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Wavelength tunable passively mode-locked bismuth oxide-based erbium-doped fiber laser

Hideyuki Sotobayashi *, Juliet T. Gopinath, Elisabeth M. Koontz [1], Leslie A. Kolodziejski, Erich P. Ippen

Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

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Abstract

The broadband gain of bismuth oxide-based erbium-doped fiber has been used to obtain wavelength-tunable mode-locking over a 30 nm range from 1570 to 1600 nm. Passive mode-locking using a proton-bombarded semiconductor saturable absorber mirror produces 2.2-ps pulses at a repetition rate of 17 MHz. After external frequency chirp compensation, 288-fs pulses are obtained at 1600 nm.

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Keywords: Fiber lasers

1. Introduction

The development of optical amplifiers that open up new amplification wavelength bands is key to expanding the usable bandwidth of optical transport systems. In particular, rare-earth-doped fiber amplifiers using new host materials are particularly promising for fiber systems. Thulium-doped fiber amplifiers can provide gain in the 1480–1510 nm wavelength band, opening access to wavelengths shorter than those of conventional silica-based erbium-doped fiber amplifiers (EDFAs) [1]. Tellurite-based erbium-doped fiber amplifiers have a gain bandwidth of 76 nm that covers not only the conventional gain band of the silica based EDFA but also somewhat longer wavelengths [2]. Bismuth oxide (Bi_2O_3) based EDFAs (Bi-EDFAs) are also promising for broadband signal amplification around 1550 nm [3–5]. CW signal amplification over the range of 1520–1620 nm using a Bi-EDFA has been demonstrated [3] and picosecond pulse amplification in the 1520–1600 nm band has been observed [5].

In this paper, we report demonstration of passive mode-locking of a bismuth oxide-based erbium-doped fiber laser (Bi-EDFL) that is tunable

* Corresponding author. Tel.: +1-617-253-8949; fax: +1-617-253-9611.
E-mail address: hideyuki@mit.edu (H. Sotobayashi).
[1] Silicon Technology Development, Texas Instruments Inc., 13560 North Central Expressway, Dallas, TX 75243, USA.

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over the wavelength range of 1570–1600 nm. Two key optical devices are a Bi-EDFA for 1570–1600 nm pulse amplification and a proton-bombarded semiconductor saturable absorber mirror as the mode-locking element. At a 16.6 MHz repetition rate, 2.2-ps pulses are obtained with a 30 nm wavelength tuning range between 1570 and 1600 nm. With external frequency chirp compensation, these pulses are compressed to a pulsewidth of 288 fs. Conventional silica based EDFAs can be used to make a L-band fiber laser by careful optimisation of the fiber length, doping concentration, and the pump power [6]. The broad gain-bandwidth with high gain of bismuth oxide-based erbium-doped fiber (Bi-EDF) now simplifies the laser and makes mode-locked fiber laser operation more readily available for the longer wavelengths of increasing importance to optical communication systems and optical sensing. The shorter gain lengths required with Bi-EDFLs also will make more compact geometries possible.

2. Experiments and discussion

Fig. 1 shows the experimental setup of the passively mode-locked Bi-EDFL. The laser is set-up in a Fabry–Perot configuration, using Bi-EDF as the gain medium [3–5], with a proton bombarded saturable absorber mirror at one end of the cavity [7]. A Bi-EDF length of only 55.6 cm is needed for sufficient gain in the 1570–1600 nm band [5]. This is enabled by the high concentration of erbium ions possible in the Bi_2O_3-based glass. The Er concentration of the Bi-EDF used was 6470 wt ppm. The refractive index of core was 2.03 and that of the cladding 2.02 at 1550 nm. Both ends of the Bi-EDF were fusion spliced to SiO_2 fibers. The Bi-EDF was bi-directionally pumped with two 975 nm diodes. The semiconductor saturable absorber mirror must have a short recovery time as well as high nonlinearity and low nonsaturable loss for the mode-locking mechanism [7–9]. Fig. 2 shows a schematic of our proton-bombarded semiconductor saturable absorber mirror [7]. It consists of a 22-pair AlAs/GaAs mirror with greater than 99.9% reflectivity at 1550 nm. A half-wave layer of InP on top of the mirror contains six centered InGaAs quantum wells with a band edge of 1580 nm. The structure was anti-reflection coated with a single $\lambda/4$ layer of Al_2O_3. The absorber was proton bombarded with 40 keV protons at a dose of 10^{14} protons/cm^2 to reduce the recovery time to 3 ps. The maximum modulation depth was 5%. A 15 nm bandwidth tunable optical filter was used to tune the center wavelength of the

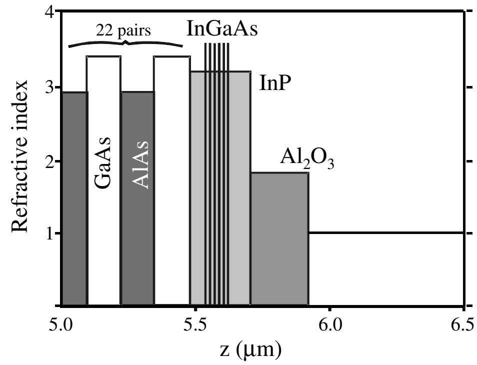

Fig. 2. Schematic of the proton-bombarded semiconductor saturable absorber mirror.

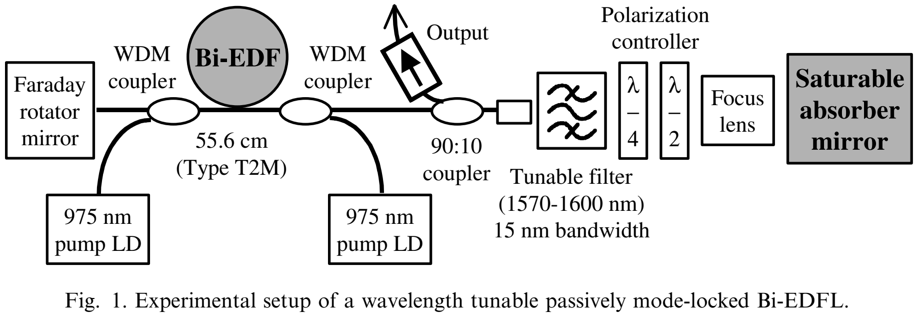

Fig. 1. Experimental setup of a wavelength tunable passively mode-locked Bi-EDFL.

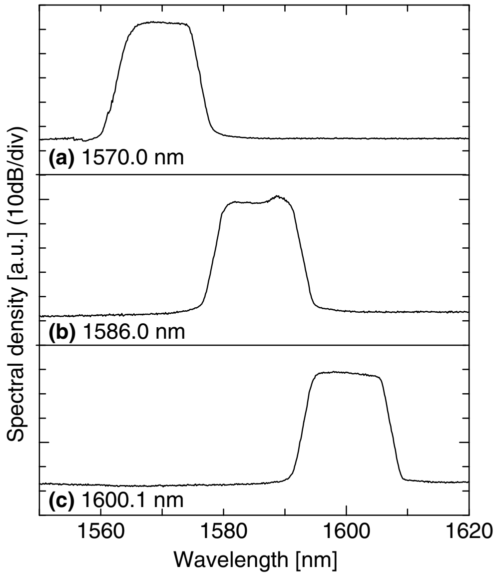

Fig. 3. Optical spectra of the output laser pulse at: (a) 1570.0 nm; (b) 1586.0 nm; (c) 1600.1 nm.

laser. A Faraday rotator mirror was placed at one end of the laser cavity in order to suppress the effects of the polarization fluctuation inside the cavity, and a 10% coupler was used as an output port.

Fig. 3(a)–(c) shows the optical spectra of the laser output at three different wavelengths. The center wavelength was tuned from 1570 to 1600 nm using an optical filter. The spectral widths varied from 9.1 to 9.8 nm. The signal-to-noise ratio in the optical spectral domain was greater than 47 dB in each case. Fig. 4(a)–(c) shows the sampling oscilloscope traces of the output pulses at 1570, 1586, and 1600 nm, respectively, measured using a 3 GHz bandwidth photodetector. In order to avoid multiple pulsing [10], the pump powers were set at 255 and 168 mW. The output powers when the laser was at the fundamental repetition rate were 596 μW at 1570.0 nm, 421 μW at 1586.0 nm, and 340 μW at 1600.1 nm, respectively. Fig. 4(d) shows the measured RF spectrum of the laser output at 1600 nm. The repetition rate was 16.56 MHz and the signal-to-noise ratio in the RF spectral domain was 60.1 dB. The output pulse width was measured using an autocorrelator, and the pulse width was estimated assuming a hyperbolic secant pulse shape. As shown in Fig. 5, the full widths at half maximum (FWHM) of the pulses and the time-bandwidth products were 2.20 ps and 2.51 at 1570.0 nm, 2.26 ps and 2.53 at 1586.0 nm, and 2.16 ps and 2.72 at 1600.1 nm,

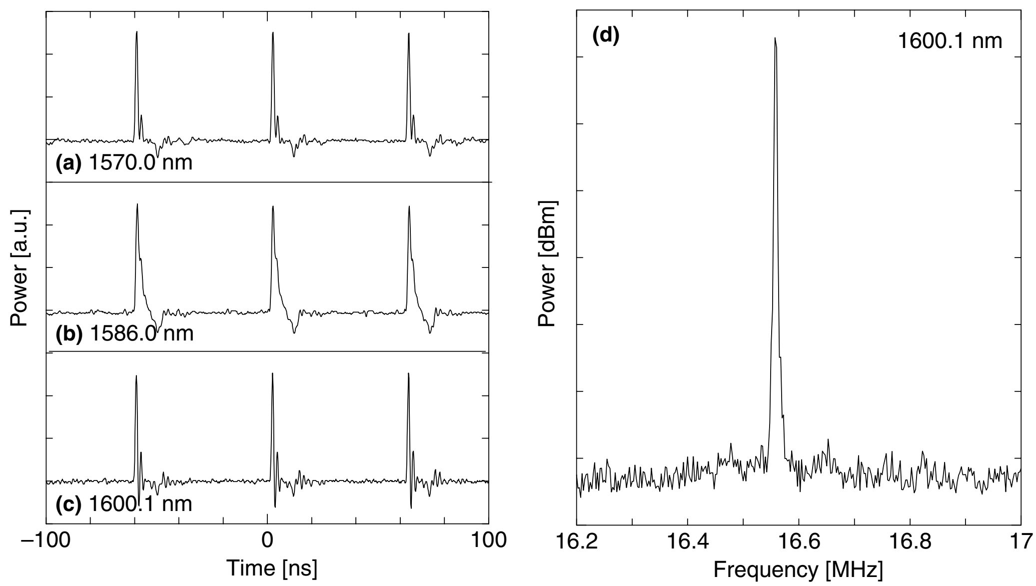

Fig. 4. Sampling oscilloscope traces of the output laser pulses at: (a) 1570.0 nm, (b) 1586.0 nm, (c) 1600.1 nm, respectively. And (d) the RF spectrum of the output laser pulse at 1600.1 nm.

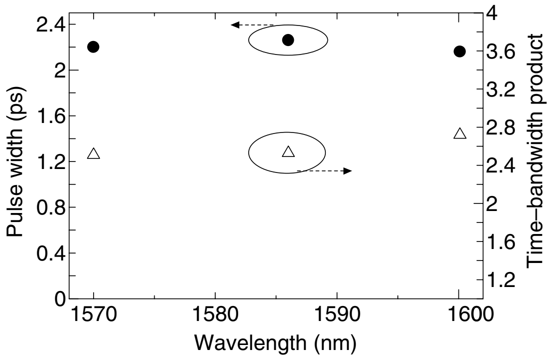

Fig. 5. Pulse width and the time-bandwidth product versus the center wavelength of the output laser pulse.

respectively. The large time-bandwidth products are consistent with the fact that the output laser pulses were highly chirped because of the net normal group velocity dispersion of the laser cavity. These chirped laser pulses were easily compressed by external cavity dispersion compensation. A 100-m large-effective-area non-zero dispersion shifted single-mode fiber was used for the compensation. The total dispersion value was -356×10^{-27} at 1600 nm. Fig. 6 shows the autocorrelation traces of the laser output pulse and the compressed pulse. The compressed pulse width was 288 fs and the time-bandwidth product was 0.35. This was almost transform-limited.

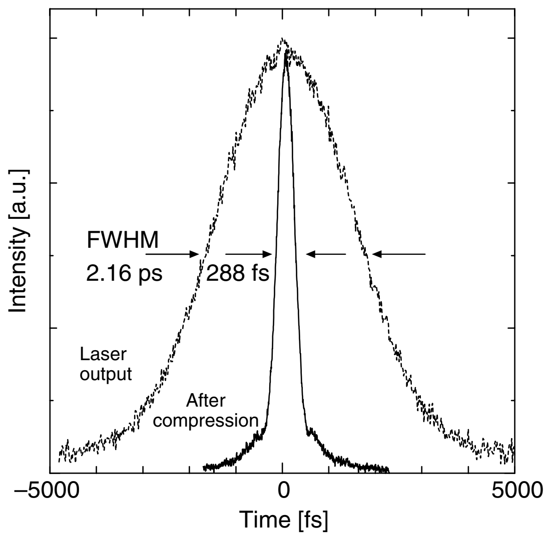

Fig. 6. Autocorrelation traces of the laser output pulse and the compressed pulse at 1600.1 nm. A hyperbolic secant pulse shape is assumed.

3. Conclusions

In conclusion, we have demonstrated a wavelength tunable passively mode-locked fiber laser using a Bi_2O_3-based EDFA and a fast semiconductor saturable absorber. A 2.2-ps pulse train at 16.6 MHz has been obtained with a wavelength tuning range from 1570 to 1600 nm. By external frequency chirp compensation, transform-limited 288-fs pulses train were obtained at 1600 nm. The tuning range of the laser was limited by the optical filter. However, considering the gain bandwidth of the Bi-EDF, the wavelength tunability with nearly 100 nm should be possible in the 1550 nm region. These results showed one of the promising applications of the newly developed potential optical fiber amplifier, which will be important in telecommunications, photonic processing, and optical sensing that utilize the longer wavelength band.

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References

[1] S. Aozasa, H. Masuda, H. Ono, T. Sakamoto, T. Kanamori, Y. Ohishi, M. Shimizu, 1480–1510 nm-band Tm doped fiber amplifier (TDFA) with a high power conversion efficiency of 42%, in: Proceedings of the Optical Fiber Communication Conference (OFC 2001), paper PD1, Anaheim, March 2001.
[2] M. Yamada, A. Mori, K. Kobayashi, H. Ono, T. Kanamori, K. Oikawa, Y. Nishida, Y. Ohishi, IEEE Photon. Technol. Lett. 10 (9) (1998) 1244.
[3] N. Sugimoto, J. Am. Ceram. Soc. 85 (2002) 1083.
[4] K. Taira, K. Kikuchi, N. Sugimoto, Dispersion and pulse amplification characteristics of bismuth oxide-based er-

bium doped fiber amplifiers, in: Proceedings of the Optical Amplifies and Applications Conference (OAA 2002), paper OTuC2, Vancouver, July 2002.
[5] H. Sotobayashi, J.T. Gopinath, E.P. Ippen, IEE Electron. Lett. 39 (19) (2003) 1374.
[6] K. Tamura, Y. Kimura, M. Nakazawa, IEE Electron. Lett. 31 (13) (1995) 1062.
[7] Y. Kuroiwa, N. Sugimoto, K. Ochiai, S. Ohara, Y. Fukasawa, S. Ito, S. Tanabe, T. Hanada, Fusion spliceable and high efficient Bi_2O_3-based EDF for short length and broadband amplification pumped at 1480 nm, in: Proceedings of the Optical Fiber Communication Conference (OFC 2001), paper TuI5, Anaheim, March 2001.
[8] J.T. Gopinath, E.R. Thoen, E.M. Koontz, M.E. Grein, L.A. Kolodziejski, E.P. Ippen, J.P. Donnelly, Appl. Phys. Lett. 78 (22) (2001) 3409.
[9] E.R. Thoen, E.M. Koontz, D.J. Jones, F.X. Kartner, E.P. Ippen, L.A. Kolodziejski, IEEE Photon. Technol. Lett. 12 (2000) 149.
[10] B.C. Collings, K. Bergman, S.T. Cundiff, S. Tsuda, J.N. Kutz, J.E. Cunningham, W.Y. Jan, M. Koch, W.H. Knox, IEEE J. Sel. Top. Quant. Electron. 3 (4) (1997) 1065.