

# Single-frequency, all-fiber Q-switched laser at 1550-nm

Yushi Kaneda, Yongdan Hu, Christine Spiegelberg, Jihong Geng, Shibin Jiang

NP Photonics, 9030 S. Rita Rd., Ste 120, Tucson, Arizona 85747  
kaneda@npphotonics.com

**Abstract:** We present a novel actively Q-switched single frequency all-fiber laser using fast stress-induced birefringence modulation. We demonstrate 25-W peak power in 12-ns, 0.3- $\mu$ J pulses at a repetition rate of 80 kHz.

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## Introduction

Compact pulsed laser sources in the eye-safe spectral region have a variety of applications including LIDAR, DIAL, OTDR, and other sensing schemes such as fiber optic Brillouin scattering distributed sensing. Q-switching is an attractive way to produce short optical pulses with high peak power. Several demonstrations have been made combining an optical fiber with free-space Q-switching devices. High peak powers and good efficiencies could be demonstrated at the cost of additional free-space alignment within the laser resonator - a major challenge in manufacturing. All-fiber Q-switched lasers were demonstrated using complex configurations to switch the resonator[1,2]. In these demonstrations, the pulsewidth was fairly long, 150~500 ns. Passively Q-switched fiber lasers were also demonstrated[3], but there has not been, to the authors' knowledge, any all-fiber passively Q-switched laser. In this paper, we report a novel and simple technique to actively Q-switch all-fiber lasers, and demonstrate peak powers exceeding 20 W without any external amplifier, pulsewidth of 12 ns and average power of 24 mW at 80 kHz. The laser can be operated at repetition rates of up to 325 kHz. We have confirmed stable single-frequency operation in the Q-switched regime, which should make this laser a valuable tool for applications involving coherent detection. The all-fiber-construction eliminates any free-space optical alignment process and gives excellent compatibility with existing fiber-optic components.

## Experimental Setup

A schematic of the laser resonator is shown in Fig. 1. The laser consists of a 2-cm long Yb/Er-doped phosphate glass fiber that is spliced between a pair of fiber Bragg gratings (FBGs). Owing to its high solubility, the phosphate glass allows high doping concentration of active ions, enabling efficient laser with an active fiber only a few centimeters long. One FBG has high reflectivity (HR) and is imprinted on a standard silica fiber. The other FBG acts as the output coupler (R~70%) and is written into a polarization-maintaining (PM) fiber, splitting the reflection wavelength for different polarizations, each having approximately 10 GHz of bandwidth. The reflection band of the high reflector is matched to only one of the reflection bands of the output coupler, making the laser cavity polarization dependent. The HR-FBG on a standard fiber is cleaved and spliced a few millimeters away from the FBG, leaving room to be stressed to produce birefringence. The longitudinal mode spacing of the cavity is 2.5-3 GHz and only a few longitudinal modes are supported within reflection band of the output coupler FBG. Single-frequency operation can be maintained by proper adjustment of the temperature of the FBGs as well as the entire cavity[4]. Due to their monolithic nature, such lasers exhibit very narrow linewidth in continuous-wave operation. Typical heterodyne linewidth is as narrow as a few kHz.

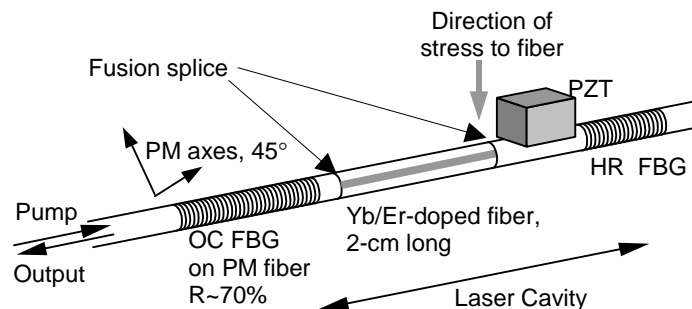


Fig. 1. Schematic of the all-fiber Q-switched laser

In order to modulate the internal resonator loss, we clamped a small piezoelectric actuator (PZT) on top of the fiber section between the splice and the high-reflection FBG, introducing the birefringence in the fiber[5]. Because of the polarization dependence of the resonator, the loss of the resonator can be modulated. In order to maintain high contrast in the loss-modulation, the orientation of the stress was keyed at 45 degrees with respect to the slow/fast axes of the PM fiber.

The laser is pumped by a fiber-pigtailed, single-mode, 976-nm diode used in telecommunication applications, giving an output power of 370 mW. The pump light is coupled to the laser cavity through the output coupler, which is spliced to a WDM coupler to separate the pump from the laser output.

## Results

The laser operates in a continuous-wave mode when no voltage is applied to the PZT. With 370 mW of pump power, approximately 66 mW of output power was obtained in single-frequency at 1550 nm, as shown in Fig. 2. The lasing spectrum is shown in the insets of Fig. 2. When a DC voltage was applied to the PZT, the laser output varied as the effective loss of the cavity changed (shown in Fig. 3). It can be seen that less than 80 V of applied voltage completely inhibited the laser oscillation. A bias voltage of up to 25 V did not affect the output, indicating a small gap between the fiber and the PZT at zero-bias. In a separate experiment, it was confirmed that the propagation loss of the fiber itself is not changing when we apply the stress to the fiber.

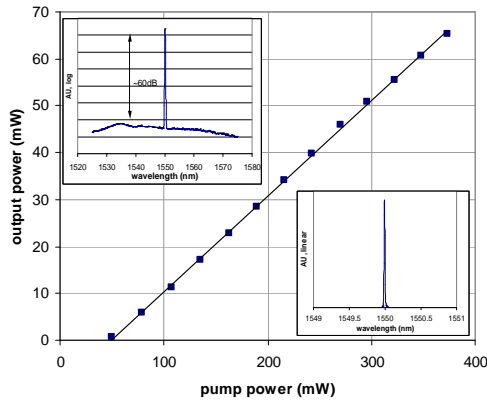


Fig. 2. Input-output characteristic of the fiber laser in cw and its lasing spectrum.

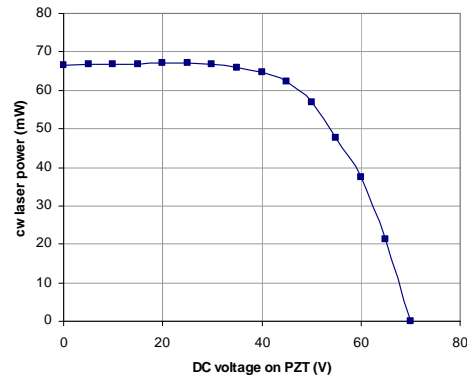


Fig. 3. CW laser output power as a function of the voltage applied to the PZT

A repetitive voltage signal was applied to the PZT to produce Q-switched pulse trains. In this experiment, we kept the pump power constant at the maximum level of 370 mW. At each repetition frequency, the bias and the amplitude to the PZT had to be carefully adjusted to eliminate any after-pulses at the maximum pump power. Due to the limitation of the PZT device as well as the driver used in this experiment, after-pulses were not suppressed at repetition rates below 80 kHz. Fig. 4 shows the average power, peak power, pulse energy and pulsewidth against the pulse repetition frequency. Fig. 5 shows the pulse shape at 3 different repetition frequencies.

At lower pump levels, slightly above the threshold, elimination of the after-pulses is straightforward. The adjustment of PZT bias and amplitude was much less delicate and after-pulses were easily eliminated at lower repetition rates.

The highest peak power obtained from this laser was  $\sim 25$  W at the repetition rate of 80 kHz. The average power was 24 mW with a pulsewidth of 12 ns. The average power increased up to 54 mW at 325 kHz. The pulse energy changed from 0.3  $\mu$ J at 80 kHz to 0.16  $\mu$ J at 325 kHz. 325-kHz modulation seemed to correspond to the resonant frequency of the PZT as the switching was more effective compared to at other frequencies.

In another experiment, where we used a different pump source with higher output power, after-pulses were eliminated only at this repetition frequency. In this experiment, with 780 mW of pump power, an average power of 85 mW, pulse energy of 0.26  $\mu$ J, pulsewidth of 16 ns were generated.

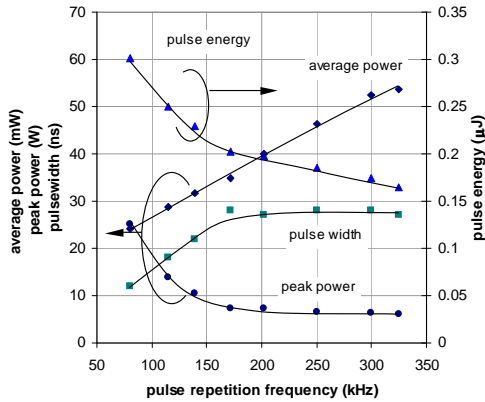


Fig. 4. Average power, peak power, pulse energy and FWHM pulsewidth of the Q-switched fiber laser

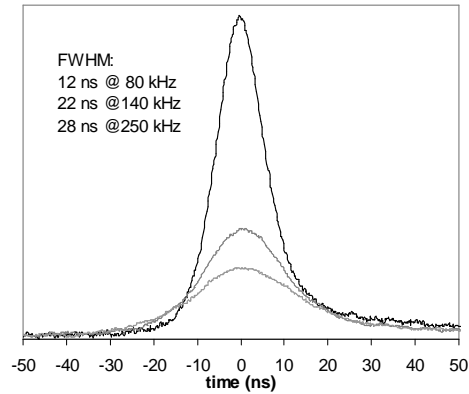


Fig. 5. Typical pulseshape of Q-switched fiber laser

The laser spectrum was observed with a scanning Fabry Perot interferometer under pulsed condition. We first operated the laser in the continuous-wave mode and observed the transmitted signal and record the timing for scanning 1 FSR of the Fabry-Perot. We also observed the transmitted signal when the laser is operating in a pulsed mode. The signal showed bursts of the pulses at the pulse repetition rate only under the transmission peaks of the Fabry-Perot, spaced by 1 FSR. From this observation, we believe that the laser operates in single frequency in the Q-switched mode as well.

It is also noted that none of the resonator components or any of the passive components; WDM, isolator, tap, was damaged during the experiments. The peak intensity in the components was approximately  $30 \text{ MW/cm}^2$ .

### Discussion

The length of the section of the fiber that is stressed by the PZT is 3 mm. According to reference [5], the force that was necessary to generate quarter-wave retardance is approximately 3N. Such force would compress a 125- $\mu\text{m}$ -diameter silica fiber, having a Young's modulus of 73 GPa, by less than 0.1  $\mu\text{m}$ . However, from the voltage it took to drive the resonator to the low-Q state, a few tens of volts, the motion of the PZT should be nearly 1  $\mu\text{m}$ . This difference is probably caused by the fact that the neither the PZT nor the mount on which the fiber was placed was perfectly rigid, and was being compressed as well, reducing the compression on the fiber. An improved mechanical design would yield higher sensitivity of the resonator loss to the force generated by the PZT.

Another limitation we faced in our preliminary experiments was the frequency response of the PZT as well as the driver. Because of the fairly large capacitance of the PZT used in the experiments, the slew-rate was limited, which also limited the switching speed. We believe that this effect is the limiting factor of the present experiments for the low-repetition rate operation under high-gain operation. Proper choice of driver and transducer will improve the performance of the laser.

### Conclusion

We have presented a novel technique for Q-switching an all-fiber laser. The resonator is entirely contained in the optical fiber, without any free-space optics, eliminating all the cost and alignment issues associated with lasers having free-space optical components. In our preliminary experiments, we have obtained a train of 0.3- $\mu\text{J}$ , 12-ns pulses at 80-kHz repetition rate at 1550 nm. The laser has also produced 0.28- $\mu\text{J}$ , 16-ns pulses at 325 kHz using higher pump powers. Future work will include the development for higher power and pulse energies.

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