An Electronically Wavelength-Tunable Mode-Locked Fiber Laser Using an All-Fiber Acoustooptic Tunable Filter

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Abstract—**We have demonstrated a novel scheme of a continuously wavelength-tunable and passively mode-locked fiber laser by using the sliding frequency effect of an all-fiber acoustooptic tunable filter. Stable and nearly transform-limited pulses of 800-fs pulsewidth were produced with this laser scheme for a wavelength tuning range of 17 nm at around 1550 nm.**

ULTRASHORT pulse generation from fiber lasers is one of the challenging subjects in all-fiber optic telecommunication technologies. A variety of actively and passively mode-locked fiber laser schemes have been investigated for the short pulse generation [1]–[5]. Among them, the passively mode-locked fiber laser schemes are known to be superior in delivering stable short laser pulses of high peak powers.

An additional wavelength-tuning capability of the passively mode-locked fiber lasers has been recognized as an important parameter for application to wavelength-division multiplexing (WDM) systems. Recently, pulse-generation schemes utilizing the combined action of frequency shifting and spectral reshaping induced by the nonlinear spectral broadening and filtering effects have been demonstrated to achieve wavelength-tunable and stable short laser pulses [6]–[10]. These schemes are similar to the sliding-frequency guiding filter method used for soliton jitter control [11]. A demonstration of a sliding-frequency soliton laser in an all-fiber configuration incorporating an acoustooptic filter/frequency shifter based on a null coupler has been also reported in [10]. The all-fiber filter/frequency shifter have a very low insertion loss compared to the bulk-optic counterparts such as the Fabry–Perot filter and the Bragg-cell in [8]. However, the continuous wavelength tuning over only a few nanometers and relatively long pulses of 18-ps width have been achieved with this all-fiber device because of the imperfect filter characteristics of the device showing a few number of transmission peaks beside the main transmission peaks.

Recently, we have demonstrated a stable and easy-starting 340-fs passively mode-locked fiber laser by utilizing a nonlinear amplifying loop mirror (NALM) [12]. The optimum condition for a nonlinear interference in the NALM to initialize the passive mode-locking mechanism was fulfilled by use of a Faraday rotating mirror (FRM) attached to it. In this letter, we describe the first experimental demonstration of a wavelength tunable and sliding-frequency mode-locked fiber laser operation in an NALM-FRM geometry with an all-fiber acoustooptic tunable filter (AOTF)/frequency shifter based on two-mode fiber. Stable and high-peak powered pulses of subpicosecond pulselength were obtained in a wavelength range of 17 nm which is the widest tuning range ever achieved with the fiber lasers incorporating the AOTF.

The schematic diagram of our experimental setup for the NALM-FRM laser is shown in Fig. 1. The mode-locking mechanism is based on the saturable absorber role of the NALM. The NALM consists of a 48:52 fiber coupler, a polarization controller, an erbium-doped fiber, a WDM fiber coupler, a pump laser diode, and a dispersion-shifted fiber. The linear mirror section is composed of a polarization controller, an AOTF, and a FRM. The FRM was used to eliminate the linear phase drift between the two polarization eigenmodes of the cavity. The NALM-FRM cavity laser delivers an environmentally stable output, and its lasing condition is easily initiable compared to the passive mode-locking condition of the conventional figure-of-eight fiber lasers [12]. The all-fiber AOTF is placed between the FRM and the NALM. The amplifier section comprises a 10-m-long erbium-doped fiber of 800-ppm concentration and a quantum-well laser diode of 980-nm pump wavelength. The output pulses are extracted from the transmission port of the NALM and are monitored with a background free autocorrelator, a power meter, an oscilloscope, and an optical spectrum analyzer. The lengths of the NALM and linear section are 29 m and 10 m, respectively. The total optical path corresponding to the measured axial mode spacing of 4.2 MHz is about 49 m long.

The schematic diagram of the all-fiber AOTF used in our experiment is shown in Fig. 2. The primary operating mechanism is based on the mode coupling between the LP_{01} and LP_{11} modes in a two-mode fiber influenced by a flexural acoustic wave. The AOTF operates as a bandpass filter along with a static mode converter inserted before the second mode stripper as shown in Fig. 2. Light circulating in the laser cavity

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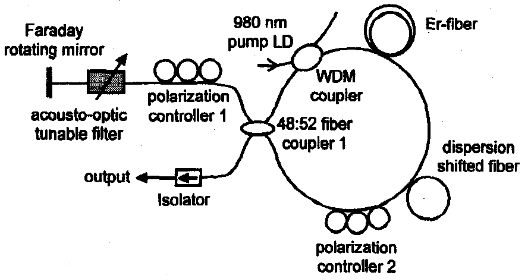


Fig. 1. Schematic diagram of the experimental set-up.

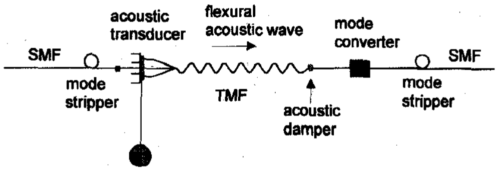


Fig. 2. Schematic diagram of the all-fiber AOTF.

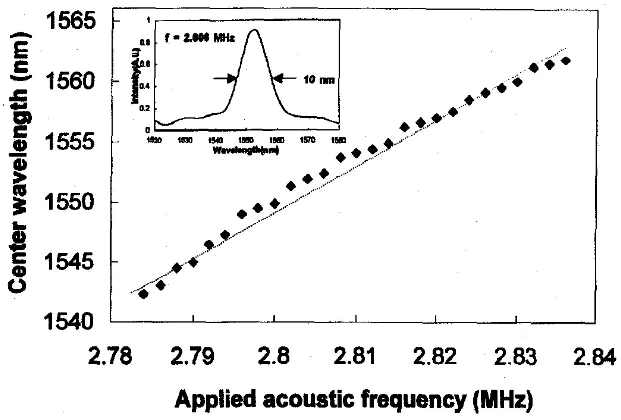


Fig. 3. Tuning curve of AOTF with an inset showing the transmission peak at an acoustic drive frequency of 2.806 MHz.

shown in Fig. 1 experiences a frequency shift of twice the acoustic frequency per round-trip [13]. The flexural acoustic wave guided along the fiber produces a mode coupling only for spectral components whose beat length is the same as the acoustic wavelength. For a given acoustic wavelength, the mode conversion efficiency depends on the optical wavelength because of the wavelength dependence of the beat length. Therefore, the center wavelength of the filter can be tuned by adjusting the acoustic frequency. The fiber used in the device was specially designed so as to guide the two spatial modes at $\lambda = 1550$ nm.

Fig. 3 shows the tuning curve of the AOTF measured with the broadband polarized ASE of a semiconductor laser amplifier. Continuous tuning of the center wavelength was obtained over 20 nm from 1542 nm to 1562 nm, as the acoustic frequency was varied from 2.784 MHz to 2.838 MHz. The measured center wavelength line slightly deviated from the linear dependence on the applied acoustic frequency, which is mainly attributed to the mode interference due to an imperfect mode conversion of the static mode converter in the AOTF. The inset of Fig. 3 shows the typical spectral response of the AOTF at 2.806 MHz. The 3-dB bandwidth of the AOTF was about 10 nm, as expected from the fiber design parameter and the acoustooptic interaction length of 7 cm in the AOTF. The measured total insertion loss of the AOTF was about 1.5 dB, including the splice loss between the two-mode fiber and conventional single-mode fibers, which is about 0.3 dB for each splicing point.

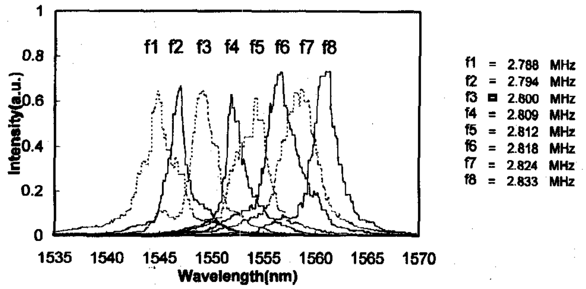
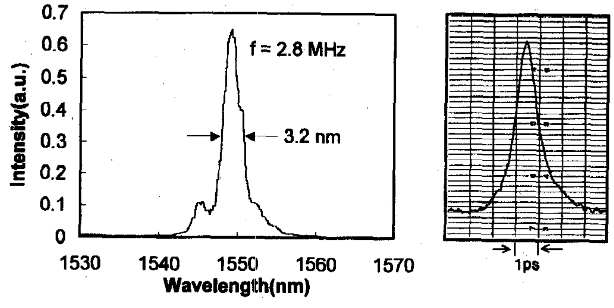


Fig. 4. Wavelength-tuned laser outputs according to the frequencies applied to the AOTF.



(a) (b)

Fig. 5. Optical spectrum and autocorrelation trace of the mode-locked laser output at a fixed frequency of the AOTF.

The threshold pump power of the NALM-FRM laser shown in Fig. 1 was about 7 mW. At the pump power levels higher than 15 mW, the passively mode-locked condition at the fundamental cavity frequency was easily achieved. The CW lasing was suppressed by the frequency shift and filtering action of the AOTF. However, pulsed mode lasing can be reshaped after the frequency shift and filtering action because of the Kerr nonlinearity of the laser cavity. The wavelength tuning of the short pulse could be obtained by changing the frequency applied to the AOTF as mentioned above. Because of a small polarization dependence of the AOTF [13], [14], another polarization controller PC1 was positioned in the linear cavity, and was adjusted for the maximum laser output power. As the acoustic frequency was varied from 2.788 MHz to 2.833 MHz, the center wavelength of the passively mode-locked pulses was tuned from 1544 nm to 1561 nm with a slope coefficient of 0.38 nm/kHz rate. Figure 4 shows the tunable mode-locked laser outputs achieved at various wavelengths when the frequency applied to the AOTF was changed to several different values. The continuous wavelength tuning over 17 nm without loss of the mode-locking condition was successfully obtained. This is an improved result compared to that obtained with a conventional ring-type fiber laser containing an acoustooptic filter in [10]. The typical optical spectrum and background-free autocorrelation trace of the laser output are shown in Fig. 5(a) and (b), respectively, at the acoustic frequency of 2.800 MHz. The temporal and spectral full widths at half maximum (FWHM) of the mode-locked pulses are 800 fs, assuming a sech^2 profile, and 3.2 nm, respectively. The time-bandwidth product of 0.32 indicates that laser pulses are nearly transform-limited to the hyperbolic sech pulse shape. It is noted that the temporal pulse width varies slightly as the laser wavelength is tuned. The obtained laser pulses are much shorter than those previously reported by others with the sliding-frequency lasers, which are a few picoseconds long. This may be attributed to the fact that the bandpass of our AOTF is wider than that used by others [7]–[10]. For this pulsewidth, the average output power was measured to be 2.3 mW and the peak pulse energy was approximately 560 pJ.

In conclusion, we report the first demonstration, to our knowledge, of a widely tunable short-pulse fiber laser with an NALM-FRM geometry and an all-fiber acoustooptic tunable filter based on two-mode fiber. The wavelength-tunable subpicosecond pulses were obtained in a tuning range over 17 nm. The very stable laser output and the transform-limited pulse generation were achieved with the proposed scheme.

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