Electronically Controlled High-Speed Wavelength-Tunable Femtosecond Soliton Pulse Generation Using Acoustooptic Modulator

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***Abstract*—The compact system of electronically controlled high-speed wavelength-tunable femtosecond (fs) soliton pulse generation is realized for the first time using a passively mode-locked fs fiber laser, a polarization maintaining optical fiber, and an acoustooptic (A-O) modulator. The wavelength of the output pulses can be continuously tuned simply by controlling the input voltage into the A-O modulator. The wavelength of the soliton pulses can be changed at 2.5-μs intervals. Wavelength stabilization, time division wavelength multiplexed soliton pulse generation, and wavelength scanner have been demonstrated.**

***Index Terms*—Acoustooptic modulator, nonlinear fiber optics, optical fiber applications, optical fiber lasers, optical pulse generation, optical soliton.**

I. Introduction

ULTRASHORT pulse laser is a very important light source in the fields of optoelectronics, ultrafast optical measurements, optical chemistry, and ultrafast spectroscopy. In those fields, the wavelength tunable ultrashort pulse laser with the wide wavelength-tunable region and high tuning speed provides many applications. The Ti:sapphire laser and the dye laser are known as the typical wavelength-tunable ultrashort pulse laser. However, the whole system is rather large and it is difficult to tune the wavelength of ultrashort pulse in wide wavelength range at high speed.

Recently, we have successfully realized the compact system of wavelength-tunable femtosecond (fs) soliton pulse generation using a fs fiber laser and a polarization maintaining (PM) fiber [1]. The wavelength of the soliton pulses can be continuously shifted by varying the fiber input power in the wavelength region of 1.56–2.03 μm. In the same way, the wavelength tuning in the region of 1.32–1.75 μm has been reported by the stokes and antistokes pulse generation in a dispersion-shifted polarization maintaining optical fiber [2]. As an example of the application of these systems, the high-power laser at 1 μm using the second-harmonic generation (SHG) crystal and the Yb fiber amplifier has been reported [3]. The technique of wavelength tuning with optical fibers has absorbed considerable attention lately, and it is very useful for practical applications.

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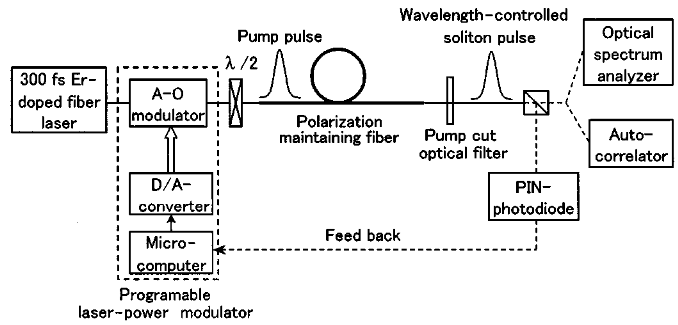
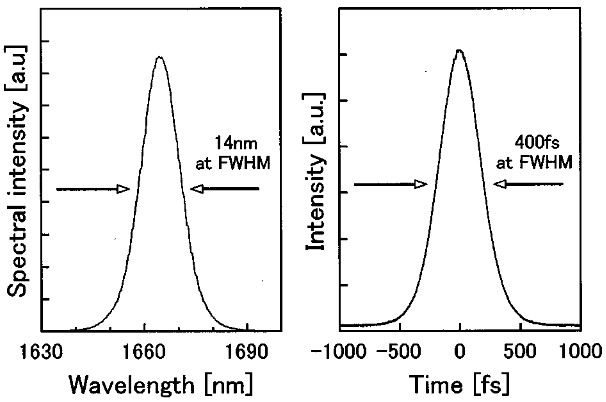


Fig. 1. Experimental setup of electronically controlled high-speed wavelength-tunable femtosecond soliton pulse generation.

In this letter, the compact system of high-speed wavelength-tunable fs pulse generation is proposed using an acoustooptic (A-O) modulator. In this system, the wavelength can be tuned continuously and arbitrarily simply by controlling the input voltage into the A-O modulator. The tuning speed of the wavelength is very fast and the ideal sech^2 soliton pulses are generated.

The experimental setup is shown in Fig. 1. For the pump pulse source, a passively mode-locked Er-doped fiber laser (IMRA Femtolite 780 Model FA1550/30SA) is used. The nearly sech^2 pulses, whose pulsewidths are 300 fs at full-width at half-maximum (FWHM), are generated at the repetition rate of 48 MHz and the center wavelength is 1.56 μm. For the modulation of laser power, a Bragg diffraction type A-O modulator (BRIMROSE SMM-27-2-1550) is used. The frequency of the acoustic wave at the A-O device is 27 MHz and the diffraction efficiency is changed by varying the modulator-input voltage. Using this modulator, the transmissivity of the laser beam can be continuously modulated from 0% to 80% by varying the modulator-input voltage from 0 to 1 V. For the optical fiber, the PM optical fiber of 220-m length is used. The mode-field diameter is 5.84 μm and the magnitude of dispersion is -15 ps^2/km at the wavelength of 1.55 μm.

When the input power of the PM fiber is larger than the threshold power, the soliton pulse with the ideal sech^2 shape is created at the longer wavelength side of the pump pulse through the pulse breakup and the soliton self-frequency shift in the fiber [4], [5]. The wavelengths of the soliton pulse can be shifted continuously by increasing the fiber-input power [1]. Since the wavelength shift of the soliton pulse is caused only by propagation of the pulse in the fiber, no mechanical action



(a) (b)

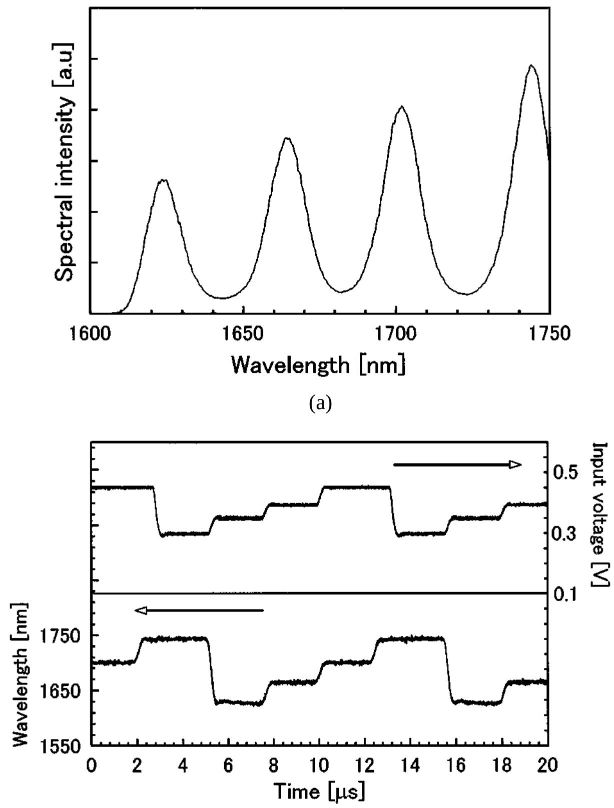
Fig. 2. (a) Optical spectrum and (b) autocorrelation trace of the output pulses at 1667 nm when the wavelength of the soliton pulses is stabilized using the feedback control system.

is needed for wavelength tuning. Additionally, the wavelength of the soliton pulse is changed as soon as the inputted power into the fiber is varied.

In the experiment, the intensity of the pulses from the fiber laser are modulated through the A-O modulator and the throughput pulses are inputted into PM fiber. The polarization direction is adjusted to one of the birefringent axes of the PM fiber by using the $\lambda/2$ plate in front of the PM fiber. The wavelengths of the soliton pulses can be tuned simply by controlling the input voltage into the A-O modulator. We used an optical filter to remove the pump pulses at 1.56 μm coming together with the soliton pulses.

At first, we inputted the constant voltage into the modulator and generated the monocolored soliton pulses. We can determine the wavelength of the soliton pulses by the modulator-input voltage. Although the wavelength of the soliton pulses is stable without any control, we have succeeded in the wavelength stabilization for the long period of time by the feedback-control using a part of the fiber-output beam whose power is dependent on the wavelength. Fig. 2(a) shows the spectrum of the soliton pulses at 1667 nm measured with the optical spectrum analyzer (Anritsu MS9710B). The average power inputted into the fiber is 6.7 mW. The spectrum width is about 14 nm at FWHM and it is almost constant even if the soliton wavelength is changed. Fig. 2(b) shows the autocorrelation trace measured with the autocorrelator (Femtochrome Research FR-103MN). The pedestal free good trace is observed, and this trace is well fitted to that of the sech^2 pulse. The temporal width of the autocorrelation trace is 400 fs at FWHM, and that of the soliton pulse is estimated to be 260 fs. The temporal width of the soliton pulse is almost constant when the wavelength of the soliton pulse is changed. The time-bandwidth product is 0.367, and this value is almost in agreement with that of the transform-limited sech^2 pulse, which is 0.315.

Next, we have demonstrated the generation of time division wavelength multiplexed soliton pulses. The soliton pulses with four different wavelengths, which are 1625, 1667, 1704, and 1746 nm, are generated, and the wavelengths are changed at 2.5-μs intervals by inputting the step voltage into the modulator. The output wavelengths are determined by the modulator-input



(b)

Fig. 3. (a) Optical spectra observed with optical spectrum analyzer when time division wavelength multiplexed soliton pulses are generated. The soliton pulses at the wavelengths of 1625, 1667, 1704, and 1746 nm are generated at about 2.5-μs intervals. (b) Temporal change of the modulator-input voltage and the corresponding wavelengths of the output pulses.

voltage that is controlled by the microcomputer. This voltage was programmed in the microcomputer previously and fed into the A-O modulator at 2.5-μs intervals through the D/A converter. Fig. 3(a) shows the spectra observed with the optical spectrum analyzer. The soliton pulses with four different wavelengths are observed simultaneously, because the time taken for changing the four wavelengths (about 10 μs) is fast enough compared with the scanning time at the spectrum analyzer (about 0.2 s). The spectra of the fiber-output pulses are observed stably and the spectral width is almost constant and independent of the wavelength. The small spectral component between the solitons is the detected component while the wavelength is changing.

Fig. 3(b) shows the temporal change of the modulator-input voltage and the output wavelength. The detected voltage at the p-i-n photodiode changes almost linearly for the wavelength of the output soliton pulse. Thus, we can obtain the temporal change of the wavelength by the result of the previous measurement of the relation between the voltage of the p-i-n photodiode and the soliton wavelength. The output wavelength is changed following the modulator-input voltage. It is observed that the delay time until the wavelength changes after ordering a wavelength to the modulator is about 2.4 μs. The delay time is composed of the propagation time of the pulse along the fiber and the delay time at the modulator, which are about 1.1 μs and 1.3 μs in this system, respectively. The autocorrelation traces of the wavelength multiplexed soliton pulses are well fitted to that of

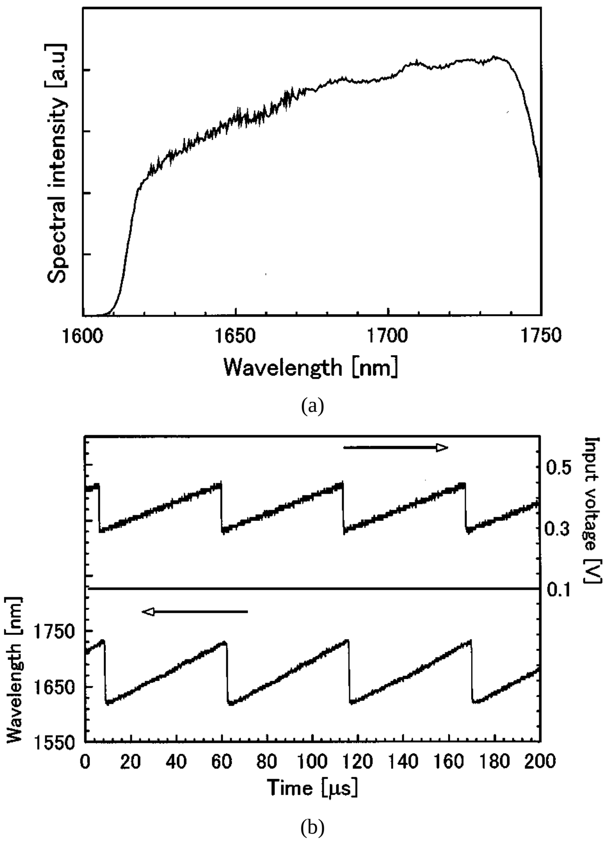


Fig. 4. (a) Observed optical spectra of the wavelength scanner, when the wavelengths of the soliton pulses are changed continuously at the wavelength region of 1.62–1.74 μm. (b) Temporal change of the modulator-input voltage and the corresponding wavelengths of the output pulses.

the sech^2 pulse, which are almost the same as that of the single wavelength output.

Finally, the wide-band wavelength scanner has been demonstrated in this system. Fig. 4(a) shows the optical spectra observed with the optical spectrum analyzer, when the wavelengths of the soliton pulses are changed continuously from 1.62 to 1.74 μm by inputting the sawtooth voltage into the modulator. Since the repetition rate of the sawtooth signal is about 19 kHz, the observed optical spectra look like the continuum of spectra. The temporal shape of the modulator-input voltage and that of the output wavelength are shown in Fig. 4(b). The optical spectra are very stable and the wavelengths of the soliton pulses can be changed continuously and smoothly. In this experiment, the wavelength region of the optical spectral measurement is limited by the sensitivity of the optical spectrum analyzer. In this system, we can change the wavelength of the soliton pulses up to about 1.94 μm. This system acts as the wavelength scanner and is useful for spectroscopic measurement.

In these experiments, the minimum time interval of the wavelengths' change is 2.5 μs, because we use the standard microcomputer and the D/A converter as the wavelength controller. This interval can be made much shorter by using the high-speed modulation controller. The response time of the A-O modulator is 300 ns, which determines the maximum tuning speed of the wavelength in this system. This tuning speed can be made much faster by using the electrooptical (E-O) modulator. The maximum speed of the wavelength change is limited by the repetition frequency of the pump laser.

In conclusion, the compact system of electronically controlled high-speed wavelength-tunable fs soliton pulse generation has been successfully demonstrated using a fiber laser, a PM fiber, and an A-O modulator. The wavelength of the output pulses can be arbitrarily tuned only by controlling the input voltage into the A-O modulator. The pedestal free ideal soliton pulse whose temporal width is about 260 fs is generated. In this system, the tuning speed of the wavelength is very fast, since any mechanical action is not required. Controlling the modulator-input voltage, the wavelength stabilization, the wavelength scanner, and the time division wavelength multiplexed light source has been demonstrated. Since the whole system is very compact and the wavelength can be controlled electronically, it is very useful for practical applications.

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