Dual-wavelength stable nanosecond pulses generation from cladding-pumped fiber laser

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In this paper, the generation of dual-wavelength stable nanosecond pulses by a laser diode pumped Yb-doped double-clad fiber laser is presented. In the experiment, the fiber laser with two-mirror cavity is approved which operates in a self-Q-switching regime. The Q-switching mechanism is based on stimulated Brillouin scattering (SBS). When the pump power achieves the SBS threshold, the fiber laser changes from the start resonator to the SBS resonator. With different reflectivities of the second mirror, stable dual-wavelength pulses with the pulse width range from 10 ns to less than 2 ns are obtained. The result was explained theoretically by birefringency (including stochastic birefringency and bend birefringency).

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Rare-earth-doped double-clad fiber (DCF) lasers can offer an excellent combination of high power laser output and good spatial beam quality[1−3]. DCF lasers have almost all the advantages of conventional fiber lasers and utilize relatively cheap high-power diodes for power scaling[4]. It is well known that Yb-doped DCF laser is a good laser candidate for generating tunable radiation in a wide wavelength range of 1.0—1.1 μm[5,6]. The combination of the cladding–pumping scheme and Q-switching leads to both high peak power and high pulse energy. High peak power pulse fiber lasers are attractive for medical and industrial applications, range finding, remote sensing, fiber sensors, and even optical parametric oscillators.

Because high intensity can be achieved in a fiber core, the stimulated Brillouin scattering (SBS) plays an important role in generating short pulses[7,8]. Recently, the pulse fiber lasers with the duration less than 5 ns were reported by use of the distributed SBS in a single-mode fiber as a passive Q-switching shutter[2]. For self-Q-switched fiber lasers based on SBS effect, the pulse duration is usually only a few nanoseconds and is independent of the cavity lifetime rather than the dependence of the dynamics of SBS in fibers. However, because of the nature of the nonlinear process in silica fibers, the repetition rate and the intensity of laser pulses are often unstable.

In this paper we report the generation of dual-wavelength, stable nanosecond pulses directly from cladding-pumped self-Q-switched fiber laser. With continuous wave (CW) pumping, the shortest pulse width of 1.4 ns was demonstrated and two wavelengths were observed from OSA. With increasing the reflectivity of the second cavity mirror, the laser pulse duration decreased.

The experimental setup is shown in Fig. 1. The fiber laser is pumped by a fiber coupled laser diode (LD) system. The output fiber diameter of the LD is 800 μm with numerical aperture (NA) of 0.22. We used D-shaped Yb-doped silica DCF (with inner cladding of 340×400 (μm), NA = 0.37) as the gain medium. The parameters of the fiber are fiber length of 20 m, the doping concentration of 0.65 mol% (Yb_2O_3), core diameter of 10.6 μm, and NA of 0.16. The pump light was launched into the inner cladding of the DCF through compound lens. Thus we calculated that the fiber core can support two transverse modes at 1.1 μm and more than 99% of the pump power was absorbed by the DCF.

A dichroic mirror with high transmission (HT) coating at 975 nm and high reflection (HR) at 1064 nm was attached to one end of the DCF as the input cavity mirror, with which and the other fiber end and a HR mirror ($R > 70\%$) to compose a two-mirror cavity. In details, the output emission of the fiber was collimated with a half-ball microlens, and then went to the reflective mirror. The light beam was partly feedback to the fiber and the other part went out of the cavity as the loss. The characteristics of output pulses were observed by fast photon detector and 500-MHz oscilloscope, and the spectrum was measured by an optical spectrum analyzer (OSA).

The comparison of the output characteristics between the two-mirror cavity and the resonator by using the

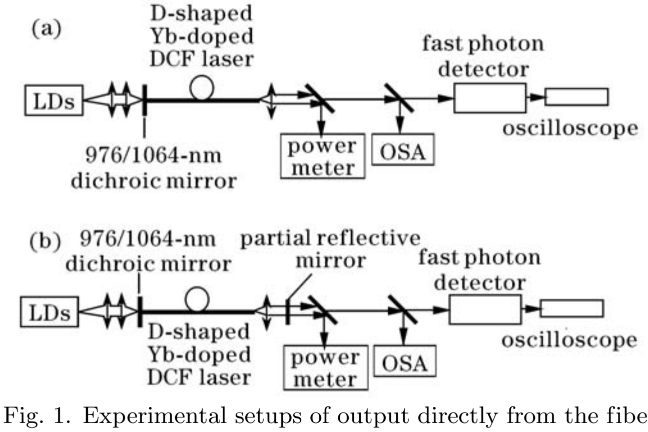

Fig. 1. Experimental setups of output directly from the fiber end (a) and two-mirror cavity resonator (b).

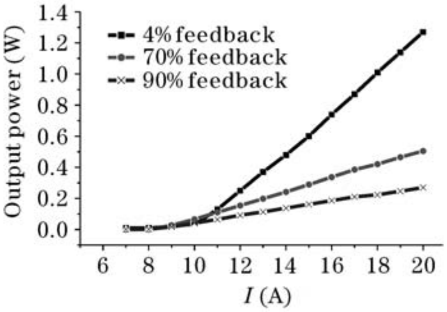

Fig. 2. Relationship between total output power and pump current when the fiber laser has 4% Fresnel feedback, 70% and 90% feedback.

Fresnel reflection of end surface of the fiber was shown in Fig. 2. It also gives the threshold and slope efficiency with 4% Fresnel feedback, 70%, and 90% feedback. By using a similar compound lens, we achieved the maximum pump power of 2.94 W. Without the second resonator mirror, there exists no external cavity, the fiber laser threshold P_{th} is 300 mW, maximum output power is 2.32 W, and slope efficiency is 86.6%. With 70% feedback, the threshold is 143 mW, slope efficiency is 29.5%. With 90% feedback, the threshold is 112 mW, slope efficiency is 13.6%. By comparison of the above results we found that the threshold decreased strongly with the end coupling of the resonator, the output power and the slope efficiency of the laser are reduced rather notably.

Once pump power P_{p} reached the laser threshold P_{th}, it would be lasing on. With two-mirror cavity configuration, output loss became less; the light intensity density inside the cavity was much higher than that of without the external cavity. Continuously increasing the pump power, at the beginning there exists irregular microsecond self-pulsing. The self-pulsing became stronger with the increase of the pump power, as shown in Fig. 3(a).

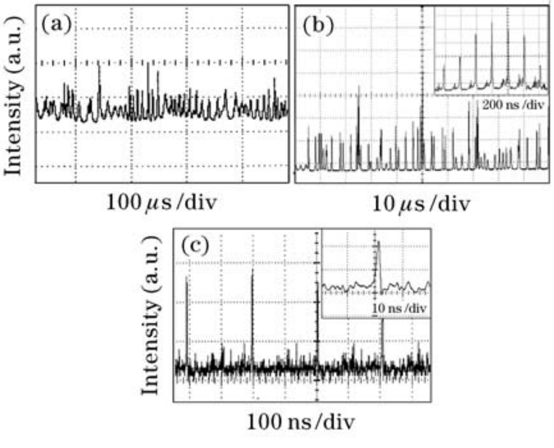

Fig. 3. (a) Spikes output when the pump power is higher than the laser threshold; (b) self-pulsing and its details when the pump power is near SBS threshold, the inset is the expending of one pulse; (c) charactersitics of stable output pulses, the inset is the expending of each SBS pulse.

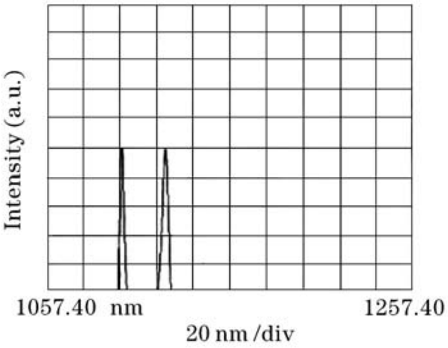

Fig. 4. Spectra of stable output pulses. $\lambda_1 = 1.1096$ μm, $\lambda_2 = 1.1276$ μm.

We get stochastic pulses on oscilloscope when P_{p} reaches the threshold of SBS effect P_{SBS}. At this time, microsecond pulses evolved into pulse trains. By researching the expanded pulse trains, we can find that each pulse train contains a lot of pulses, which is several tens of nanosecond in pulse width and the intensities of the nanosecond pulses are different, as shown in Fig. 3(b). If continuously increasing the pump power, the pulse number in one pulse train decreased. Further increasing P_{p}, from OSA we observed dual-wavelength laser output as shown in Fig. 4. The space between the two wavelengths was about 20 nm. From Fig. 3(c) it can be seen that the output characteristics in the time domain were stable, fixed period pulses. The period is about 206 ns, the repetition rate is 4.85 MHz, which is determined by the cavity length, and the amplitude flutter of the pulses on the screen is little. But pulse width is different with different end mirrors. With 70% reflectivity mirror, the pulse width is 10 ns, total mean output power reaches 505 mW. And for 90% reflectivity mirror, the pulse width is 1.4 ns, total mean output power reaches 270 mW.

In optical fibers the SBS threshold can be decreased to very low value, so the SBS reflectivity was obtained with CW pumping with very low pump power. Even to a high power fiber laser, the SBS has still the lowest threshold of the nonlinearities inside an optical active fiber.

Fiber laser typically starts to oscillate in the spiking regime. To the cladding-pumped Yb-doped fiber laser, because the Yb^{3+} ions have considerably longer fluorescence lifetime than the photons in the resonator, the fiber laser also starts to oscillate in the spiking regime. Therefore a spike grew up in the start resonator when the pump power reached the laser threshold. The spike power continues to grow in the start resonator until the SBS threshold is reached. Then the SBS reflectivity increases with the pump power rapidly. This increase happens in a much shorter time than the Q-switch-pulse duration. Thus the laser action changes from the start resonator to the SBS resonator, and a Q-switching pulse is emitted out of the SBS resonator. If the SBS threshold is not reached by the spike power, the SBS mirror is not activated and thus the fiber laser operates in the spiking regime only.

The pump light of the SBS effect is the laser signal generated in the start resonator of the SBS Q-switched fiber laser. When the pump power achieved SBS threshold, the laser resonator changed to SBS resonator, which was composed of dichroic mirror, the SBS reflection, and the reflector M. The reflectivity of SBS has a close relationship with the reflectivity of $M^{[9]}$. Thus, the pump power of SBS is higher when the reflectivity of M increased, as a result the feedback generated by SBS also increased. Furthermore, the duration of the laser pulses became narrower because of the co-action of SBS reflection and the second output mirror. The phenomenon of the pulse duration decreased with the reflectivity of M was explained.

The dual-wavelength ($\lambda_1 = 1.1096$ μm, $\lambda_2 = 1.1276$ μm) is a consequence of the birefringence. Generally the stochastic birefringence $B_{\rm st}$ is form 10^{-5} to 10^{-6}, which is corresponded to the fiber drawing process[10]. Furthermore winding up the fiber will also result in the bending birefringence[10], to the fused quartz, $B_{\rm bend} = 0.093(A/R)^2$, where A is the fiber outsider diameter and R is the bend radium. In the case of our experiments, we assumed that there exist no other acting forces, when $A = 300$ μm and $R = 10$ cm, then $B_{\rm bend} = 0.837 \times 10^{-6}$. Utilizing the equation $\Delta n = B_{\rm st} n$, and the wavelength separation formula $\Delta\lambda = \lambda^2/(\Delta n \cdot L)$, we get $\Delta\lambda$ among 4.0—22 nm, which is agreed with the results. We observed 5 wavelength outputs at most. Then we can conclude that the birefringence consists of two part, one is the stochastic birefringence, the other is bending birefringence. The birefringence results in the generation of stable, nanosecond pulses from Yb-doped DCF laser.

In conclusion, in this paper the generation of dual-wavelength, a stable nanosecond pulse directly from cladding-pumped self-Q-switched fiber laser is presented. With CW pumping, the shortest pulse duration of 1.4 ns of the giant pulse train was demonstrated and from OSA we observed two wavelengths.

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