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# Single-channel Q-switching in a system of coherently combined fiber lasers

**Boris Rosenstein · Avry Shirakov · Daniel Belker · Amiel A. Ishaaya**

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**Abstract** We experimentally investigate passive interferometric coherent combining of two photonic crystal fiber laser channels within a common cavity, wherein only one channel is Q-switched. We demonstrate an average power of more than 20 W and the peak power of 97 kW with more than 98 % combining efficiency. The measured spectral bandwidth is 0.13 nm, and it does not change at different operation conditions. Our results show efficient imposing of temporal and spectral characteristics of the Q-switched channel on the free-running channel.

## 1 Introduction

In light of power scaling efforts, combining laser sources has gained significant interest in the past decade. Various approaches for coherent beam combining have been investigated in an attempt to distribute the total output power between several "independent" laser channels [1–5]. As a result, the output peak and average power can be increased with increasing number of combined channels, while maintaining the adequate beam quality of a single channel.

To coherently combine beams, their relative phases must be locked properly. Phase-locking can be achieved either actively by using electro-optic feedback loops, or passively by using a passive coupling mechanism wherein the fields are self-phase-locked. Although passive techniques are often regarded as limited in terms of the maximum number of combined laser channels [6], they are generally simpler, more robust and require no phase-controlling feedback loops. Feedback loops can be considered a challenge in itself, especially in short-pulsed lasing systems [7].

Obtaining high-peak-power ns pulses from a laser oscillator typically involves active Q-switching. To allow proper temporal synchronization, Q-switching in coherently combined lasers needs to be simultaneous for all channels; this goal can be achieved with three different techniques. First, the beams from all combined laser channels can be brought together without overlapping, such that they are assembled into one closely packed group (in free space) that is passed through a single Q-switch [8]. Although this technique is relatively easy to perform, the limited clear aperture of the Q-switches limits the number of beams that can be clustered together and passed through a given Q-switch. A second technique is based upon the coherent combining configuration. Usually, a coherently combined laser system includes a combining element placed in front of the laser (toward the output coupler) to superpose the beams [3, 4]. The Q-switch can be placed in front of the oscillator, i.e., between the combining element and the output coupler (OC); however, in fiber lasers, such configuration would cause parasitic lasing due to high gain. On the other hand, an additional combining element can be placed at the rear end of the laser to further combine the beams, and the single superposed beam is then passed through a single Q-switch. The major disadvantage of this technique is a double restriction on the common longitudinal modes (namely the front and rear combining elements). Such double-phase relation conditions limit the maximum number of channels that can be efficiently

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B. Rosenstein (✉) · A. Shirakov · D. Belker · A. A. Ishaaya
Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, 84105 Beer-Sheva, Israel
e-mail: borisros@ee.bgu.ac.il

A. Shirakov
Department of Physics, Ben-Gurion University of the Negev, 84105 Beer-Sheva, Israel

combined because all channels should have the same phase relation and common longitudinal modes [6]. A third technique involves several Q-switches that are electronically synchronized. This method is challenging because of the precise timing required of each Q-switch.

Despite their different advantages and caveats, the three techniques assume that all laser channels must be Q-switched to be coherently combined. However, it is interesting to examine the effect of Q-switching only a single channel in this system; since the channels are coupled, the temporal characteristics of the Q-switched channel could be imposed on free-running channels, such that the channels are pulsed synchronously. Apart from the more basic laser physics aspects, there are several practical advantages to this technique, in comparison with previous techniques. These include less limitations in terms of phase-locking and Q-switching, relatively low intensity on the Q-switch crystal, and fewer Q-switched crystals when scaling to multiple channels. Thus, a laser system based on this technique is expected to be simpler, cheaper, and more robust.

Here, we describe the experimental investigation of passive interferometric coherent combining of two active, rod-type, photonic crystal fiber (PCF) laser channels within a common cavity, wherein only one channel is Q-switched. In this novel approach, the two identical single-mode laser channels are operated in a phase-locked manner and the output beam is a coherent superposition of the individual beams, which preserves an excellent beam quality. This is the first study, to the best of our knowledge, to show that Q-switching only one of the fiber laser channels allows its temporal characteristics to be efficiently imposed on the free-running channel, such that both channels operate together. Moreover, we provide experimental data demonstrating high power spectral content imposing of one channel on the other.

## 2 Experimental setup and results

Our experimental PCF laser setup is schematically depicted in Fig. 1. It comprises two identical PCF lasers passively combined in a coherent manner into a single output. The resonator is formed by two active fibers; a highly reflective (HR) broadband rear mirror in one of the channels and a HR narrowband (<0.2 nm FWHM spectral width) volume Bragg grating (VBG) rear mirror in the other; a partially reflective OC with 4 % reflectivity; and an acousto-optic Q-switch (AOQ) placed in the channel containing the VBG. As a gain medium, we use two identical, commercially available, 55-cm-long, double-clad, active (Yb-doped), single-mode, rod-type PCF (NKT DC-200/70-PM-Yb-ROD) with a core diameter of 70 μm and mode field diameter of ~55 μm. Each channel includes a 30-W fiber coupled pump diode with central wavelength of 976 nm, a dichroic mirror to separate between the pump and lasing beams, and suitable coupling optics. To enable intracavity interferometric coherent combining of the channels, the resonator includes a common OC mirror for both channels and a non-polarized 50:50 beam splitter (BS). Due to the intracavity mode competition, the relative phase between the channels is passively locked by choosing the lowest loss state. This approach results in a constructive interference at the BS's output that contributes to the intracavity circulating energy (directed toward the OC), and in zero output from the loss channel (Fig. 1) due to destructive interference at the BS's loss output [9].

## 3 Experimental procedure and results

The coherently combined laser output characteristics are shown in Fig. 2 as a function of the single-channel-launched pump power in CW mode (Fig. 2a) and under different repetition rates (Fig. 2b–d). In each investigated condition, the combining efficiency (measured as the ratio between the power emitted from the OC and the sum of the powers emitted from OC and the loss channel) was found to be more than 98 %. The combining efficiency slightly decreased with increasing pump power, probably due to the increase of gain in the fibers with increasing pump powers, which in turn translates to beam wandering when aligning the two beams (angularly and laterally) on the BS. Such wandering decreases the combining efficiency, which strongly depends on the spatial overlap of the beams on the combining element. We believe that this beam wandering, which occurs only when attempting to combine the two channels, is due to the non-strict spatial single-mode

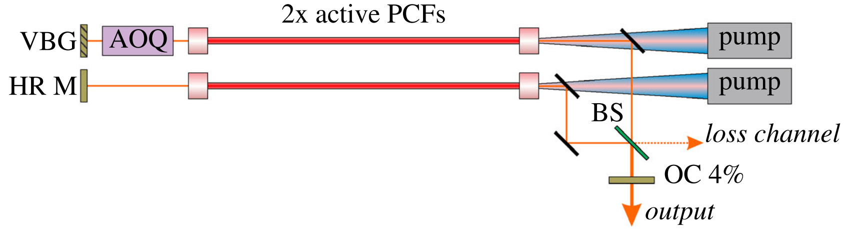

**Fig. 1** (Color online) Schematic configuration of the Q-switched intracavity coherently combined fiber laser

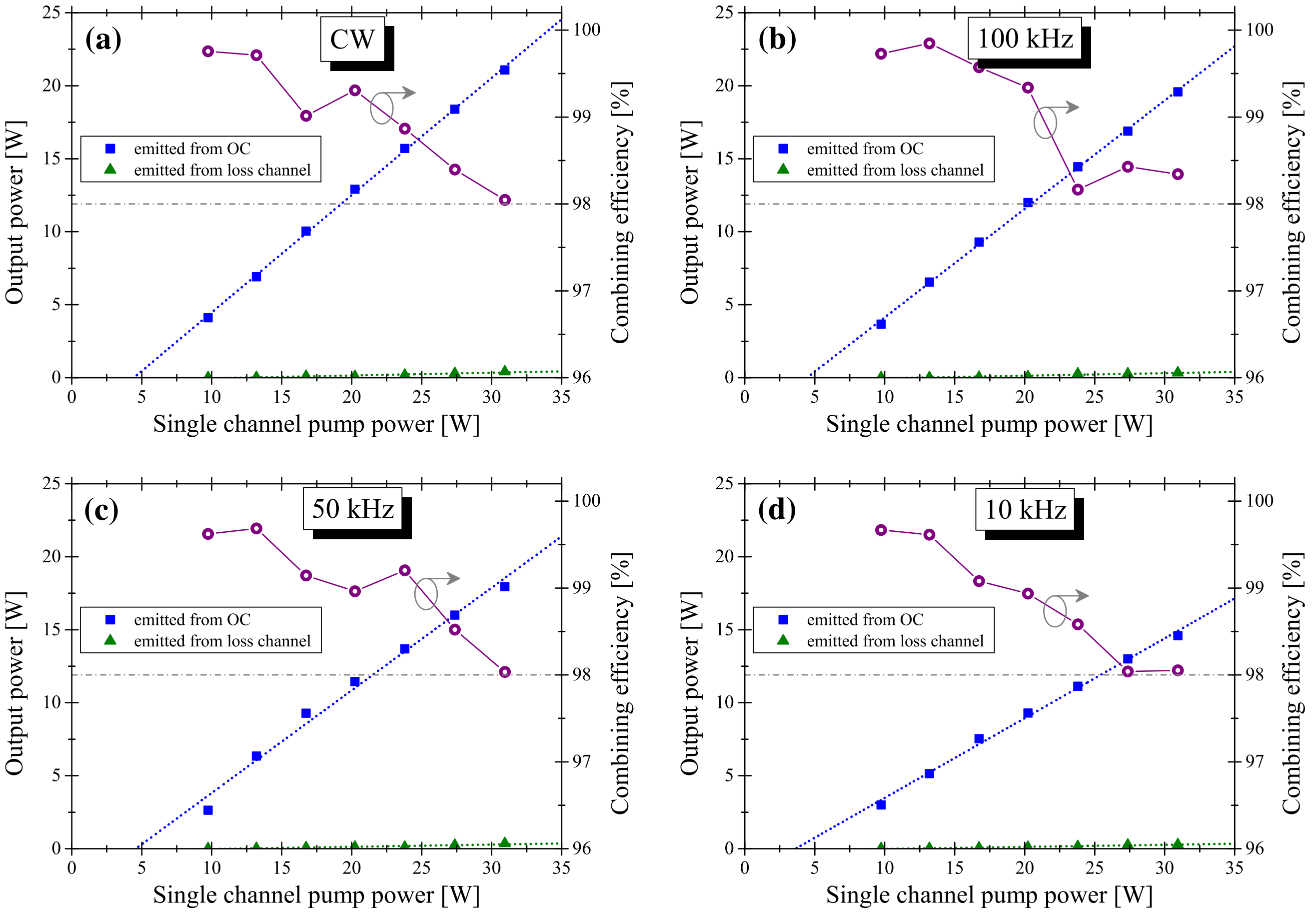

**Fig. 2** (Color online) Measured laser output characteristics of the coherently combined laser system as a function of the single-channel-launched pump power. **a** CW mode; **b–d** pulsed mode with 100 kHz (**b**), 50 kHz (**c**), and 10 kHz (**d**) repetition rates. *Blue squares* represent the output power emitted from the OC. *Green triangles* represent the power emitted from the loss channel. *Purple circles*, connected by the lines to show a trend, represent the combining efficiency as function of the launched pump power (values shown on the right *y-axis*). *Dotted lines* indicate a linear fit between the measured values

operation of the particular rod-type PCFs used in the experiments [10].

The maximum output power in CW mode reached 21 W and was limited by the available pump source. As expected [11], the output power at a high repetition rate (100 kHz) was very similar to that obtained in CW mode and reached a maximum of 20 W. At a 50-kHz repetition rate, the average output power was reduced and reached a maximum of ~18 W and the measured pulse energy reached a maximal value of 0.6 mJ with pulse duration of 43 ns and a corresponding peak power of 13 kW. Finally, at a 10-kHz repetition rate, the output power reached a maximum of 14.6 W and the measured pulse energy reached a maximal value of 1.46 mJ with pulse duration of 15 ns, corresponding to a peak power of 97 kW.

We claim that these results indicate that the free-running channel “chooses” the lowest loss state and lases in a pulsed mode simultaneously with the Q-switched channel. An alternative interpretation is that the free-running channel lased independently between the pulses of the Q-switched channel; however, this alternative is highly unlikely given the interference observed on the BS. More specifically, in the latter scenario, interference is not expected to occur and both channels would suffer a 50 % intracavity loss. Such losses should have been reflected in the combining efficiency and overall performance of the laser (compared to the CW mode), which was not observed in our measurements (see Fig. 2). In addition, the output power characteristics found in the current study are similar to those reported in a previous study [8], wherein both channels were directly Q-switched, which further supports our claim. Finally, the pulse energy at 10-kHz repetition rate is confirmed by an additional measurement with an energy meter; due to perfect correlation, we can conclude that no parasitic lasing exists between the pulses so that both channels operate in a synchronized manner.

A low-resolution measurement of the output spectrum from each channel operating separately is presented in

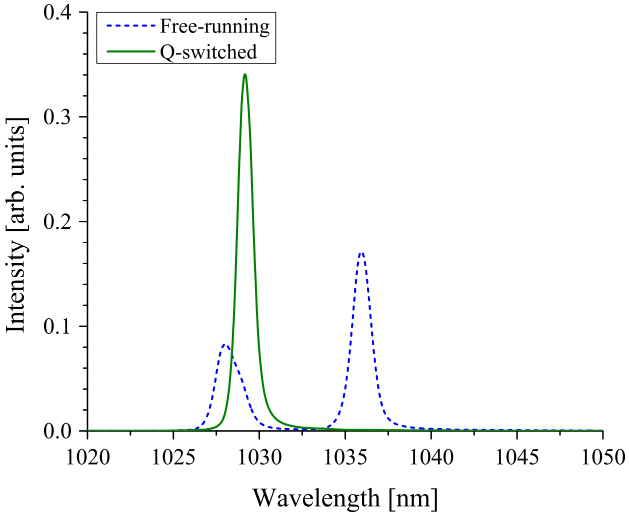

**Fig. 3** (Color online) Measured output spectrum of the free-running channel (*blue dashed curve*) and from the Q-switched channel (*green curve*) when operating separately

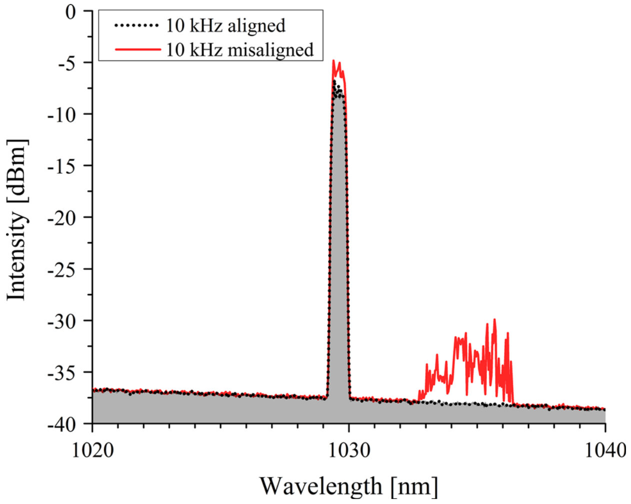

**Fig. 5** (Color online) Measured output spectrum from the coherently combined pulsed laser (repetition rate: 10 kHz) with aligned (*black with filled area*) and misaligned (*red curve*) channel polarization

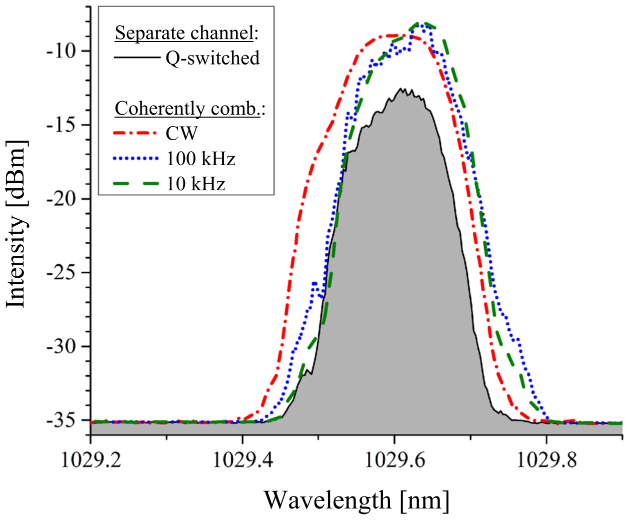

**Fig. 4** (Color online) High-resolution measurements of the output spectrum from the narrowband Q-switched channel operated separately (*black curve* with filled area) and from the coherently combined two-arm laser at CW mode (*red dash-dot curve*), at the 100 kHz pulsed mode (*blue dotted curve*) and at 10 kHz pulsed mode (*green dashed curve*). Measurement obtained with an optical spectrum analyzer

Fig. 3. As expected, a broadband output spectrum was found for the free-running channel and a narrowband output spectrum was found for the Q-switched channel. The narrowband VBG rear mirror in the Q-switched channel and the broadband rear mirror in the free-running channel were used here to achieve further evidence of temporal locking between the channels. Thus, if the channel possessing the Q-switch imposes its temporal characteristics on the other channel (such that both channels lase simultaneously), the spectral properties of both channels is expected to be identical due to constructive interference on the BS output [9]. In this scenario, the free-running channel would have the same narrowband spectrum as the Q-switched channel. In contrast, if both channels do not operate in a locked manner, the output spectrum is expected to be the superposition of the spectral contents from both channels, which would naturally be broadband due to the broadband rear mirror embedded in the free-running channel (Fig. 3).

The measured output spectrum of the separately operated Q-switched channel and of the coherently combined laser system is shown in Fig. 4. The Q-switched channel demonstrated a very narrowband spectrum due to the VBG rear mirror. Moreover, no significant difference was observed in spectra between the different conditions, and the measured spectral width (FWHM) was ~0.13 nm in all operation modes. Thus, the narrowband spectral content of the Q-switched channel was efficiently imposed on the free-running, naturally broadband channel.

Next, we examined the effect of partial phase-locking on the output spectrum (at 10-kHz repetition rate) by slightly misaligning the relative polarization of one channel (Fig. 5). Whereas the aligned system demonstrated a clear narrowband output spectral content (similar to that shown in Fig. 4), misaligning the relative polarization resulted in both a narrowband and a broadband output spectrum. The former originated mainly from the Q-switched channel and partially from the free-running channel, whereas the latter originated exclusively from the free-running channel, and specifically from its unlocked part of the lasing.

## 4 Discussion

In the results presented above, we obtained a maximum peak power of 97 kW, which was limited by the available pump power. Higher pump power or lower repetition rates will lead to higher intracavity net-gain, which in turn will lead to higher peak power pulses. In comparison with our previous study [8], both the maximum average power and a slope efficiency values are similar (at the same operating conditions). Here, the highest slope efficiency is 40 % in the CW case and the lowest is 23 % in pulsed case at 10-kHz repetition rate. We believe this relatively low (for fiber lasers) slope efficiency could be improved by optimized optical components and design. Finally, in the present work, we succeeded to achieve higher combining efficiency, which is more than 98 % in comparison with 95 % presented previously.

On the other hand, in spite of the fact we did not observed it, there is a possibility that higher intracavity net-gain will lead to independent lasing of the free-running channel. This means that theoretically there should be a limit (in terms of intracavity net-gain) where the imposing process fails and the free-running channel starts to lase independently. This is expected due to the same physical mechanism, which is responsible for parasitic lasing between pulses in a standard Q-switched laser, when the hold-off of the Q-switch is not high enough. In this case, the small feedback from the mirrors is high enough to induce lasing.

## 5 Conclusions

In the present study, we experimentally investigated the passive interferometric coherent combining of a two-arm fiber laser within a common cavity, wherein only one of the laser channels is Q-switched. Our results show strong evidence that the spectral and temporal characteristics of the Q-switched channel are imposed onto the free-running channel within a rod-type PCF laser system. Furthermore, we demonstrate very efficient coherent combining with high output power, which seems to be only limited by the available pump power. Future studies may use a similar laser system with higher pump powers to investigate the effects of higher net-gain on the temporal and spectral content imposing, and the effect of various system parameters on the peak power limitation. It would also be interesting to numerically model the imposing reported here, which is expected to contribute to the understanding of the physics behind this phenomenon.

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