All-fiber Q-switched single-frequency Tm-doped laser near 2 μm

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We present an all-fiber Q-switched single-frequency laser oscillator operating in the eye-safe region at 1950 nm. It is based on the stress-induced polarization modulation in a Tm-doped distributed Bragg reflector fiber laser. The laser emits Q-switched single-frequency laser pulses with a pulse repetition rate ranging from tens of hertz to hundreds of kilohertz and an average power of several milliwatts. Pulse duration and laser spectral linewidth have been characterized. This is, to our best knowledge, the first demonstration of a Q-switched single-frequency fiber laser near 2 μm. © 2009 Optical Society of America

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Many applications, such as coherent lidar and atmospheric sensing, require compact coherent pulsed laser sources preferably operating in the eye-safe spectral region near 2 μm, because some important greenhouse gas molecules and water vapor in the atmosphere exhibit characteristic absorption lines in this region. For decades, Q-switched single-frequency Tm- or Ho-doped crystal lasers have been used in these applications [1], although they suffer from a complicated free-space laser cavity design. All-fiber monolithic laser sources are highly desirable for these applications, especially for airborne and spaceborne applications, because fiber-based sources offer a much more compact and robust solution. With the advances in photonic component technologies developed mainly for telecommunication and fiber laser industries in recent years, all-fiber single-frequency pulsed laser sources become readily available at shorter wavelengths, i.e., 1.55 and 1 μm as well. High-power single-frequency pulse radiation can simply be generated from directly modulated distributed feedback semiconductor lasers and/or single-frequency fiber oscillators in combination with fiber- or crystal-based high-power amplifiers. For the long wavelengths near 2 μm, fiber components are not as readily available as those at the short wavelengths (1.55 and 1 μm). Although cw single-frequency fiber lasers near 2 μm have been demonstrated in several research groups in recent years [2–6], pulsed single-frequency fiber sources have never been reported at the wavelength. In this Letter, we report an all-fiber Q-switched single-frequency laser oscillator near 2 μm, which is—to our knowledge—the first report of this kind of laser in the 2 μm region.

Figure 1 shows our experimental setup. The approach for an all-fiber Q-switched single-frequency laser is based on the polarization modulation of a short-cavity fiber laser by using stress-induced birefringence [7], as we demonstrated in Er- and Yb-doped fiber lasers previously [8,9]. The design concept is that a single-frequency fiber laser with distributed Bragg reflector (DBR) cavity configuration is formed by a non-polarization-maintaining (non-PM) high-reflectivity fiber Bragg grating (FBG) and a polarization-maintaining (PM) narrowband FBG that acts as an output coupler. The combined use of a short laser cavity (a few centimeters in length) and narrowband DBRs (i.e., FBGs) ensures a robust single-frequency operation in the fiber laser. Because of the birefringence in the PM fiber, the PM FBG has two different reflective wavelengths, originating from different refractive indices along two polarization axes (i.e., slow and fast axes) of the PM fiber. These two FBGs are designed so that only for one specific state of polarization the PM FBG has a matched reflective wavelength with that of the non-PM FBG, thereby resulting in laser oscillation in this specific state of polarization. For the orthogonal polarization direction, no laser oscillation can occur. To achieve Q switching in the fiber laser, an appropriate amount of preloaded stress is applied to a small section of the active fiber inside the laser cavity at an angle of 45° relative to the axes of the PM FBG. This stress-induced birefringence acts as a wave plate so that the intracavity light has the orthogonal direction of polarization with a low Q value in the fiber laser cavity, thereby preventing laser oscillation. A small piezo actuator is used to quickly release the preload stress to obtain a high Q value in the cavity,

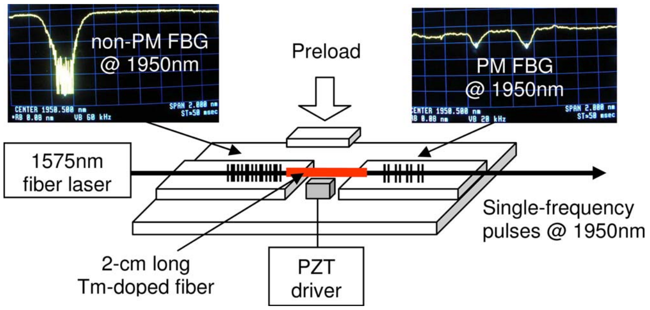

Fig. 1. (Color online) Diagram of the experimental setup. A Tm-doped DBR fiber cavity was formed by two FBGs. Preload force and PZT-induced stress are applied to a small section of the active fiber for polarization modulation. Inset, transmission spectra of the two FBGs measured with an in-house 2 μm broadband fiber source.

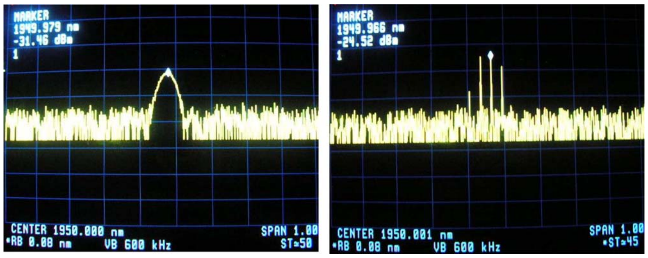

Fig. 2. (Color online) Laser spectra of the DBR fiber laser in cw (left) and Q-switched (right) modes. The four peaks in the graph on the right correspond to four sequential Q-switched pulses when the Hewlett Packard OSA was scanning across the laser wavelength.

resulting in the generation of Q-switched single-frequency pulses in the preferred specific state of polarization. More detailed information about stress-induced birefringence in an optical fiber for the Q-switching operation has been discussed previously [7,8].

In this experiment, the reflective wavelength along the fast axis of the PM FBG (~70% reflectivity) was matched with the reflection band of the non-PM FBG (>99% reflectivity) as shown in the inset pictures of Fig. 1. A short piece (~2 cm long) of active fiber was spliced with the two FBGs to form a DBR fiber cavity for single-frequency laser operation. The active fiber is a non-PM fiber, which is our newly developed single-mode Tm-doped silicate fiber. The fiber has a core diameter of 10 μm and an NA of 0.136 with a Tm-doping concentration of 5 wt. %. High doping concentration of the fiber enables efficient cross relaxation. Our earlier experiments have demonstrated high pump absorption and high gain per unit length with the fiber under both core- and cladding-pump configurations [10].

The DBR fiber laser was core pumped with a fiber master oscillator power amplifier system operating at 1575 nm wavelength. The master oscillator was a 45 mW single-mode diode-pumped Er-doped fiber laser, and its power was boosted by a cladding-pumped Er/Yb co-doped fiber amplifier delivering a maximum output power of 600 mW at 1575 nm. Core-pump absorption of our Tm-doped fiber was measured to be about 1.7 dB/cm at 1575 nm. In the cw single-frequency operation, the DBR fiber laser has a threshold pump power of 150 mW with a slope efficiency of 37% relative to the absorbed pump power [10]. Tens of milliwatts output power has been generated from the laser in the cw mode. The relatively high laser threshold was attributed to high cavity loss, including output coupling loss (~70% reflectivity) and splicing losses (~2.2 dB) between the active fiber and two FBGs.

Figure 2 shows the spectra of the DBR laser in the cw and Q-switched mode operations. Since both the preloaded stress and the piezoelectric transducer (PZT)-induced stress were applied only to the section of the active fiber, rather than the FBGs, the laser center wavelength keeps unchanged when switching the laser from cw mode to Q-switching mode. The laser spectral linewidth cannot be directly obtained from these spectra because the spectral linewidth of the laser is expected to be much narrower than the minimum spectral resolution (~0.08 nm) of the optical spectrum analyzer (OSA).

When the preload stress was applied to the active fiber, the polarization of the intracavity beam could be modulated by the PZT-induced stress, which offers the Q-switching mechanism in the all-fiber laser. Figure 3 shows typical traces of the Q-switched pulse trains and the corresponding PZT drive signals. The repetition rate of the Q-switched fiber laser can be tuned from tens of hertz to hundreds of kilohertz simply by using different PZT drive signals. When changing the repetition rate, however, the pump power and the PZT drive signal need to be adjusted for optimal Q-switching operation. When the Q-switched laser operates at a high pump power or at a low repetition rate (<500 Hz), more care needs to be taken for preventing the laser from parasitic pulse oscillation. Several milliwatt average output power can be readily generated from the Q-switched laser, but it has a much lower slope efficiency (~5%) than that of the laser in the cw mode (~37%). The lower efficiency in the Q-switching operation is attributed to an additional cavity loss induced by the preload due to microbending of the active fiber near the edge of the small piezo actuator. A better design for the preloading mechanism may eliminate the microbending loss and significantly improve the laser efficiency.

As can be seen in Fig. 3, the buildup time (or delay) of Q-switched pulses with respect to their drive signals was varied with the repetition rate and pump power as well. At a specific repetition rate and pump power, no significant pulse jitter was observed on the oscilloscope in short term, but in long-term operation the pulse buildup time could change owing to the slow slippage of either the preload or the PZT-induced stress and temperature redistribution along the fiber as well. In the optimal Q-switching operation, the short-term peak-to-peak power variation can be less than 5%.

The pulse duration of the Q-switched 2 μm laser was measured with a 40 MHz bandwidth photodiode (Thorlab, PDA10D). Figure 4 shows typical traces of the Q-switched pulses. The laser pulse duration is dependent on both the repetition rate and the pump power. When operating at the repetition rates below several tens of kilohertz, the laser delivers short pulses with a measured duration of about 40 ns or

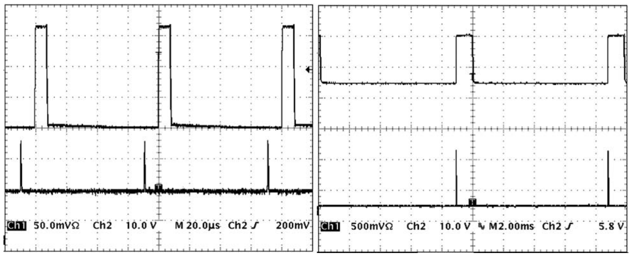

Fig. 3. Typical traces of the Q-switched pulse trains (lower trace) and the corresponding PZT drive signals (upper trace) for repetition rates of 12.5 kHz (left) and 100 Hz (right).

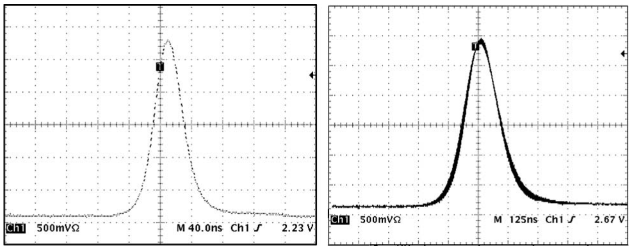

Fig. 4. Typical traces of the Q-switched pulses at 12.5 kHz (left: <40 ns) and 125 kHz (right: >100 ns).

less, which was limited by the bandwidth of the photodiode. When the repetition rate was higher (e.g., >100 kHz), the pulses were longer (100–200 ns) than the resolution limit of the photodiode. The observed pulse width dependence on the repetition rate is qualitatively consistent with the previous reports [8,9].

Single-frequency laser operation in the Q-switched mode was confirmed by using an in-house fiber-based scanning Fabry–Perot (FP) interferometer. The interferometer was constructed with two identical high-reflective FBGs at the same wavelength as the laser wavelength (1950 nm), which were fusion-spliced together with a distance of about 12 cm. It was scanned by applying a saw tooth voltage over a small piece of piezo actuator, on which a portion of the fiber of the interferometer was glued. Figure 5 shows the laser spectra when the interferometer was scanned over one free spectral range (FSR ~ 800 MHz). These spectra correspond to the Q-switched pulses at two different repetition rates (125 and 12.5 kHz). From these data, it can be seen that the spectral linewidth of the Q-switched pulses is determined by their pulse duration, which is in turn determined by the pulse repetition rate and the pump power. When the repetition rate is high (>100 kHz), the Q-switched laser has a long pulse duration (100–200 ns) but with a narrow spectral linewidth (~15 MHz), which is close to the resolution limit of the FP interferometer (with an estimated finesse of about 100) used in the experiment. Figure 5(a) shows the spectrum of the Q-switched pulses at the repetition rate of 12.5 kHz. The spectral linewidth can be estimated to be about 30 MHz. Assuming that the Q-switched pulses are Fourier transform limited as shown in an Er-fiber system [11], the duration of the pulses at 12.5 kHz should be about 10 ns, instead of 40 ns shown in Fig. 4.

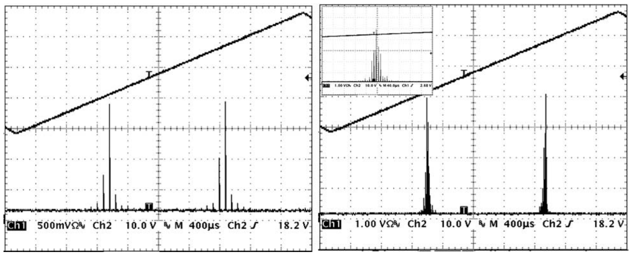

Fig. 5. Laser spectrum over one free spectral range (FSR ~ 800 MHz) of an FP interferometer that verified single-frequency operation of the all-fiber Q-switched laser at 12.5 (left) and 125 (right) kHz. The inset in the right graph shows a zoom-in spectrum.

In summary, an all-fiber Q-switched single-frequency laser operating in the 2 μm region has been demonstrated for what we believe to be the first time. The Q-switched laser can be operated in a wide range of repetition rates ranging from tens of hertz to hundreds of kilohertz with several milliwatt average output power and with tens of megahertz spectral linewidth. The power of the narrow-linewidth Q-switched laser pulses can be readily boosted by using multistage Tm-doped fiber amplifiers as done in the 1.55 μm fiber system [11], which could find potential applications for airborne coherent lidar and atmosphere remote sensing.

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