Power scaling of Q-switched fiber lasers in a multi-arm resonator

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ABSTRACT

Q-switched erbium doped fiber lasers offer a simple and robust way for the generation of high energy nanosecond pulses at wavelengths about 1550 nm, which are suitable for a large number of applications. Nevertheless, pulse peak power is limited taking into account the specific characteristics of the fiber lasers such as their long cavity length and the low level of pump power with the core pumping technique. Recently, we have demonstrated highly efficient coherent combining of radiations emitted by two amplifying fibers inside a common cavity in the continuous wave regime. The principle of this method is based on the self-organization property of lasers ensuring operation on modes of lowest losses in a Mach-Zehnder interferometer resonator geometry. We have shown that the output power level is twice the one of a unique laser. We report the power rising of an actively Q-switched erbium doped fiber laser by using two coupled cavities with amplifying fibers in an interferometer configuration. This study shows that the pulse peak power obtained is 1.7 higher than in a case of a unique laser. This concept brings some novel perspectives for scaling the output peak power of monomode Q-switched fiber lasers.

Keywords: fiber laser, Q-switch, coherent combining, interferometer.

1. INTRODUCTION

Q-switched pulses with nanosecond durations in the 1.5 μm wavelength region are required for applications such as range finding (at an eye-safe wavelength) or for the pumping of nonlinear devices such as optical parametric oscillators[1]. *Q*-switched bulk lasers using erbium-doped glasses can deliver several millijoules of energy in this wavelength region[2] but are limited in average power and repetition rate by thermal effects. Passively *Q*-switched microchip lasers[3-4] can generate single frequency output without delivered pulse energy more than 12 μJ. Fiber laser systems based on singlemode erbium-doped fibers can be used as compact, simple, and stable sources of *Q*-switched pulses with a spatial mode of high quality and the potential possibility to tune the wavelength over a wide range. Until recently, typical pulse energies from such systems, using standard fiber design are limited to tens microjoules. This limitation is essentially due to the generation of too strong non-linear effects (Stimulated Raman Scattering, Stimulated Brillouin Scattering, four Wave Mixing ...) at high pump power. These effects increase with the pump power level as well as the fiber laser length. Nevertheless, some applications like continuum generation or parametric operations need transverse single mode pulses of energy greater than a few microjoules. Significant improvements in available pulse energies were recently made by using large mode area fibers (LMA). With this concept, pulse energies of a few mJ have been demonstrated[5-6].

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An alternative way for power scaling is also offered by coherent combining of several lasers which permits to extent the use of an available technology and of an already optimised laser.[1]

High efficiency coherent combining of two fiber lasers in continuous operation has recently been demonstrated[7-10]. The combining method is obtained in a multi-arm resonator in an interferometric configuration. Michelson and Mach-Zehnder type resonators have been successfully experimented to reach nearly 100% combining efficiency with two fiber lasers. Recently, 8 fiber lasers have been combined to produce 2.65W in the continuous regime with 85% of power combining efficiency[11].

2. PRINCIPLE OF THE COHERENT COMBINING METHOD

The principle of our coherent combining method is based both on the self-organization property of lasers ensuring operation on modes of lowest losses[12], and on the use of an interferometric resonator configuration. A typical cavity, the Michelson laser, depicted figure 1a, is built up around a standard 50/50 coupler with each output port connected to an amplifying fiber ended by a high reflectivity mirror. Only one input port ensures light feedback towards the amplifiers with a small reflectivity achieved by a cleave to make up a "3-mirror" laser. The fields from the two amplifiers are coherently coupled by interfering on the coupler. Any parasitic feedback from the opposite port of the coupler into the Michelson laser is avoided by cleaving in angle the fiber. In that way, only the resonant frequencies with minimum losses in the shared arm (input port of the coupler with normal cleave), are amplified. Therefore, the laser spontaneously oscillates on the gain peaks which correspond to the coherent combining. The reflectivity transfer function in intensity of such an interferometer without gain is well-known and is described by: $R(\omega) = \sin^2(\omega.\Delta L/c)$ where ΔL denotes the difference in effective length between the two arms ($\Delta L = L_2\text{-}L_1$; see figure 1a). Assuming an equal gain on each arm of the interferometer, the net gain profile provided by the set-up is modulated by $R(\omega)$ with a maximum modulation depth. The interferometer resonator acts as a spectral periodic filter of period $\Delta\nu = c/(2.\Delta L)$. It is also possible to achieve laser combining from a Mach-Zehnder type resonator[8], shown in figure 1b. Both configurations, (the Mach-Zehnder fiber laser MZFL and the Michelson fiber laser MFL) operate in the same manner and they have the same features. Nevertheless, the Mach-Zehnder configuration induces a spectral filtering with a periodicity of $\Delta\nu = c/\Delta L$ which is twice broader than the one obtained with the Michelson configuration (see figure 1b). The advantage of this configuration consists in the use of a single fiber Bragg grating as a cavity rear mirror. The coherent combining occurs here on both sides of the interferometer.

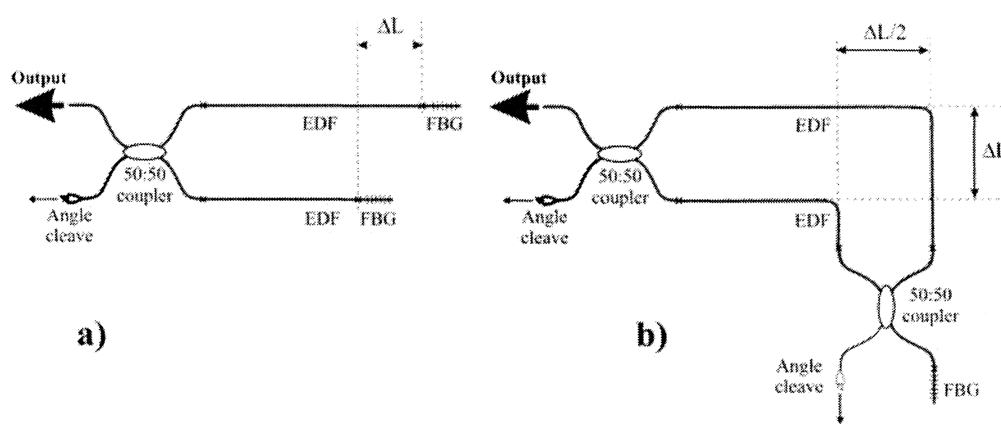

Fig. 1. Interferometric resonator configurations used for power combining: a) Michelson Fiber Laser (MFL). b) Mach-Zehnder Fiber Laser (MZFL). EDF: Erbium Doped Fiber; FBG: Fiber Bragg Grating.

We report in this paper the realization of an actively *Q*-switched Erbium doped fiber laser in a Mach-Zehnder interferometer configuration. This power combining process has the advantages to increase the emitted pulse peak power while increasing the thresholds of the non-linear effects. It has to be noted that the aim of our experiment was not to break a new record of pulses peak power, but just to demonstrate that the combining method is compatible with the *Q*-switch operation.

3. EXPERIMENTAL SETUP

Our experimental device, shown in figure 2a, consists of two independent Erbium doped fiber amplifiers which are core pumped by two pigtailed laser diodes emitting at 980nm with a power up to 100mW. The Er-fibers (EDF) have lengths of ~5m. The two arms of the active interferometer are spliced to two 50/50 couplers. A pigtailed acousto-optic modulator, to perform in a simple way the Q-switch regime, is placed between one of the output ports of the coupler C1 and the back mirror of the cavity (fiber Bragg gratings R≥98% at 1530 nm, 1 nm bandwidth). The other output port is angle cleave to avoid light feedback in the cavity. The output coupler of the *Q*-switched Mach-Zehnder fiber laser (QSMZFL) has a 4% reflectivity by cleaving the fiber of one input port of the other 50/50 coupler (C2). The second input port of the coupler is angle cleaved to avoid any reflection. We also insert a SMF of 1m length in one arm to prevent the interferometric instabilities[8]. Moreover, the polarization states of the two beams interfering on the 50/50 couplers are adjusted by a polarization controller (PC) to optimize the combining efficiency.

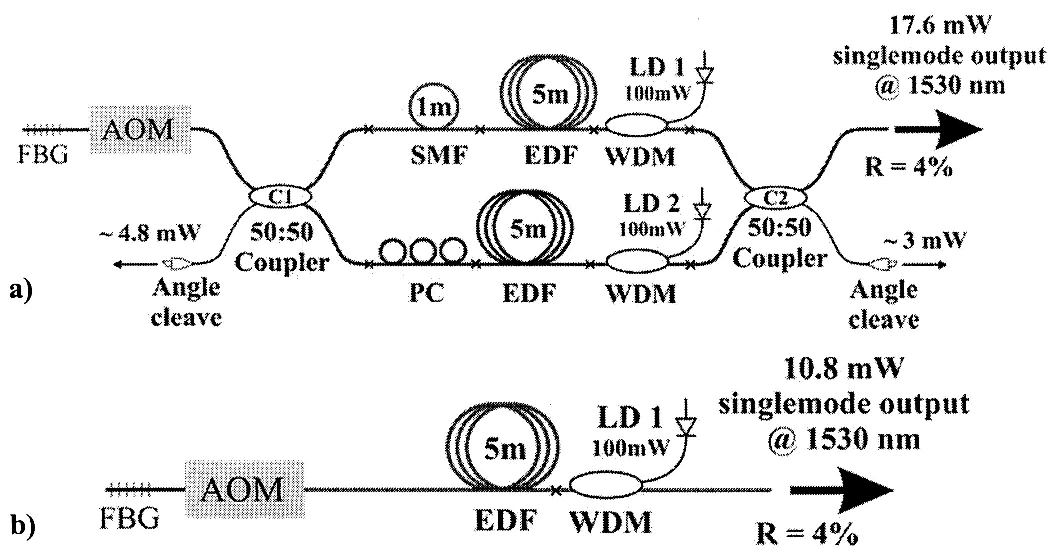

Figure 2. a) Experimental set-up of the Q-switched Mach-Zehnder Fiber Laser (QSMZFL); b) Experimental set-up of the Q-switched Individual Fiber Laser (QSIFL); LD1, LD2: 980nm Pump laser diodes; EDF: Erbium doped fiber; FBG: fiber Bragg grating @ 1530nm; WDM: Wavelength-division multiplexer; PC: Polarization controller; AOM: acousto-optic modulator.

4. EXPERIMENTAL RESULTS

We first compare the output average power of the QSMZFL to the one of the Q-switched individual fiber laser (QSIFL). QSIFL is based on the components making up one branch of the MZFL as shown in figure 2b.
With these two configurations, stable Q-switch pulses were generated with pulse durations of almost 650 ns (FWHM) (see figure 3). At the highest pumping level of 2x100mW, from pulse repetition rates of 10 kHz the QSMZFL delivered an average output power P_{out} = 17.6mW, corresponding of about 1.7 times the average output power of one QSIFL (10.8mW) with the same pulse durations and repetition rates.

As a result, we have experimentally shown that our combining method, developed in a first step for CW fiber lasers, is compatible with Q-switch operation. One of the main advantages of this process is the fact that the amplifying fibers keep a constant and optimized length while the total pump power increases in proportion with the number of interferometer arms (two in the present case). Moreover, there is only a short fiber length along which the pulses are combined and so with a possible high energy. These last remarks show that such configuration with parallel amplification seems to be suited to high energetic emission. It has to be noted that the average output powers obtained as well as with the QSIFL than with the QSMZFL are weak. It can be explained by the important insertion losses of the acousto-optic modulator which ensures the Q-switch operation. Nevertheless, our combining method is independent of the employed Q-switch method which enables the use of more efficient Q-switch methods.

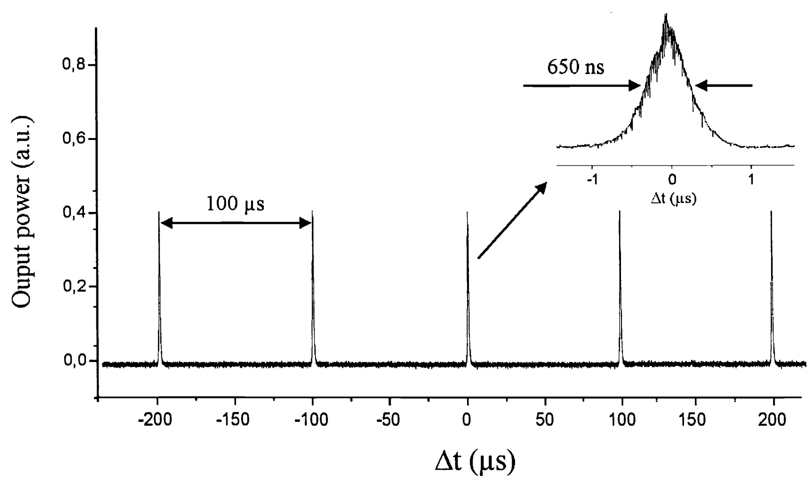

Fig. 3. Temporal pulse train obtained with the Q-switched Mach-Zehnder Fiber Laser (QSMZFL), inset: temporal pulse profile

5. CONCLUSION

We have experimentally demonstrated efficient coherent combining of two fiber lasers in an interferometer resonator operating in Q-switched regime thanks to an acousto-optic modulator. This new concept of coherent combining, which is compatible with more powerfull pumping method such as cladding pumping[9] and with more efficient Q-switching methods, brings some novel perspectives for high power single mode pulsed fiber lasers.

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