Single-frequency gain-switched Ho-doped fiber laser

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Received July 5, 2012; revised July 31, 2012; accepted July 31, 2012;
posted July 31, 2012 (Doc. ID 171929); published September 6, 2012

We demonstrate a single-frequency gain-switched Ho-doped fiber laser based on heavily doped silicate glass fiber fabricated in-house. A *Q*-switched Tm-doped fiber laser at 1.95 μm was used to gain-switch the Ho-doped fiber laser via in-band pumping. Output power of the single-frequency gain-switched pulses has been amplified in a cladding-pumped Tm-Ho-codoped fiber amplifier with 1.2 m active fiber pumped at 803 nm. Two different nonlinear effects, i.e., modulation instability and stimulated Brillouin scattering, could be seen in the 10 μm-core fiber amplifier when the peak power exceeds 3 kW. The single-frequency gain-switched fiber laser was operated at 2.05 μm, a popular laser wavelength for Doppler lidar application. This is the first demonstration of this kind of fiber laser.

OCIS codes: 060.2320, 140.3510, 140.3538, 140.3570.

Single-frequency pulsed laser sources in the eye-safe spectral region near 2 μm are of particular interest to some applications. For example, Doppler lidar wind measurements require highly reliable compact single-frequency laser pulses near 2 μm for use in airborne and space-borne platforms [1,2]. Another emerging application is to use single-frequency pulsed 2 μm lasers as pump sources for narrowband longer wavelength infrared or terahertz generation via nonlinear frequency conversion techniques, such as optical parametric oscillator (OPO) [3] or difference frequency generation (DFG).

Both Tm and Ho ions exhibit high laser gain near 2 μm when they are doped in optical media, including crystals and various glass fibers. To date, Tm-doped fiber lasers have dominated research interest in the 2 μm fiber lasers. Indeed, Tm-doped fibers have the potential to generate laser wavelengths far beyond 2.0 μm, up to 2.1 μm, which covers most of the gain spectral range offered by Ho-doped fibers. However, for single-frequency laser operation Tm-doped fibers cannot go that far. This is because Tm ions dramatically reduce their emission cross section with wavelength. For laser operation at the wavelengths far beyond 2 μm, a prolonged length of Tm-doped gain fiber has to be used to generate sufficient laser gain, which is prohibited for single-frequency laser operation. The reported longest single-frequency laser wavelength so far from a Tm-doped fiber laser was near 2.02 μm [4]. For atmospheric Doppler lidar application, however, one popular wavelength region is 2.05–2.06 μm, at which high-energy Ho:Tm:YLF and Ho:YLF crystal-based power amplifiers are readily available for joule-level pulse energy single-frequency laser generation. In this configuration, it requires single-frequency seeder laser at the wavelength near 2.05–2.06 μm. This is a challenge if using Tm-doped fibers, but it is readily achievable with Ho-doped fibers. In fact, Wu *et al.* demonstrated the first single-frequency fiber laser at that wavelength by using heavily Ho-doped germanate glass fiber [5], which was operated in a CW mode. Although Eichhorn and Jackson did pioneering research on pulsed Ho-doped fiber lasers by *Q*-switching [6] or gain-switching [7], none of these lasers were operated in single-frequency mode. In this Letter, we report a single-frequency pulsed fiber laser using a very short piece of heavily Ho-doped silicate glass fiber, which was gain-switched by a *Q*-switched Tm-doped fiber laser. This is, to our knowledge, the first demonstration of this kind of laser.

Heavily Ho-doped multicomponent silicate glass and fiber were fabricated in-house. Single-mode Ho-doped fiber used in this experiment has a doping concentration of 3 wt. % with a core diameter of 10 μm and 0.124 NA. Experiments show that the Ho-doped fiber has a peak absorption wavelength near 1.95 μm ($\sim$1.0 dB/cm). This enables us to use a very short piece ($\sim$2 cm long) of the Ho-doped fiber as the gain fiber for single-frequency gain-switched laser operation when pumped by a *Q*-switched Tm-doped fiber laser operating at 1.95 μm.

An in-house *Q*-switched Tm-doped fiber laser (AdValue Photonics, Model AP-Tm-QS) was used as a pump source to pump a single-frequency Ho-doped fiber laser, which was formed by a 2 cm-long piece of the Ho-doped fiber and a pair of fiber Bragg gratings at 2.052 μm, including a high-reflectivity grating written in Corning SMF-28 fiber and an output coupler grating in polarization-maintaining fiber PM1550. The grating pair was designed for single polarization laser oscillation along the slow axis of the output grating, which emitted linearly polarized laser radiation with $>$20 dB polarization extinction ratio (PER). The pump laser, i.e., single-mode *Q*-switched Tm-doped fiber laser, delivers 20 kHz pulses at 1.95 μm with a pulsewidth ranging from 15 to $\sim$100 ns (inversely proportional to average output power approximately, with a maximum average power of about 300 mW). Figure 1 shows the laser output power as a function of launching pump power at 20 kHz rep rate. The slope efficiency was about 5%, which was at least one order of magnitude lower than other in-band pumped Ho-doped fiber lasers [6,7]. Mode mismatch loss and high splicing loss (with total insertion loss of $\sim$2.2 dB) between the Ho-doped silicate fiber and the grating fiber in the fiber laser chain was partly responsible for the low laser efficiency. More improvement is required for high laser efficiency.

Optical spectra of the pump laser pulses and the gain-switched laser pulses are shown in the inset of Fig. 1. The gain-switched laser wavelength was measured to be

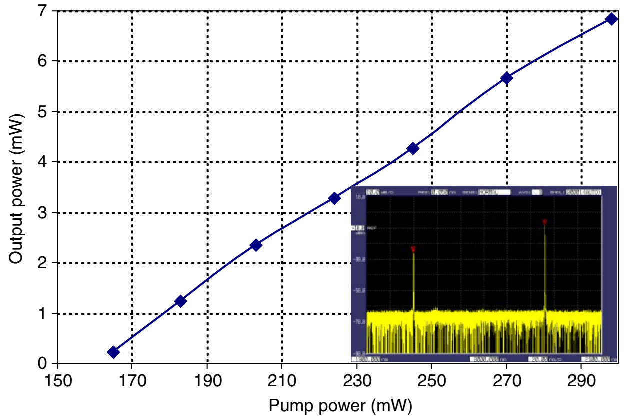

Fig. 1. (Color online) Laser output power versus launched pump power. Inset: spectrum of the pump pulses and signal pulses.

2.052 μm, which was close to the wavelength required for atmosphere Doppler lidar applications.

Temporal profiles of the pump pulses and the gain-switched pulses were measured by using a fast photodiode (Electro-Optical Technology, Model ET-5010 with bandwidth >7 GHz) and a digital oscilloscope, with a typical oscilloscope trace shown in Fig. 2. Trace #1 was the optical signal, showing the 1.95 μm pump pulse and the subsequent gain-switched pulse at 2.052 μm, while trace #2 was the electrical signal that was used to trigger the *Q*-switched Tm-doped fiber laser. Pulse build-up time and the pulsewidth of the gain-switched laser were strongly dependent on pumping power and the pulsewidth of the 1.95 μm pump laser. As the pump power increases, the 1.95 μm pump pulses become shorter, both of which lead to the reduction in build-up time and pulsewidth of the gain-switched pulses. As a result, the gain-switched pulsewidth could be as short as 7–8 ns at high pump power, but it could also be as long as >100 ns near the pump threshold. From the trace #1 in Fig. 2, it can clearly be seen that the 1.95 μm pulse profile is spiky due to mode beating, but the 2.052 μm pulse has a very smooth profile, suggesting that the gain-switched fiber laser was in single-frequency laser operation.

The single-frequency operation was verified by using a scanning fiber Fabry–Perot (FP) interferometer with a

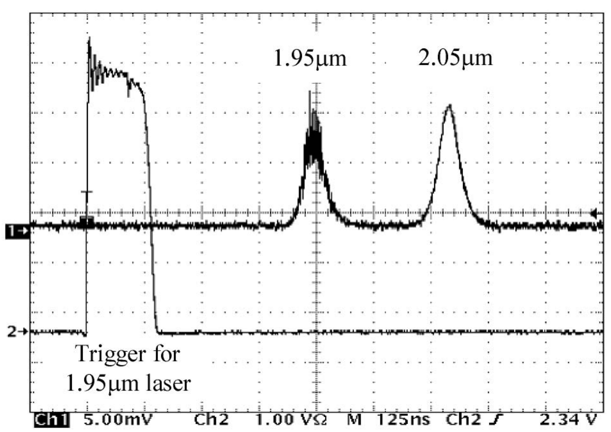

Fig. 2. Typical temporal profiles of a pump and gain-switched pulse for trace #1, and pump trigger for trace #2.

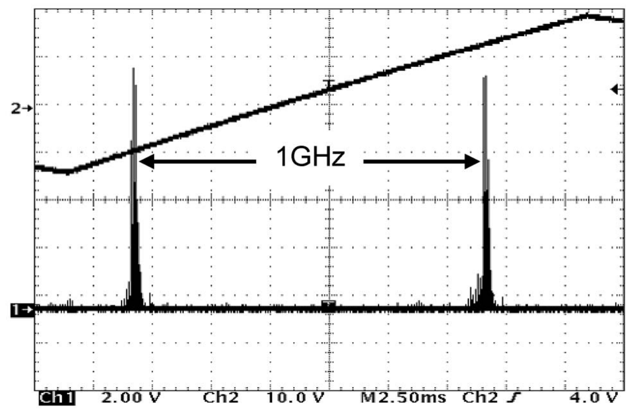

Fig. 3. Scanning FP interferometric spectrum of the gain-switched Ho-doped fiber laser verifying single-frequency operation.

1 GHz free-spectrum range (made by Micro-Optics). Within one free-spectrum range, there was only one peak in the FP spectra, as shown in Fig. 3, thereby confirming single-frequency laser operation at the wavelength of 2.052 μm. Spectral resolution of the scanning FP interferometer was calibrated by the laser in a CW operation mode, which was ∼4 MHz. In the gain-switched mode, typical laser pulses have a transform-limited linewidth ranging from <10 MHz to ∼40 MHz, depending on the pulsewidth of gain-switched pulses.

Output power of the single-frequency gain-switched laser was further boosted by a single-mode cladding-pumped nonpolarization-maintaining fiber amplifier, in which the active fiber was a 1.2 m-long piece of home-made Tm-Ho-codoped silicate glass fiber pumped by a multimode laser diode at 803 nm. The heavily codoped fiber has a 10 μm core diameter (0.14 NA) with 6 wt. % Tm-doping and 0.4 wt % Ho-doping. The co-doped active fiber enables direct diode-pumping with 0.8 μm laser diodes, as demonstrated in a mode-locked fiber laser operating at 2.06 μm reported recently [8]. A 1 m-long piece of passive fiber was spliced with the gain fiber to remove the residual pump from the fiber cladding and deliver the amplified single-mode gain-switched pulses at 2.052 μm. Figure 4 shows the output power from the fiber amplifier

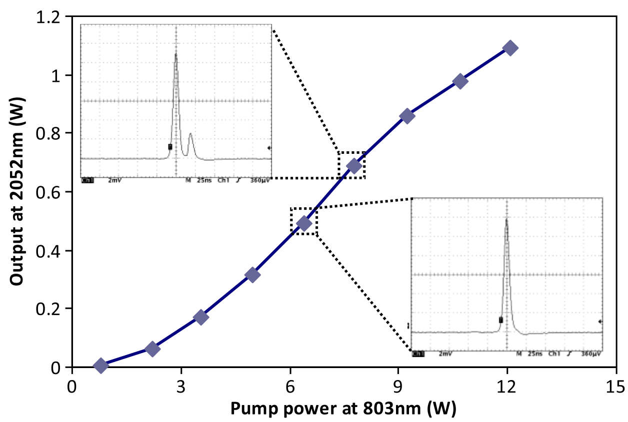

Fig. 4. (Color online) Output power extracted from the fiber power amplifier. Insets: temporal profiles of the amplified pulses at average powers of 500 and 750 mW, corresponding peak power of 3 and 4.5 kW.

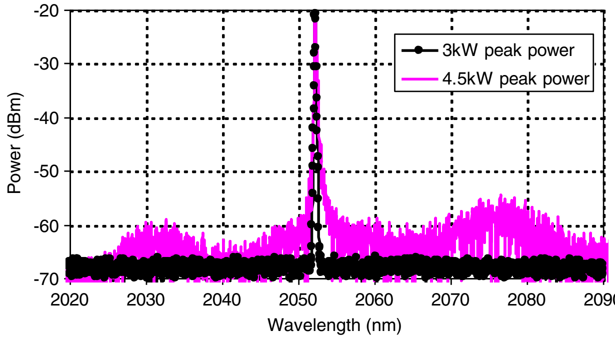

Fig. 5. (Color online) Optical spectra of the amplified laser pulses at ∼3 kW peak power (black) and ∼4.5 kW peak power (pink). MI side-bands appeared when the peak power was 4.5 kW.

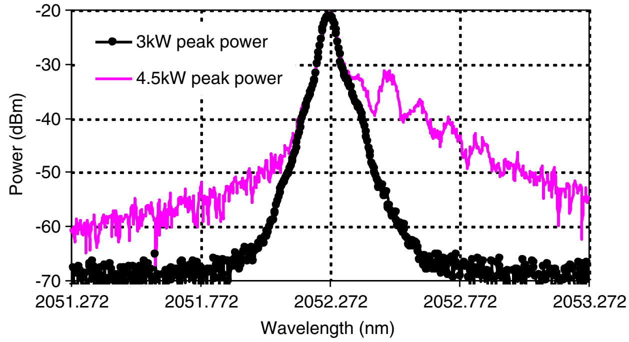

Fig. 6. (Color online) Zoom-in spectra of the amplified laser pulses at ∼3 kW peak power (black) and ∼4.5 kW peak power (pink). Stimulated Brillouin scattering appeared when the peak power was 4.5 kW.

as a function of pump power. The maximum extractable output power could reach 1.1 W at a pump power of 12 W with a slope efficiency of about 11%, corresponding to a maximum peak power of 7 kW approximately.

Two inset pictures in Fig. 4 show a typical pulse shape of the laser at two different average output powers, i.e., 500 and 750 mW. Since the pulsewidth was about 8 ns, the corresponding peak power was about 3 kW and 4.5 kW, respectively. It can be clearly seen that a small satellite pulse appears right after the main pulse when the peak power exceeds 3 kW, indicating strong nonlinear effects.

When observing the laser optical spectra, it is revealed that two different nonlinear effects are involved at a high peak power. One was four-wave mixing or modulation instability (MI), as we observed in another experiment with a kW-peak-power single-frequency Tm-doped fiber laser [9]. This kind of nonlinear effect was evidenced by the appearance of MI sidebands in the laser output spectra. Figure 5 shows the optical spectra of the amplified laser pulses at the two different peak powers. At relatively low power (∼500 mW average power or ∼3 kW peak power), no significant nonlinear effect was observed. But at higher pump power (∼750 mW average power or ∼4.5 kW peak power), two symmetrical broad side-bands gradually grew up at both spectral sides of the laser line with 40 dB signal-to-noise ratio and 20 nm spectral spacing.

The other kind of nonlinear effect can also be seen when zooming in the spectra, as shown in Fig. 6. Multiple spectral components appeared at the long wavelength side of the laser line when the peak power was 4.5 kW. These red-shift spectral components were assigned as the Stokes components of stimulated Brillouin scattering (SBS) since the spectral spacing between those components exactly corresponds to a Brillouin frequency shift. Thus, the satellite pulse appeing in the inset picture of Fig. 5 was also the result of SBS in the fiber amplifier. Obviously, the peak power (∼4.5 kW) of the single-frequency laser pulses was too high for 10 μm core fiber even at a fiber length of ∼2 m. To mitigate these two kinds of nonlinear effects, a simple solution is to use active fiber with larger core diameter for higher-power single-frequency pulsed output at 2.05 μm.

In summary, a single-frequency gain-switched Ho-doped fiber laser operating at a popular wavelength near 2.05 μm has been demonstrated by using heavily doped silicate glass fiber. The laser was pumped by a Q-switched Tm-doped fiber laser at 1.95 μm. Output peak power of the gain-switched single-frequency pulses has been amplified up to kilowatt level with 1.2 m double-cladding Tm-Ho-codoped fiber pumped at 803 nm. Both MI and SBS were observed when the peak power exceeds 3 kW with 10 μm-core fiber.

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