Demonstration of fiber pulsed light source at 1.6 μm with adjustable pulse duration

Xue Feng (冯 雪), Lei Zhang (张 磊), and Xiaoming Liu (刘小明)

Department of Electronic Engineering, Tsinghua University, Beijing 100084

Received October 19, 2006

A novel practical 1.66-μm pulse light source with adjustable pulse duration is proposed. A 2.5-km Raman fiber is placed into a ring type Q-switched erbium-doped fiber laser (Q-EDFL), serving as both delay line fiber and Raman gain medium so that in addition to the wavelength shifted to 1.6 μm, the pulse duration and the buildup time can be relatively extended. By properly controlling the fall edge of the acousto-optic switch (AOS), the pulse duration of 30—345 ns for $\sim$ 770-Hz repetition frequency with power of 1—1.6 W is achieved.

OCIS codes: 140.3500, 140.3540, 190.5650.

Pulsed light source has wide applications in optical time-domain reflectometry (OTDR) type of information systems, such as fiber distributed temperature sensing (FDTS) based on spontaneous Raman scattering[1,2]. In the earlier works, 1.5-μm Q-switched erbium-doped fiber laser (Q-EDFL) is widely used because the Q-EDFL can easily provide high-power, low repetition frequency, and short pulses at fiber's low loss window with practical, efficient diode pumping sources[3]. Lately, the pulsed source at 1.6 μm is proposed because the weak temperature dependent on anti-Stokes signal can fall onto the low-loss window of transmission fiber around 1.5 μm[4] and the output pulse from Q-EDFL is easily shifted to 1.6 μm by the stimulated Raman scattering (SRS) in a single mode fiber.

For Raman FDTS, one meets a conflict that the spatial resolution can be improved by decreasing the pulse duration[5], but the intensity of the backscattered signal will be weakened down due to the reduction of the power integration over the pulse duration[5]. Meanwhile, wider detector bandwidth is required as the pulse duration decreases, which will introduce more noise into the detector[6]. On the other hand, the pulse peak power must be limited below 1—2 W to avoid the stimulated Brillouin scattering (SBS) and SRS[3], so the achievable signal to noise ratio (SNR) is limited. To achieve sufficient SNR, numerous measurements with average treatment of data are usually required, since the SNR can be improved by a square-root of the averaged times[6]. As a result, the average time will be increased and the refreshing time interval of the FDTS system may become rather long if high spatial resolution is necessary.

In this letter, we propose a novel 1.6-μm pulse light source with adjustable pulse duration to solve the conflict that the long pulse duration with the short refreshing time is employed to monitor the temperature variation while the short pulse duration with the relatively long refreshing time is used to locate accurately the position of the exceptional temperature. A long Raman fiber is placed into a ring type Q-EDFL, serving as delay line fiber and Raman gain medium, so in addition to the wavelength shifted to 1.6 μm, the pulse duration and also the buildup time can be relatively extended. Then by adjusting the open duration of the acousto-optic switcher (AOS), the rear part of the pulse is truncated and the pulse duration is varied. Experimentally, 30—345 ns duration for 770-Hz repetition frequency with about $1-1.6$ W optical peak power at 1.6 μm is demonstrated, which corresponds to a spatial resolution of 3—34.5 m.

The scheme of our proposed fiber light source is shown in Fig. 1. The ring cavity is composed of an erbium-doped fiber amplifier (EDFA), an AOS, a Raman gain fiber, and a 1.5 μm/1.6 μm output wavelength divided multiplexing (WDM) coupler. Here, the Raman gain fiber also acts as a delay line. AOS is driven by a low repetition pulse signal with the open interval larger than the cavity round-trip time. During the time of AOS closed, Q value of the cavity is low and the population inversion is accumulated. Once AOS opens, the initial amplified spontaneous emission (ASE) starts to travel around the cavity. At the beginning, both the ASE power and Raman gain are low, so there is no 1.6-μm light output from the WDM coupler. After one or more round-trip, the ASE power increases and huge optical power builds up via the amplification of EDFA. Meanwhile, 1.6-μm output power grows up via the Raman gain. Then the huge optical power depletes the population inversion quickly, so the optical power drops down so that single or multiple optical pulses are formed. The number of pulses, the pulse duration, and the pulse buildup time are related to the cavity length, cavity loss, and the ratio of the population inversion at the moment of AOS closing and

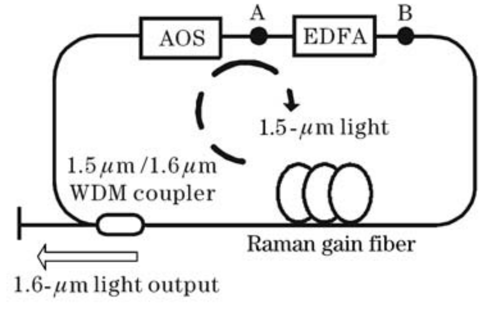

Fig. 1. Schematic of the 1.6-μm ring laser with adjustable pulse duration.

1671-7694/2007/020099-03 © 2007 Chinese Optics Letters

opening, the AOS open interval, and its rise/fall time[3]. In general Q-EDFL, as short as several tens meters cavity length is usually employed to achieve about several tens nanoseconds of pulse duration with several hundred nanoseconds of buildup time.

Different from general Q-EDFL, as long as several kilometers delay fiber is introduced in the scheme, the round-trip time of the cavity τ_r is in the order of tens of microsecond, consequently the pulse duration and the buildup time can be quite long. If the close time of AOS is set properly, the rear tail of the Q-switched pulse is truncated, so the shorter and adjustable pulse duration is achievable. It is worth mentioning that, 1.5-μm pulsed power builds up inside the cavity without output loss before the power becomes high enough to achieve sufficient Raman amplification, which is favored for the initial power accumulation and the multi-peak structure in general Q-EDFL is clean up in the 1.6-μm output. Furthermore, low speed AOS driven by low frequency signal is enough to achieve short optical pulse duration since the pulse buildup time is long, which makes the proposed light source practical for real applications.

The experimental setup is the same as Fig. 1. Figure 2 is the detail configuration of the used EDFA, which consists of two erbium-doped fibers (EDFs) with 7 and 9 m in length. A 980-nm laser diode (LD) pumps both EDFs through a 1:1 coupler (coupler1). A circulator with a fiber Bragg grating (FBG, $\lambda = 1552.8$ nm, 3-dB bandwidth 0.1 nm) is inserted between AOS and the input end of EDFA to ensure the wavelength of Q-switched pulse within the best isolation wavelength range of 1550 nm/1650 nm WDM coupler. At the output end of EDFA, a 99:1 coupler (coupler2) is used to inspect the optical power at 1.55 μm. The length of Raman gain fiber is 2.5 km, which results in the round-trip time of 13 μs. The peak Raman gain coefficient and frequency shift are 2.5 W/km and 13.5 THz, respectively. The attenuation of the Raman fiber is measured to be about 1.5—1.6 dB within 1540—1670 nm, including the splicing loss. The AOS (26027-2-1.55-FO-1st NEOS) is driven by an electronic function generator (KENWOOD FG-273A) with adjustable repetition frequency of 0—2 MHz and duty cycle of 1:1—1:50. The total loss of the passive ring cavity (without EDFA) is measured to be about 8.4 dB/> 60 dB at 1552.8 nm when the AOS is open/closed. The best isolation of output WDM coupler is about 21 dB, another 1550 nm/1650 nm WDM coupler is followed (not shown in the figure) to achieve about 41.7-dB isolation, so that all of the output power from WDM is purely at 1.66 μm, while most of 1.55-μm power is still inside the cavity.

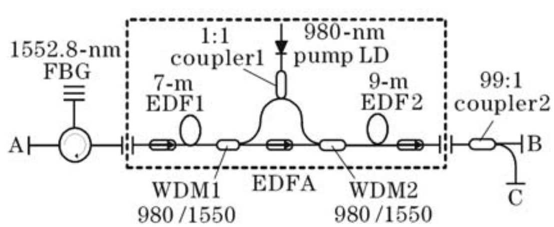

Fig. 2. Detail configuration of EDFA with the FBG and coupler.

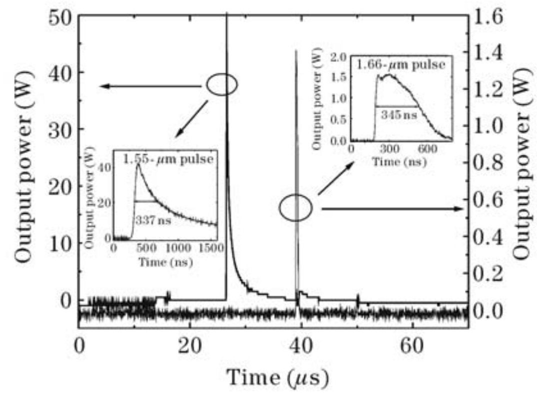

Fig. 3. Measured 1.55- and 1.66-μm pulses while $\tau_d \approx 1$ ms.

First, the pump power was set at ~ 75 mW, and the AOS was set at 500 Hz in repetition frequency and 1:1 in duty cycle. The corresponding open duration was $\tau_d \approx 1$ ms, which is much longer than the round-trip time of 13 μs. The optical pulses at 1.55 and 1.66 μm were measured at coupler2 (point C) and cavity output by using a high speed PIN detector with an oscilloscope. Additional ~ 36-dB attenuation was inserted before the PIN detector to avoid saturation. The optical power can be estimated through the data from oscilloscope with the calibration of loss. Figure 3 is the measured pulses, where the zero of time is triggered by the rising edge of the driving signal, which is also the moment that the AOS is opened. It can be seen that a 1.55-μm peak with about 43-W peak power appears after about $2\tau_r$ (26 μs), the full-width half maximum (FWHM) is ~ 337 ns as shown in the left inset. A 1.66-μm peak appears after about $3\tau_r$ (39 μs) with ~ 1.6-W peak power and ~ 345-ns FWHM as shown in the right inset. The time difference between the two pulses is about τ_r, because the 1.66-μm peak is measured after one more τ_r through the Raman gain fiber.

The open duration of AOS can be adjusted by setting different repetition frequencies and duty cycles. For example, if the setting is at 770 Hz with 1:50, τ_d is about 26 μs, which is almost the time of 1.55-μm peak showing up, so that the rear trail of the pulse may be truncated. The rise/fall time of the used AOS is ~ 70 ns. Figures 4(a) and (b) are the measured pulses for 1.55- and 1.66-μm, respectively, when τ_d is varied from 25097 to 25981 ns. It can be seen that the trail tails of the pulses are truncated more and more as τ_d decreases.

For clarity, the measured peak power and FWHM are summarized in Fig. 5. The solid squares and dots represent the FWHM for 1.55- and 1.66-μm while the open squares and circles represent the peak powers, respectively. In range of $\tau_d > 25500$ ns (range I), although the trail is truncated by the fall edge of AOS, the main part of the pulse is almost not affected, so the peak power and FWHM are nearly constant. In range of 25500 ns $> \tau_d >$ 25200 ns (range II), the main part of pulse starts to be truncated so the FWHM is reduced linearly with τ_d, while the peak powers are still constant because the highest peak is still not affected yet. In both ranges I and II, the FWHM for 1.66 and 1.55 μm is almost same, while the peak powers are nearly consistent with each

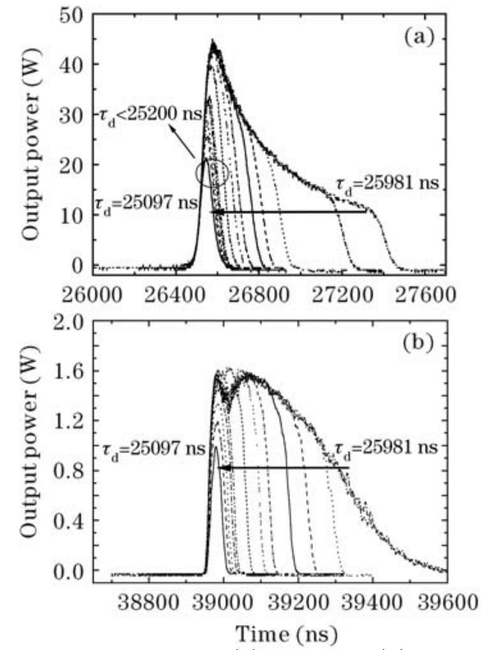

Fig. 4. Measured pulses at (a) 1.55 and (b) 1.66 μm when the AOS's open duration is varied.

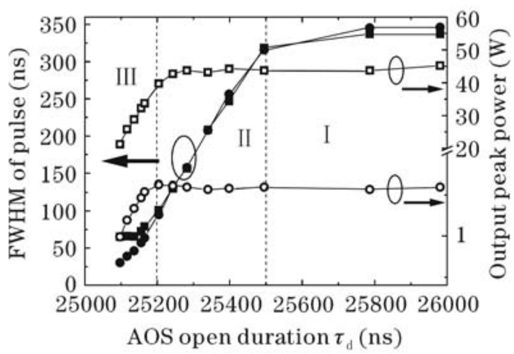

Fig. 5. Summarized results of pulse durations at 1.55 (solid squares) and 1.66 μm (dots) and peak powers at 1.55 (open squares) and 1.66 μm (circles) for AOS open duration $\tau_{\rm d}$.

other. But in range of $\tau_{\rm d} < 25200$ ns (range III), the open interval of AOS is reduced more, even the rising edge of the pulse is truncated, so the peak powers and also FWHM are reduced. However, the FWHM of 1.55 μm is never below 66 ns while that of 1.66 μm is further reduced to about 30 ns. The reason is that, as the rising edge is truncated more, both amplitude and width of 1.55 μm-pulse are reduced, so FWHM is varied little; while as power is lowered down, the power of the pulse's edge part is not high enough to achieve sufficient Raman gain, so the edge of 1.66-μm pulses is cut down. The best result at 1.66 μm is about 100 ns of FWHM with as high as possible 1.6-W peak power, when $\tau_{\rm d}$ is about 25200 ns. Or we can choose about 30 ns of FWHM with about 1-W peak power. If further improvement is desired, shorter rise/fall time of AOS with optimization of all the parameters may be helpful.

Aimed at Raman FDTS applications, a novel practical 1.66-μm pulse light source with adjustable pulse duration is proposed. In stead of short cavity length in general Q-EDFL, a long Raman fiber is used as both gain medium and delay line, so the resulted pulse duration and buildup time are relatively long. By properly controlling the fall edge of the AOS, the rear tail of the pulse is truncated and variation of pulse duration is realized. Experimentally, pulses duration range from 30 to 345 ns for 770-Hz repetition frequency with power of 1—1.6 W at 1.66 μm is demonstrated, which corresponds to spatial resolution range from 3 to 34.5 m for about 130-km sensing length.

X. Feng's e-mail address is x-feng@tsinghua.edu.cn.

References

1. A. Hartog, Proc. SPIE **4578,** 43 (2002).
2. J. S. Namkung, C. W. Aude, A. C. Lavarias, R. S. Rogowski, and M. L. Hoke, Proc. SPIE **1918,** 82 (1993).
3. S. Adachi and Y. Koyamada, J. Lightwave Technol. **20,** 1506 (2002).
4. H. H. Kee, G. P. Lees, and T. P. Newson, Proc. SPIE **4074,** 280 (2000).
5. R. Feced, M. Farhadiroushan, V. A. Handerek, and A. J. Rogers, IEE Proc.-Optoelectron. **144,** 183 (1997).
6. M. Wegmuller, F. Scholder, and N. Gisin, J. Lightwave Technol. **22,** 390 (2004).