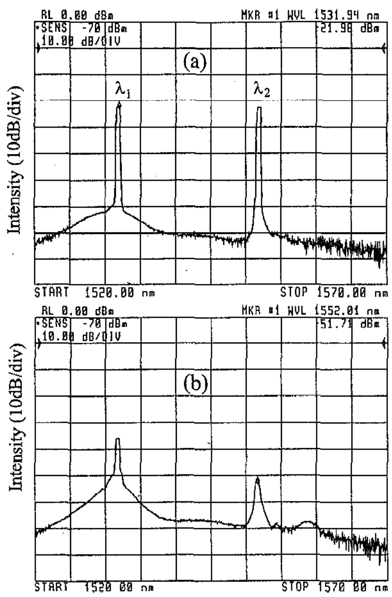
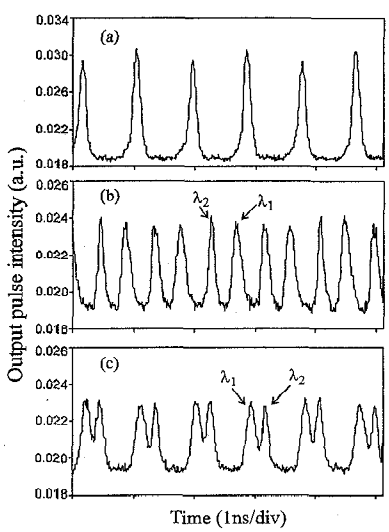


CFE4 Fig. 2. (a) Output spectrum when the laser was mode locked at the 108th harmonic (f = 1106.186 MHz) of the FBG cavity (loop 1 + loop 2). (b) Output spectrum when the laser was detuned.

output pulse waveform for the spectrum shown in Fig. 2(a) is given in Fig. 3(a). Figures 3(b) and 3(c) show, respectively, the pulse waveforms after 0.2-km-high dispersion fiber (D = ~−95 ps/km-nm), or 5.27-km standard single-mode fiber (D = ~18 ps/km-nm) was spliced to the output port. It should be noted that, in Fig. 3(c), the pulses of two wavelengths were separated by more than two pulse periods. The superimposed pulse train at the output coupler was split into two pulse trains after traveling through the extra fibers with anomalous dispersion, indicating that the output



CFE4 Fig. 3. Output pulse waveform from the multiwavelength mode-locked fiber laser; the corresponding spectrum is shown in Fig. 2(a). (a) Before adding extra dispersion fibers; (b) after adding 0.2-km-high dispersion fiber; (c) after adding 5.27-km standard single-mode fiber.

from the laser contained two synchronous pulse trains with two different wavelengths.

In conclusion, a novel configuration of multiwavelength operation of a mode-locked fiber laser using FBGs was successfully demonstrated. Comparing with previous configurations, this scheme has the following advantages: (1) because the light components of all wavelengths selected by the FBGs travel the same route, the cavity lengths for those wavelengths are equal automatically; (2) only one cavity length stabilizing feedback system is needed to achieve stable output pulses; (3) multiple FBGs can be directly cascaded in the laser cavity to select the desired wavelengths.

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CFE5 **11:30 am**

Self-matched stretched-pulse additive-pulse mode-locked fiber lasers formed with apodized chirped gratings

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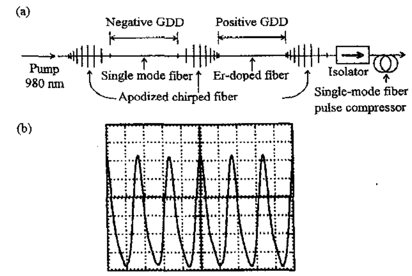
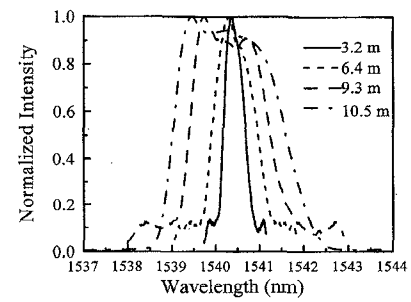
Without critical wavelength-order cavity-length matching, coupled-cavity passively mode-locked fiber lasers using fiber gratings have been proved to give stable mode-locked pulses. According to our previous work,[1] the cavity-length self-matching is originated from the wavelength-dependent effective penetration lengths of the gratings. The mismatch of the cavity lengths is compensated by the difference of the effective penetration lengths between the gratings.

In this paper, we present a system using apodized chirped fiber gratings to achieve the cavity-length self-matching operation. Furthermore, due to the special dispersion characteristics of apodized chirped gratings, pulses will have stretched-pulse amplification actions in such a laser system. Part (a) of Fig. 1 shows the system configuration of the additive-pulse mode-locked fiber laser. The cavities are formed with three apodized chirped gratings. For all the gratings, the grating length is 16 mm, the chirp parameter is 0.2 nm/cm, the refractive-index profile is Gaussian apodized, the central Bragg wavelength is 1540.26 nm, and the spectral width is 0.27 nm. Their peak reflectance values are 0.93, 0.92, and 0.8, respectively.

In the theoretical study, the group-delay dispersion in the gratings was calculated to give a smooth variation over the reflection window. The dispersion values are 125 ps^2 from the small-period side and -125 ps^2 from the large-period side of the apodized chirped grating. In this laser system, the chirped gratings were arranged to make the small-period sides face to face to form the main cavity and



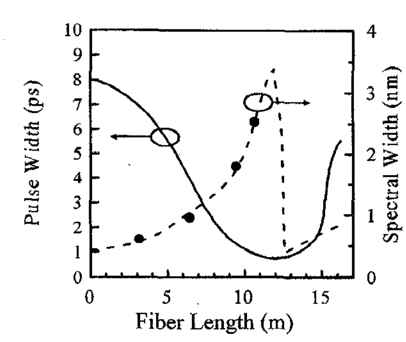
CFE5 Fig. 1. (a) System configuration of an additive-pulse mode-locked fiber laser with self-matched cavities formed with apodized chirped gratings. (b) Pulse train of the mode-locked laser. The pulse repetition rate is 59.4 MHz.



CFE5 Fig. 2. Measured spectra of the output pulses with different compression fiber lengths.

large-period sides face to face to form the auxiliary cavity. Therefore, the pulses experienced strong positive dispersion in the main cavity and strong negative dispersion in the auxiliary cavity. Hence, the pulses were stretched in the main cavity with Er-doped fiber to receive more energy. The output pulses were positively chirped and then compressed by a piece of single-mode fiber after the output end.[2] Part (b) of Fig. 1 shows the pulse train of the mode-locked laser, and the repetition rate is 59.4 MHz.

Figure 2 shows the output spectra measured with different lengths of the single-mode fiber. The spectral width increased with the fiber length. The pulse width was predicted to decrease with the fiber length within a certain range. The increasing trend of the spectral width was attributed to the combined effect of self-phase modulation and negative disper-



CFE5 Fig. 3. Calculated pulse width (solid line) and spectral width (dashed line) as functions of the compression fiber length. The experimental data points are represented by the filled circles.

sion. We calculated the pulse width by modeling the whole system and solving for the steady-state solutions.

Figure 3 shows the calculated pulse width and spectral width with different lengths of the output single-mode fiber. Also, the experimental data (filled circles) are shown. After compression by a 12-m-long single-mode fiber, the shortest pulse can be obtained as 0.8 ps. Meanwhile, the peak power of the compressed pulse become 7.4 times higher.

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CFE6 **11:45 am**

Wavelength-tunable active mode locking of a novel fiber laser including fiber gratings

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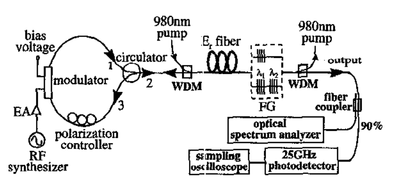
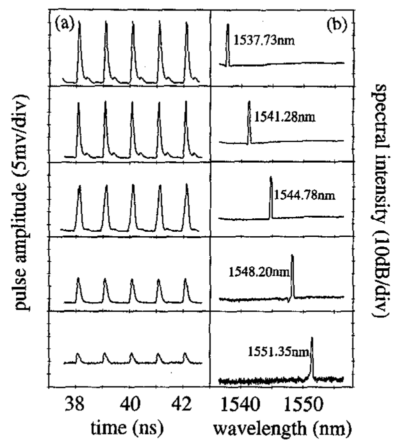
The generation of gigahertz pulse trains has been an attractive subject in many applications such as time- and wavelength-division multiplexed optical communications. Here we report a simple and novel active mode-locked fiber laser.

The experimental setup is shown in Fig. 1. Unlike previously reported work,[1] fiber gratings are used here to play the simultaneous roles of wavelength-selective mirrors, tunable optical filters, and output fiber couplers. An erbium-doped fiber of 11 m with a doping concentration of 220 ppm is used to provide optical gain to balance the cavity loss. The active mode locker is a laboratory manufactured $LiNbO_3$ intensity modulator with an insertion loss of about 7 dB and modulation bandwidth of 6 GHz. The laser circulation path is 1→2→FG→3→1 as shown in Fig. 1.

First, only one fiber grating is used to realize single-wavelength operation. The length, the reflectivity, the center reflection wavelength, and the bandwidth of the grating are 1 cm, 75%, 1544.78 nm, and 0.2 nm, respectively. The laser cavity length measured from the center of the grating is about 54.6 m, corresponding to a round-trip frequency of 3.662 MHz. The achievable maximum repetition rate of the conventional harmonic mode locking is 3 GHz and is being limited by the driving signal from the RF synthesizer. Using 1/2 rational harmonic mode locking technique, the repetition



CFE6 Fig. 1. Experimental setup of the actively mode-locked fiber laser. EA: electrical amplifier; WDM: wavelength-division multiplexer; FG: fiber grating.

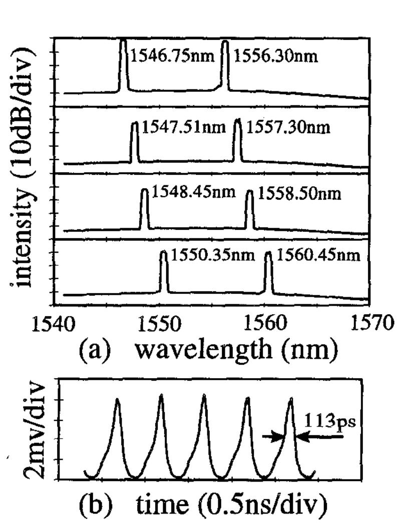


CFE6 Fig. 2. Wavelength-tunable optical output at a modulation frequency of 1002.0786 MHz. (a) Output pulse train; (b) corresponding optical spectrum.

rate can be substantially increased to about 6 GHz.[2] The typical mode-locked pulse performances, for example, at a RF frequency of 2000.8387 MHz, are: pulse width 87 ps, peak power 6.7 mW, spectral width 0.11 nm. Our experimental observations are in good agreement with the standard active mode-locking theory.[3]

Instead of using a Fabry–Perot tunable filter, wavelength tuning is realized by changing the Bragg period of the fiber grating by our newly developed strain tuning method. The advantage of this method is its flexibility in tuning toward both a shorter and a longer wavelength. Figure 2 shows some examples of wavelength tuning. The output can be tuned from 1537.73 to 1551.35 nm spanning a continuous range of 13.62 nm. The output decrease with the wavelength increase is owing to a reduction of optical gain in the Er^{3+}-doped fiber.

Simultaneous dual-wavelength operation has also been successfully demonstrated using



CFE6 Fig. 3. Dual-wavelength mode-locked laser output obtained by the strain tuning method at a modulation frequency of 2006.4478 MHz. (a) Optical spectra showing the tunable output; (b) typical plot of a dual-wavelength pulse train.

two fiber gratings written in series at the wavelengths 1547.51 nm (λ_1) and 1557.30 nm (λ_2). The bandwidth and the reflectivity for λ_1 is 0.22 nm and 72% and for λ_2 is 0.19 nm and 80%, respectively. The lengths of the fiber gratings are both 1 cm, and the spacing between their center is 2 cm. The extra allowed detuning in the round-trip frequency raised by the distributed reflection of the fiber grating is the reasonable explanation for the simultaneous operation of the two lasing wavelengths. The tuning of the dual-wavelength output can also be achieved using the strain tuning method. Figure 3 shows some results at an RF frequency of 2006.4478 MHz. Nearly identical output power with a side-mode suppression ratio higher than 25 dB at the two wavelengths is obtained throughout the tuning range. A typical corresponded two-wavelength pulse train with a pulse width of 113 ps and an average power of 0.8 mW is also illustrated in Fig. 3(b).

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CFF **10:30 am–12:00 m**
Room 103

Ultrashort-pulse Characterization

Rick Trebino, *Sandia National Laboratories, Presider*

CFF1 **10:30 am**

Characterization of a femtosecond kHz amplifier chain by spectral shearing interferometry

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In a chirped-pulse amplification laser chain, as the spectral phase added by the stretcher and the group-velocity dispersion in all the materials is imperfectly compensated by the compressor, the output pulse is distorted by the residual phase, and its duration and contrast are not optimal. There is thus a need for an efficient characterization of the pulses in order to optimize the system or control a programmable spectral phase modulator. Spectral shearing interferometry[1] has been recently demonstrated as a powerful technique for measuring the amplitude and phase of ultrashort optical pulses. Its implementation is simple, and the phase retrieval from the data is straightforward.

The experimental setup for spectral shearing interferometry is exposed in Fig. 1. The dispersive delay line is a double-passed compressor with a pair of 1800 lines/mm gratings.