Smooth Pulse Generation by a Q-Switched Erbium-Doped Fiber Laser

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Abstract— **A Q-switched Erbium-doped fiber laser with symmetric cavity design is thoroughly investigated. It is shown theoretically and verified experimentally that such a laser is capable of generating stable giant pulses with smooth temporal shape and maximized peak power (∼40 W) and minimized duration (∼30 ns), as compared with an analogous laser having conventional asymmetric cavity. The principle that stands behind this performance is also discussed.**

Index Terms— **Erbium-doped fiber laser, giant pulse shape, Q-switch.**

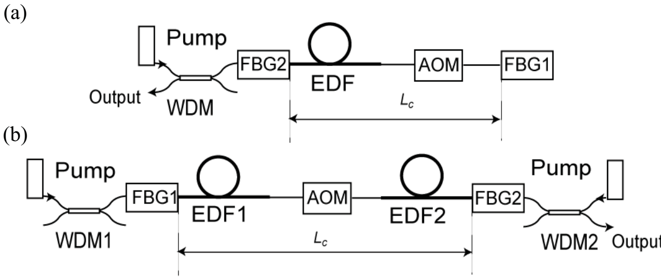

Fig. 1. QS-EDFL implemented in (a) "A" and (b) "S" designs.

I. Introduction

Q-SWITCHING (QS) is a standard technique for enforcing a laser to operate in the regime of short and powerful ("giant") pulses. Implementing of an arrangement permitting release of stable and smooth in shape QS pulses is of special need for fiber lasers (FL) where certain aspects inherent to their nature—a long active medium's length and strong confinement of optical field with fiber's core and appearance thereafter of unwanted nonlinear effects such as stimulated Brilluoin and Raman scatterings—prevent getting of repeatable smooth in shape pulses, in contrast to QS bulk lasers. Giant pulses are widely applicable in many fields of optical engineering: in time-domain reflectometry [1] and lidar [2], for super-continuum generation [3], *etc*. Apparently, methods of "active" QS, usually implemented by means of placing an acousto-optic modulator (AOM) inside the laser cavity, deserve great deal of attention as most reliable and robust amongst others.

It is known that when the photon round-trip time (t_p) in FL cavity is close to a modulator's rise ("switching on") time (which holds for a long-cavity laser) the pulse envelope breaks up into multiple sub-pulses, a deteriorating effect for most applications. This aspect of QS in a FL is somewhere addressed in terms of "self-mode locking" (see *e.g.* [4]), the latter being however nothing than a resemblance in most cases. On the other hand, as it was recently demonstrated—first theoretically [5] and then experimentally [6]—when an intra-cavity Q-modulator in an Erbium-doped FL (EDFL) is switched slowly as compared with t_p (a classical QS-regime [7]) the laser is capable to generate smooth pulses, almost free from the mentioned sub-pulse structure. To shed more light on the details of such a regime in EDFLs we found reasonable to perform further modeling for clarifying the physics that stands behind it, which is the main subject of the present letter.

Below, by means of using the traveling waves' model [5], [8], and [9], we focus on the most relevant conditions for generating the powerful and short pulses in a QS-EDFL. We theoretically inspect in details the two QS-EDFL schemes, a classic asymmetric ("A") setup (see Fig. 1(a)), where AOM is placed between an active Erbium-doped fiber (EDF) and a strong fiber Bragg grating (FBG) coupler, and a novel symmetric ("S") one [9], where AOM is placed exactly at the center of EDF (Fig. 1(b)). As it was shown in [9], the second (symmetric) arrangement allows increasing the EDF length twice as compared with the asymmetric one and as a consequence enhancing the parameters of pulses. Note that in both arrangements the EDF length is limited from above by the effect of spurious lasing that arises because of small internal reflections from AOM and turns the laser to operate in one of the "nonlinear dynamics" regimes, quite different from true Q-switching operation [10], [11].

We show as it follows from the modeling results that a QS-EDFL implemented in "A"-configuration is not the proper

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choice, in contrast to "S"-design, for producing giant pulses shorter than overall time of AOM's "on/off" cycle. We show also that the generated QS pulses always have better key parameters when the "S"-design instead of the "A" one is used. Note here that longer than AOM "on/off" cycle pulses can be easily obtained by means of direct modulation of a CW EDFL's output without using of any QS method, see *e.g.* [12].

Finally, we describe an experiment fulfilling a QS-EDFL implemented in "S"-configuration. Notice that in the present Letter we do not compare experimentally QS-EDFLs built in "A" and "S" configurations (reported in detail in [9]), aiming mainly on optimizing the latter one as a result of straightforward modeling. We demonstrate that the laser with "S"-design generates very stable, powerful (∼40 W), and rather short (∼30 ns) lone pulses per AOM modulation period without breaking into sub-pulses; it is worth noticing as well that such pulses are more than three times shorter than AOM's "on/off" cycle. Importantly, QS pulses that can be also produced "on-demand" [13] have non-detectable with our equipment temporal jitter (less than 10^{-11} seconds) and exhibit high signal-to-noise ratio. The experimental results obtained using a QS-EDFL implemented in "S"-design are shown to be entirely described by the developed theoretical model, providing a background for the modeling QS FLs based on other active fibers (say, doped with Ytterbium or Neodymium).

II. Theoretical Background

Our simulations were performed using the model described in [5], [9], assuming that EDF is a commercial *Thorlabs* M12-980-125 fiber with absorption coefficients at the laser/pump wavelengths ($\lambda_s = 1550$ nm / $\lambda_p = 977$ nm) being $\alpha_s = 17.3/\alpha_p = 11.7$ dB/m, respectively. We also assumed that couplers FBG1 and FBG2 forming the EDFL cavity have reflection coefficients 30% and 99% at λ_s and that overall cavity loss, given by fiber splices and AOM in "on" state, are estimated to be 7.5 dB. Notice that all these parameters' values were taken entirely the same as they were in the experiment we handled (see the next section).

It was implied in the modeling that the condition of temporal pulse stability requires the absence of spurious lasing when AOM is blocked. Further, it was found that, when using the chosen EDF and AOM (with a return loss between 35 and 40 dB), "true" QS regimes are observed at the maximal EDF lengths L_a of around 1 m ("A" setup) and 2 m ("S" setup, *i.e.* at ∼1 m of EDF placed at each AOM's side); otherwise the laser turns to one of its inherent nonlinear attractors.

We don't provide here the set of equations and the accompanying relations used at modeling; the reader can find these in [9]—see Eq. (2a)–(2c) and formulas (3)–(7), respectively. Also notice that the modeling results reported herein (Fig. 2) were generated by means of scanning over the key EDFL parameters (AOM's rise time t_r and cavity length L_c).

As our modeling reveals (see Fig. 2 where we show the results parameterized in terms of t_r and L_c), three areas labeled "I", "II", and "III", and separated by two straight lines "1" and "2", define the basic features of QS pulsing. Within area "I",

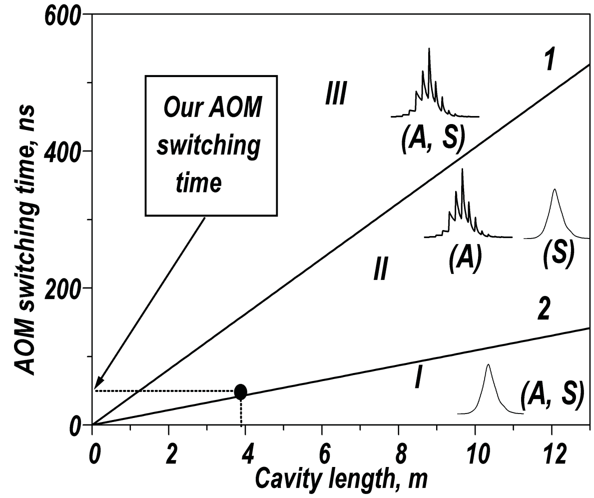

Fig. 2. Situations encountered in QS-EDFL with "A" and "S" designs. Black symbol shows a selected experimental point for "S" design.

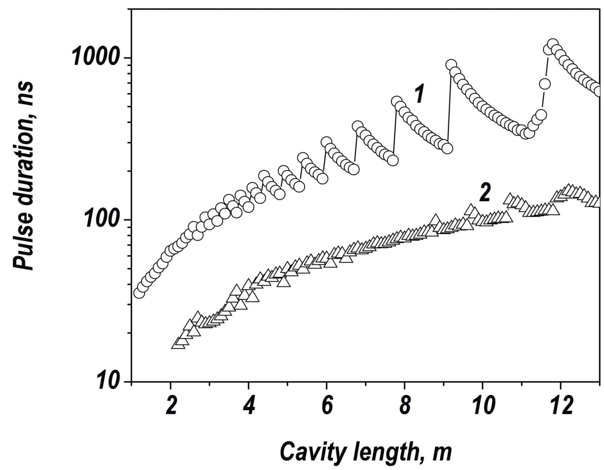

Fig. 3. QS pulsewidth versus cavity length; curves 1 and 2 are obtained for QS-EDFL implemented in "A" and "S" designs, respectively.

lasers in both ("A" and "S") implementations produce well-shaped giant pulses without sub-pulses; within section "II", such smooth pulses are obtainable from a laser having "S"-design only; and within area "III", either of the designs, "A" or "S", doesn't allow release of smooth pulses, *i.e.* in this case QS pulses are transformed to series of sub-pulses (see inserts in Fig. 2 which show shapes of the modeled pulses). Note that the borders 1 and 2 between the areas I, II, and III have been obtained for the experiment to be discussed below, while generally they depend on an EDFL's parameters (loss, EDF type, *etc.*).

Mention that, in the case of "A"-design of a QS-EDFL, generation of giant pulses without sub-pulses is allowable if AOM's rise time t_r is longer than $4t_p$. Line 1 (separating the regimes of smooth single pulses and pulses broken into a train of sub-pulses) is described at this by a relation t_r[ns] $\approx 41 \times L_c$ [m], whereas the area where smooth pulses are obtained in "S"-design only is segregated by line 2 described by a relation t_r [ns] $\approx 11 \times L_c$ [m].

Figs. 3 and 4 depict the dependences of duration and peak power of QS pulses against the cavity length, which have been calculated for AOM's rise time of 50 ns (an experimental

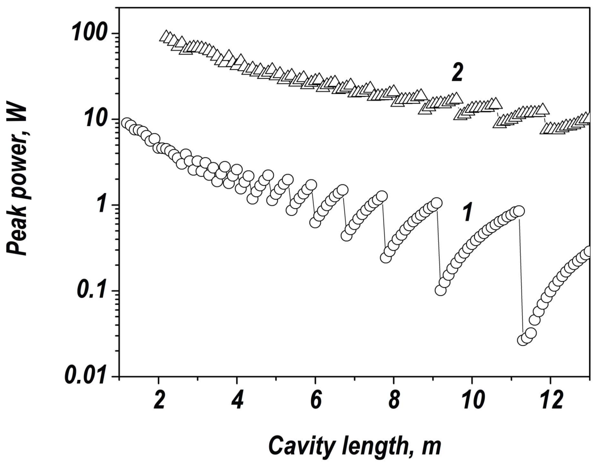

Fig. 4. Pulse peak power versus cavity length. Curves 1 and 2 are obtained for QS-EDFL implemented in "A" and "S" designs, respectively.

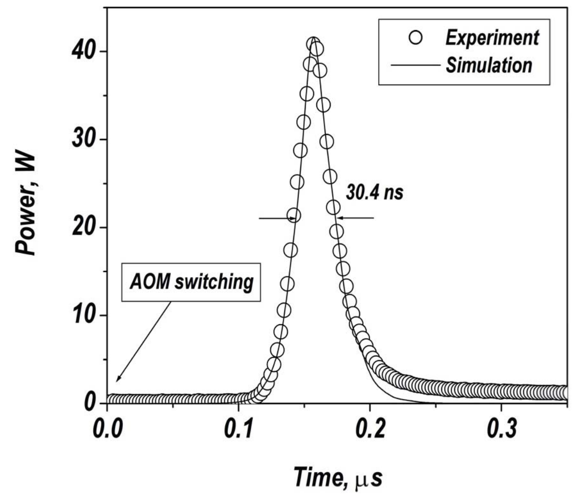

Fig. 5. Experimentally recorded QS pulse against theoretical simulation.

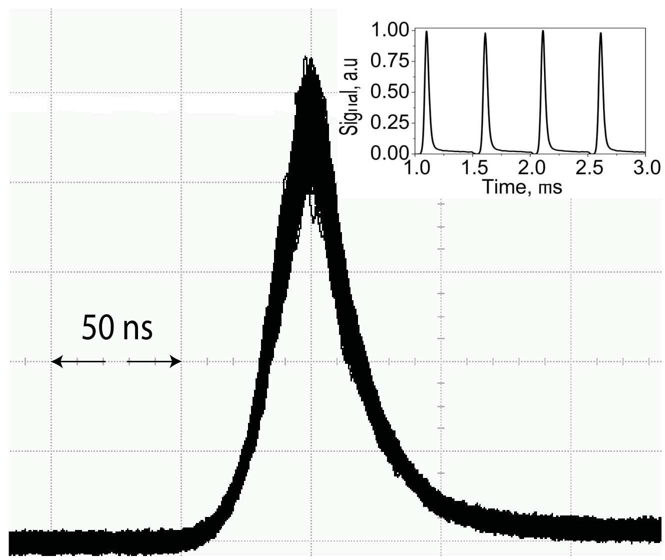

Fig. 6. Infinite persistence figure of QS regime; inset—an example of train of QS pulses (repetition rate is 100 Hz).

value). Curves 1 and 2 in both figures show the results for the QS-EDFL implemented in "A" and "S" versions, respectively (remind that all the simulations were made for maximal possible EDF lengths, at which unwanted CW lasing doesn't appear yet). It is clearly seen that "S"-design of the laser allows release of significantly shorter (Fig. 3) and much more powerful (Fig. 4) giant pulses, thus ensuring its highest capacity.

III. Experimental Setup and Results

The experimental "S" configuration of QS-EDFL was explicitly the same as shown in Fig. 1(b) (the case of "A" design of QS-EDFL, see Fig. 1(a)), was thoroughly inspected elsewhere; see, for instance [5]– [7], [9], [11], and [14]. Also emphasize that a direct comparison of "A" and "S" EDFL designs but without optimization measures undertaken has been provided in [9]; so we focus here solely on an analysis of how the developed theory matches the experiment in case of QS-EDFL implemented in "S"-configuration.

Two standard fiber-coupled semiconductor lasers with operation wavelength $\lambda_p \approx 977$ nm were used for in-core pumping of two pieces of standard low-doped EDF (*Thorlabs*, M12-980-125) through 980/1550 WDM multiplexers. A fiber-coupled AOM (*Gooch & Housego*, M111-2J-F2S) operated at a wavelength of 1550 nm with a driving frequency of 111 MHz was used as a QS unit. The AOM rise and fall times were measured to be 50 ns each.

The QS-EDFL cavity length was 3.9 m; it was composed of two 1-m pieces of the EDF spliced to the AOM's fiber tails. Two spectrally matched FBGs with reflection coefficients of 99% (FBG1) and 30% (FGB2) at $\lambda_s = 1550$ nm were used as couplers. Comparatively short pieces of passive conventional fiber were used to connect all these components together. Both EDF pieces were pumped by 200 mW at 977 nm. The laser output was monitored using fast photo-receivers (DC to 125-MHz) connected to a 2.5-GHz oscilloscope.

When AC voltage at the frequency of 111 MHz was applied to the AOM, a collimated input beam was switched between the zero and the first diffraction orders, the latter being the AOM's output. The AOM's transmittance in "on" state was measured to be 38% (≈4-dB loss). The AOM's gate was chosen to be 4 μs, allowing us to monitor complete evolution in time of QS pulses; "on/off" repetition frequency was fixed at $f_m = 100$ Hz (other details of the AOM's switching process can be found in [9]). In the course of experiments, we observed that pulse peak power is quite sensitive to the loss associated with the presence of AOM—this loss was growing at rising up the AOM diver's temperature; for this reason, we paid special attention to the driver's temperature stabilization.

The results featuring a direct comparison of theory *vs* experiment are shown in Fig. 5. It is seen that, as our simulation has predicted, the output laser pulse has duration of about 30 ns (measured at a half-height). The maximal peak power we were able to achieve is measured by ≈42 W, which also quantitatively agrees with the modeling's prediction.

Fig. 6 (main frame) shows an "infinite persistence" portrait of 30000 giant pulses acquired during 5 minutes, which means a superposition of the pulses at the AOM repetition rate of

100 Hz (notice that in the experiment the oscilloscope was triggered by a rectangular signal that controlled the AOM driver). Because of a very small duty cycle of QS pulsing ($\sim 3 \times 10^{-7}$) we found necessary to demonstrate in Fig. 6 namely "snapshot" recorded using the oscilloscope's infinite persistence mode, displaying the sampled data points for an endless timing period, in order to emphasize the experimental fact of remarkable stability of the QS regime. This figure thus illustrates negligible amplitude or temporal jittering amongst almost infinite number of sequencing QS pulses.

For more clarity, we also demonstrate an example of a few QS pulses, arbitrary taken from a 100-Hz train (see inset in Fig. 6), which additionally features their repeatability and in the meantime allows one to reveal a low noise offset.

IV. Conclusion

In this letter, we demonstrate theoretically that a QS-EDFL with asymmetric cavity design, where photon round-trip time is approximately four times less than QS modulator rise time, is a solution permitting generation of QS pulses, single per AOM "on-off" cycle and free from any breaking into sub-pulses. On the other hand, a similar solution, as our modeling shows, is a QS-EDFL with symmetric cavity configuration where photon round-trip time is close to QS modulator's rise time. Furthermore, we compare these two QS-EDFL arrangements by means of numerical modeling and show that the laser with asymmetric cavity design requires notably shorter active fiber length than the one with symmetric design for getting smooth pulses (not suffering from breaking up into multiple sub-pulses). Accordingly, QS pulses released by an EDFL with common asymmetric cavity cannot be optimized in terms of maximizing peak power and minimizing pulse width, with the latter demands being both attainable using an EDFL with symmetric cavity. Thus, the obtained results definitely reveal preference of symmetric over asymmetric cavity configuration.

As an illustration of capability of the developed approach, we demonstrate an experimental verification of the modeling results, focusing the features of a QS-EDFL with symmetric cavity. It is shown that such a solution is indeed worthy in attempt to obtain stable powerful and short giant pulses, single per AOM's cycle and smooth in shape. The pulses we have gotten experimentally are measured to be $\sim$40 W of peak power and $\sim$30 ns in width, the values being in quantitative agreement with the ones obtained theoretically.

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