Compact, single-frequency all-fiber Q-switched laser at 1 μm

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We demonstrate a unique, all-fiber, actively Q-switched laser operating in the 1 μm region. The laser is compact, single mode, single frequency, highly polarized, and exhibits high peak power. The laser cavity is constructed without external coupling, utilizing fiber Bragg gratings that permit feedback at only a single polarization. By using a piezoelectric to press the fiber and modulate the fiber birefringence, the cavity is switched between high and low loss states, permitting Q-switching. We demonstrate this Q-switching at repetition rates up to 700 KHz. © 2007 Optical Society of America

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Fiber-based Q-switched lasers are currently a very active area of research, and have many potential applications in such areas as fiber-based sensing and nonlinear frequency generation. Many groups have built Q-switched fiber lasers using acousto-optical and electro-optical modulators,[1–4] though these lasers have involved bulk components in the laser cavity that increase loss, size, and complexity. Bulk components in the laser cavity have also been used by various groups that have reported passive Q-switched fiber lasers using saturable absorbers.[5–7] All-fiber Q-switched lasers using nonlinearities, such as Raman backscattering, have been constructed, but these are emitted at multiple wavelengths, and their pulse repetition rate is unstable and pump power dependent.[8,9]

Recently, methods for actively Q-switching all-fiber lasers have been developed for communications wavelengths around 1550 nm. Reported methods include magnetostriction modulation of fiber Bragg gratings[10] (FBGs), stretching of FBGs with piezoelectric elements,[11] acoustically generated microbending,[12] and evanescent field coupling.[13] Kaneda *et al.* reported constructing an all-fiber Q-switching laser using fiber birefringence induced by stress.[14] In this method, a piezoelectric compresses a fiber creating stress birefringence, and this birefringence acts as a waveplate, changing the polarization state of the light in the fiber. This Q-switch mechanism is similar to using an electro-optic modulator, where the polarization is modulated to switch the laser between high and low feedback states.

We have used this latter method of piezo-induced birefringence to develop an all-fiber actively Q-switched laser at 1064 nm, which, to the best of our knowledge, is the first report of this type of laser in the 1 μm region. The gain medium of the laser consists of 2 cm of our proprietary phosphate glass fiber that is highly Yb doped (6% wt) as shown in Fig. 1. Yb has a broad absorption spectra, and NP Photonics typically builds cw fiber lasers from 1030 to 1070 nm using this active fiber. The high doping concentration creates a strongly absorbing active fiber, allowing for a 3.5 cm cavity length that is significantly shorter than other Q-switched fiber lasers, which can have cavity lengths of meters to kilometers.[2,4,7,8] This short cavity length creates a large longitudinal mode spacing, helping to maintain lasing on a single longitudinal mode. The active fiber is spliced between two FBGs and a short section of standard nonpolarization-maintaining (non-PM) fiber as shown in Fig. 1. A wavelength-stabilized, commercially available 976 nm diode laser pumps the cavity. This configuration allows a laser cavity where there is no coupling to external bulk components, such as acousto-optic modulators, while also eliminating fiber components within the cavity.

The two gratings act as mirrors, with the first in Fig. 1 as the high reflector (HR-FBG), and the second as a lower reflectivity output coupler (OC-FBG). The high reflector is written in a standard non-PM Hi-1060 fiber, and has a fairly broad reflection band of 0.31 nm. The output coupler has a 50% transmission grating with a narrow linewidth of 0.03 nm. The use of FBGs permitted thermal tuning of the laser by heating each grating, which has a tuning of ~0.01 nm/°C. Because OC-FBG is written in a PM fiber, the reflection band is split ~0.3 nm due to the different indexes of refraction in the fast and slow

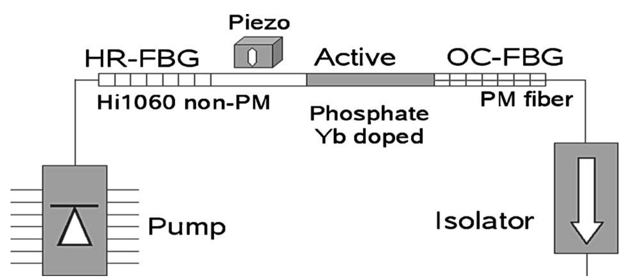

Fig. 1. Schematic of actively Q-switched all-fiber laser at 1064 nm. The direction of motion of the piezo is rotated 45° from the polarization axis of the PM fiber.

axis of the PM fiber. We selected these gratings so the fast-axis reflection would be within the reflection band of the HR-FBG, while the slow axis would be located outside the reflection band. This creates a polarization-dependent cavity where the fast axis will have optical feedback and the slow axis will not.

The polarization-dependent reflection permits Q-switching if the internal birefringence of the cavity can be modulated. We can control the polarization in the cavity by using a 2 mm long piezoelectric element to stress the fiber, with the compression axis rotated 45° relative to the axis of the PM fiber. This stress-induced birefringence acts as a waveplate, which rotates the polarization of the light inside the laser. In cw operation and at low repetition rates, compression with a piezo can produce a hold-off of over 50 dB as measured on an optical spectrum analyzer.

To characterize the Q-switched laser, we varied the repetition rate of the electrical signal to the piezo over a range of values. We were able to achieve Q-switching at a peak repetition rate of 700 KHz, which is significantly faster than other all-fiber actively Q-switched lasers.[10–14] We then changed the pump power of the diode and repeated the measurements, with the pump powers ranging from 30 to 185 mW. At high pump powers or low repetition rates, we observed parasitic pulses, multiple optical pulses for each electrical pulse of the piezo, which would be troublesome for sensing applications. By proper adjustment of the piezo offset and electrical signal, we were able to eliminate the parasitic pulses and maximize the power in the single pulse. In general, different settings of repetition rate and pump power required adjusting the offset and piezo signal to optimize performance.

The laser produced narrower pulses at lower repetition rates as shown in Fig. 2(a). However, below ~500 Hz there was little change in pulse width. Higher pumping power also led to narrower pulse widths as shown in Fig. 2(b). The pulse-width dependence with the repetition rate was well fit by a quadratic across all pump powers tested. The shortest average pulse width was 18.8 ns, and occurred at 185 mW pump power at a 5000 Hz repetition rate. The pulse width had an average relative standard deviation of 3.1% for all measurements, indicating good pulse-width stability for this laser.

We measured the average power of the laser with multiple fiber-coupled Newport integrating sphere detectors, and subtracted out the background pump and amplified spontaneous emission. The average power for the laser when Q-switching showed a roughly linear increase with repetition rate, and the slope efficiency also increased with repetition rate. However, the average power would saturate at high repetition rates. We interpret this as indicating that the usable inversion was saturated by the pulses, and further increases would likely result in little more useful power. The maximum average power was 31 mW, and occurred at the highest pump power (185 mW) and highest repetition rate (700 KHz) tested. The efficiency of the Q-switched laser increased with pump power, with a useful maximum slope efficiency, measured after the isolator and connector, of 22% at 185 mW pump.

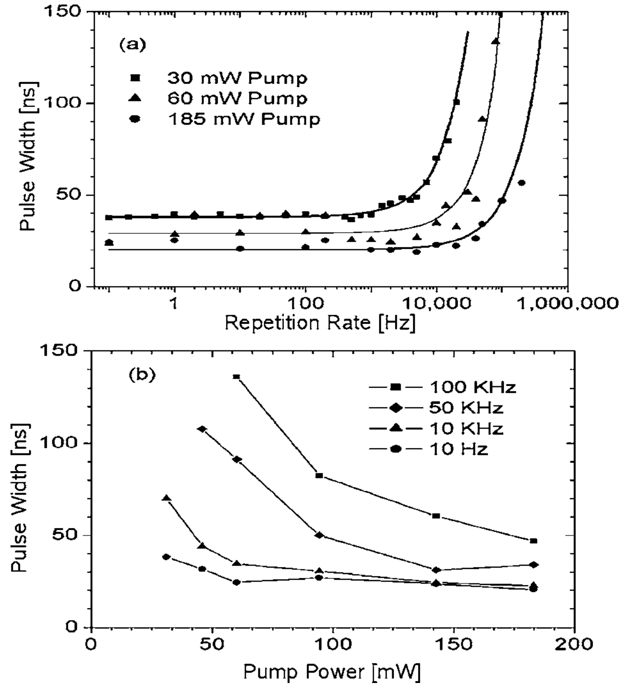

Fig. 2. Measured pulse width variation for the Q-switched laser. (a) Variation of pulse width with repetition rate for three different pump powers. Symbols indicate data, while the curves show the quadratic fit. (b) Variation of the pulse width with pump power at five different repetition rates.

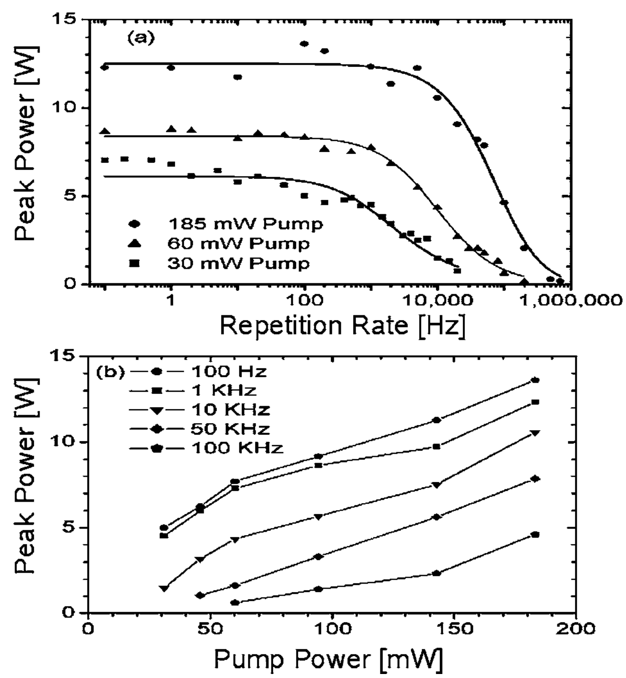

Fig. 3. Measured peak power variation for the Q-switched laser. (a) Peak power variation with repetition rate (symbols), and accompanying shifted power law fit (curves) for three different pump powers. (b) Peak power shows a consistent increase with pump power.

The peak power is often more important in fiber sensing and nonlinear generation applications than average power and pulse energy. The peak power can be calculated from the average power and pulse width, and also from a calibrated photodiode and oscilloscope. To calculate the peak power from the average power and pulse width, we approximated the pulses as Gaussian in shape. The average power effectively integrates the energy in the laser pulse over the period of one repetition rate. The pulses were well separated in time, allowing us to approximate the time duration of the repetition rate to be infinite for the purposes of integration. Using the closed-form solution for Gaussian integrals and simplifying the resulting algebra, an analytic approximation of the peak power is given by Eq. (1):

$$P_{\max} = \frac{P_{\text{ave}}}{t_{\text{FWHM}} f_{\text{RR}}} 2\sqrt{\frac{\ln 2}{\pi}}. \quad (1)$$

In this formula, $P_{\max}$ is the peak power, P_{ave} is the average power, t_{FWHM} is the temporal full-width at half-maximum of the pulse, and f_{RR} is the pulse repetition rate. The peak power obtained using average power and pulse width generally agreed with the results obtained with the photodiode.

Experimentally, the peak power was relatively constant below a repetition rate of ~500 Hz and decreased at higher repetition rates as shown in Fig. 3(a). The variation of the peak power with the pump power was roughly linear as shown in Fig. 3(b). The highest average peak power obtained was 13.6 W at a pump power of 185 mW and a repetition rate of 100 Hz. A shifted negative power law fit the repetition rate versus peak power data better than various exponential and rational functions while maintaining a minimum of fitting coefficients. The pulse energy of the laser followed a very similar pattern, with a shifted power law being an acceptable fit. The maximum average pulse energy was 0.4 μJ, which occurred at 185 mW pump power and 200 Hz repetition rate. The laser can be easily used to seed a fiber amplifier to achieve much higher peak powers and pulse energies, while still maintaining many desirable properties.

The compact cavity of the laser leads to single-frequency behavior due to wide spacing of the longitudinal modes. We estimate the longitudinal mode spacing of our laser cavity to be 3 GHz. Similar lasers have demonstrated extremely narrow linewidths.[14,15] To ensure the laser operated on a single mode we used a scanning fiber Fabry–Perot interferometer. Thermally adjusting the peak of the narrowband grating to the edge of the wideband grating moves modes outside the reflection band, suppressing their feedback. In this way a single mode can be isolated because the large mode spacing of the cavity allows few modes in the reflection band of the narrowband grating.

In conclusion, we constructed a novel, compact, all-fiber cavity, single-frequency, actively Q-switched laser that operated at 1 μm. It is capable of a 700 KHz repetition rate, as well as single-pulse operation, and was run reliably for months. The laser's short pulse widths, single frequency, and single spatial mode make it excellent for many tasks. We anticipate the development of all-fiber, single-frequency Q-switched lasers throughout the entire 1030–1070 nm range, seeding fiber amplifiers for even higher output powers.

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