fig. 4(a). It is seen that the experimental data (circles in Fig. 4(a)) are

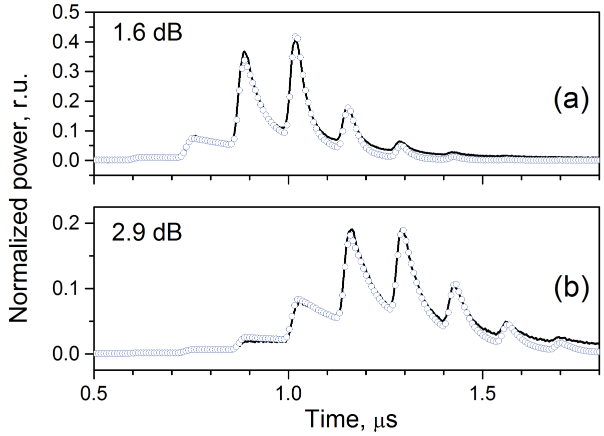

Fig. 3. Experimental (black solid lines) and simulated (blue empty circles) AQS pulses obtained for two values of VA-induced loss: (a) 1.6 dB and (b) 2.9 dB.

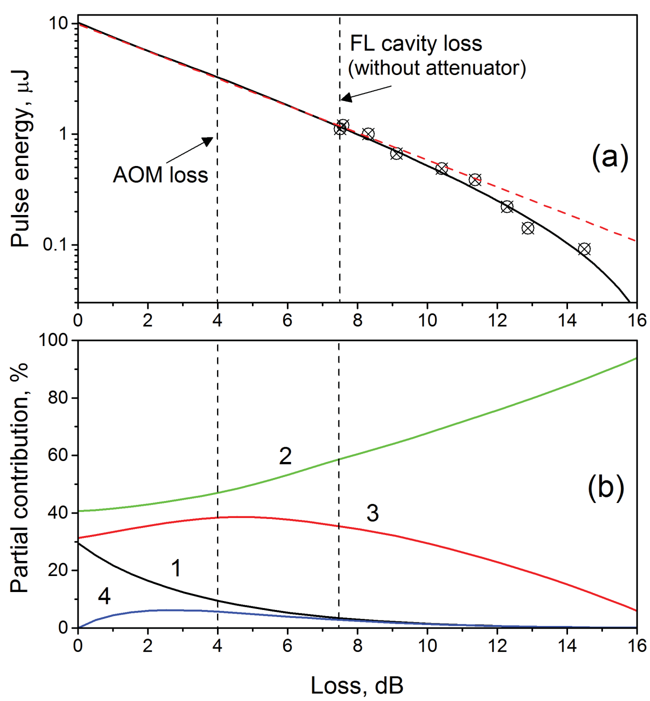

Fig. 4. (a) Pulse energy as a function of passive loss. Crossed circles – the experimental data; black solid line – the simulation result; dashed red line – the exponent asymptotic, calculated using formula (1). (b) Partial contributions of the four most important energetic processes involved at spending the initial EDF charge (100%): output QS pulse energy (black curve 1), residual EDF charge (green curve 2), energy lost due to the presence of ESA transitions (red curve 3), and due to passive intracavity loss (blue curve 4).

well fitted by the theory within the loss range measured from 7.4 to 14.5 dB.

It is also seen from the figure that, when the passive loss values become higher than ~9 dB, the pulse energy dramatically decreases while increasing the loss. Furthermore, the law that this dependence obeys is stronger than exponential for the loss >9 dB, whereas for the loss changed from zero up to ~9 dB it is fairly described by an exponent – see the dashed red curve in Fig. 4(a) (looking as a straight line in the logarithmic scale of the figure). The exponent's parameters are described as follows:

$$E_{out} = E_0 \exp\left(-\frac{\text{Loss[dB]}}{3.45\text{dB}}\right), \tag{1}$$

where E_{out} is the output pulse energy and E_0 is its value at the zeroed loss (in our case, E_0 =10.2 μJ). As it is seen from formula (1), decreasing of the loss by 1 dB results in increasing of QS pulse energy by 1.35 times. For instance, when it is equal to ~7.4 dB (in our experimental conditions, this situation takes place at no additional loss in VA), E_{out} ≈1.2 μJ. If one then hypothesizes that the losses on fibers' splices are zeroed and the passive losses thus become limited by AOM-loss only (4 dB), pulse energy would increase by ≈2.8 times, up to E_{out} ≈3.3 μJ (≈10% of the EDF's initial charge). Notice here that the initial EDF's charge is found (with a small uncertainty given by the presence of ASE contribution) as follows: $E_{EDF} = h\nu_s N_0 \pi a^2 L \approx 30\mu J$, where $h\nu_s$ is the laser photon energy (h is Plank constant and ν_s is the optical frequency), $a = 1.5$ μm is the EDF core radius, $L = 4$ m is the EDF length, and $N_0 = 7\times 10^{18}$ cm^{-3} is Er^{3+} concentration in the EDF core, calculated using the known data for the EDF [13], [23].

To clear up the physics behind AQS in the EDFL, let's briefly discuss the key mechanisms that affect the laser efficiency. Implying that the initial charge of the active fiber is fixed (given by pump power), we calculated the energy of a QS pulse, the EDF's residual charge, and the loss contributions, associated to different sources as functions of overall passive loss; the results are shown in Fig. 4(b).

This simulation, based on the traveling waves' model (see Section III), shows that the most important consumers of the initial EDF charge are QS pulses, losses on the ESA transitions, and the whole of passive intracavity losses – see curves 1, 3, and 4 in Fig. 4(b). Another significant parameter is the residual EDF charge (see curve 2 in the figure) that grows up to 90% of the initial charge at increasing the passive intracavity loss up to 16 dB, which – at such high losses – strongly limits all the above mentioned contributions. It deserves attention that the loss associated to ESA always (in the whole passive loss range) prevails over other contributions, including the energy of QS pulses. In the meantime, the energy dissipated at the ESA transitions slightly grows at increasing the passive loss up to ~4 dB (owing to growth of the number of pulse travels in the cavity) but at the higher loss it gets saturated and then decreases (due to an increase of the residual EDF charge, noticed above); see curve 3. Despite the contribution of passive loss (*i.e.* energy dissipated on AOM and fiber splices) is small (less than 10%, see curve 4), its impact on the laser performance is "intermediated" by the ESA-loss and EDF residual charge. Worth noticing is that unusual on the first glance trends that all the partial contributions demonstrate against variation of the overall loss (Fig. 4(b)) originate from the pulsed regime itself and complicate interplay of the laser and pump waves travelling in the cavity, which is apparently the result of distributed nature of all the processes involved.

V. CONCLUSION

In this letter, we discuss the results of a theoretical and experimental study of a pulsed AQS EDFL, namely, the effect of intracavity loss upon the laser performance in terms of output QS pulse energy. By employing the distributed model for travelling waves [10]–[14] in the laser cavity, we show that the pulse energy can be increased by means of diminishing the passive cavity loss. For instance, if this loss is decreased from 7.4 dB (experimental value) to 4 dB (AOM's limitation), the pulse energy increases by about 3 times (from $\approx$1.2 to $\approx$3.3 μJ, or from $\approx$3% to $\approx$10% of the initial EDF charge, the latter being a common value for AQS FLs [6]).

We also demonstrate that the factors limiting the laser performance are the EDF residual charge that strongly grows at increasing the passive loss and the loss on the ESA transitions inherent to EDF. As our simulations show, the ESA-loss is the most important factor that limits energy of QS pulses: when the laser operates at 1550 nm, the ESA transitions consume $\sim$30% of the initial EDF charge in the broad range of passive loss (varied from 0 dB in an ideal case to $\sim$10 dB). In the meantime, the residual EDF charge increases from $\sim$40% to $\sim$65% of the initial EDF charge within this range of passive loss. At higher values of passive loss (>10 dB) the AQS EDFL is quite inefficient: the extractable pulse energy is less than 1.5% of the initial EDF charge.

The approach applied in the present study for revealing the influence of the cavity loss factor upon the performance of an AQS EDFL seems to be also fruitful for characterization of other pulsed FLs based on fibers doped with active ions having prominent ESA transitions.

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