Simultaneous Generation of Wavelength Tunable Two-Colored Femtosecond Soliton Pulses Using Optical Fibers

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***Abstract*— Wavelength tunable two-colored femtosecond (fs) soliton pulse generation is proposed and demonstrated for the first time, using passively mode-locked fs fiber laser and polarization maintaining fibers. The wavelengths of the two soliton pulses can be changed arbitrarily by varying the power and polarization direction of the fiber-input pulse. Ideal two-colored soliton pulses in which the pulsewidths are about 200 fs are generated in the wavelength region of 1.56–1.70 μm for 110-m fiber. The generated pulses are almost transform-limited ones.**

***Index Terms*— Nonlinear wave propagation, optical fiber applications, optical fiber lasers, optical pulse generation, optical soliton, Raman scattering.**

ULTRASHORT optical pulses are very important light sources in the field of optoelectronics, optical chemistry, and ultrafast spectroscopy. In those fields, the wavelength tunability of the ultrashort pulses provides the wide applications. Specifically, a pair of ultrashort pulses are useful in the field of pump-probe measurements, etc.

So far, the systems of femtosecond optical pulse sources are large and complicated. Recently, passively mode-locked fiber lasers receive the most attention as the light sources of ultrashort pulses [1], [2]. However, the wavelength can be changed only in the small ranges.

Very recently, we have successfully realized the compact system of wavelength tunable monocolored femtosecond (fs) soliton pulse generation using a fs fiber laser and polarization maintaining (PM) fibers [3]. In this system, the wavelength of the soliton pulse can be changed almost linearly by varying the fiber-input power, and it is very useful for practical applications.

In this letter, as the advanced system of the above pulse generation, the system of wavelength tunable two-colored fs soliton pulse generation is proposed and experimentally demonstrated for the first time. The ideal two-colored soliton pulses are generated simultaneously and the wavelengths of the two soliton pulses can be arbitrary changed by only changing the power and the polarization direction of the fiber-input pulses.

Fig. 1 shows the experimental setup of wavelength-tunable two-colored soliton pulse generation. The passively mode-locked Er-doped fiber laser (IMRA Femtolite 780 Model FA1550/30SA) is used as the pump light source, in which the saturable absorber is used to induce the mode-locking effect [1], [2]. As a result of the nonlinear amplification, the spectrum shape is complicated and consisted of a few peaks [3]. The spectrum width is 35 nm at full-width at half-maximum (FWHM) and the center wavelength is 1556 nm. From the fiber laser, the nearly sech^2 pulses, pulsewidth of 180 fs at FWHM, are generated at the repetition rate of 48 MHz. As for the optical fibers, the PM optical fiber (3M FS-PM-7811) of 110 m length is used. The mode-field diameter is 5.5 μm for 1550-nm beam and the magnitude of birefringence is 7×10^{-4}.

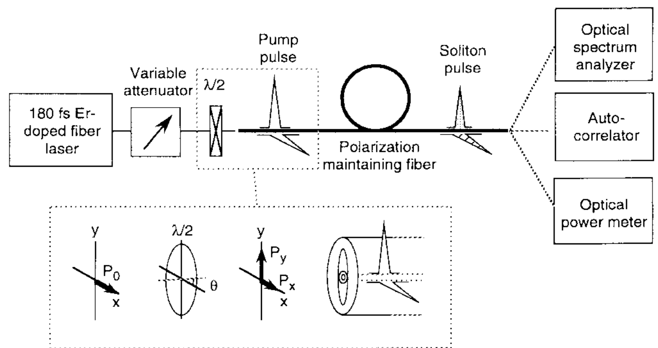

Fig. 1. Experimental setup of the proposed wavelength tunable two-colored fs soliton pulse generation.

The pump pulse from the laser is passed through the variable attenuator. In this experiment, it consists of a $\lambda/2$ plate and the polarization beam splitter (PBS) and the fiber input power is changed by rotating the $\lambda/2$ plate. Then the polarization direction is rotated by the $\lambda/2$ plate in front of the PM fiber and the pump pulse is inputted into the PM fiber. The birefringent axis of the PM fiber is adjusted to the horizontal axis x. The two orthogonal polarization components P_x and P_y are represented as

$$P_x = P_0 \cos^2 2\theta \quad P_y = P_0 \sin^2 2\theta \tag{1}$$

where P_0 is the output power from the variable attenuator and θ is the angle between the birefringent axis of $\lambda/2$ plate and the horizontal axis, as shown in Fig. 1.

In the PM fiber, the two orthogonally polarized components propagate separately due to the birefringence of the PM fiber. When the power of the polarization component is larger than the threshold power P_{th}, the ideal sech^2 shaped

Manuscript received November 4, 1998; revised December 30, 1998.
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Publisher Item Identifier S 1041-1135(99)02520-3.

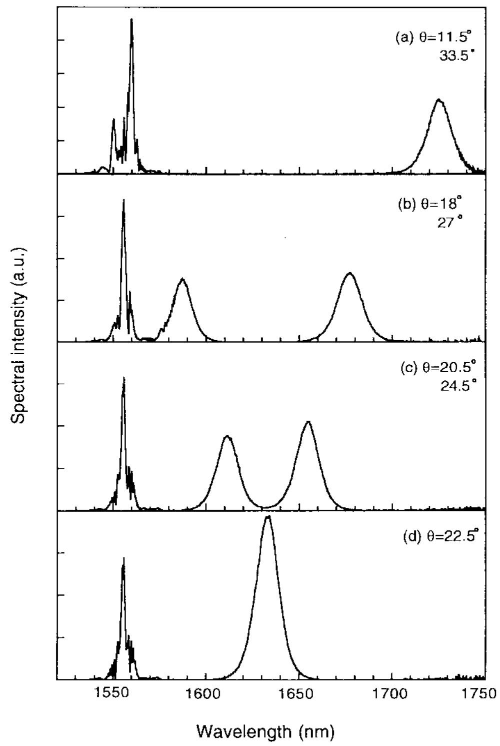

Fig. 2. Optical spectra of the output beam when θ = (a) 11.5° and 33.5°, (b) 18° and 27°, (c) 20.5° and 24.5°, and (d) 22.5°. The fiber length is 110 m and the input power is 11.2 mW.

soliton pulse is generated at the longer wavelength side of the pump pulse due to the stimulated Raman scattering and soliton effect [3], [4]. When both P_x and P_y are larger than $P_{\rm th}$, the orthogonally polarized two-colored soliton pulses are generated simultaneously. The wavelength of the soliton pulse is linearly increased as the power of the pump pulse is increased [3], [5]. Thus, the wavelengths of the two soliton pulses can be changed by varying the fiber-input power and by rotating the $\lambda/2$ plate. From the experimental results, the wavelengths of the two soliton pulses above the threshold power can be approximately represented as

$$\lambda_x = \lambda_p + \Delta\lambda(P_x - P_{\rm th}) = \lambda_p + \Delta\lambda(P_0 \cos^2 2\theta - P_{\rm th}) \quad (2)$$

$$\lambda_y = \lambda_p + \Delta\lambda(P_y - P_{\rm th}) = \lambda_p + \Delta\lambda(P_0 \sin^2 2\theta - P_{\rm th}) \quad (3)$$

where λ_p is the wavelength of the pump pulse and $\Delta\lambda$ is the rate of the wavelength shift with respect to the pump power.

The two soliton pulses and pump pulses can be separated by using the polarization beam splitter and the diffraction grating. The optical spectra of the output pulses are observed with the optical spectrum analyzer (Anritsu MS9710B). The temporal pulsewidths are measured with the auto-correlator (Femtochrome Research FR-103MN).

Fig. 2 shows the optical spectra of the fiber output when the polarization direction of the fiber input pulse is rotated by the $\lambda/2$ plate. The average of the input power is 11.2 mW and the peak power is 1.24 kW. When $\theta \sim 0°$, the polarization direction of the fiber-input pulse is almost parallel to x-axis in Fig. 1, and $P_x \sim P_0$. Thus the largely wavelength shifted mono-colored soliton pulse is generated as shown in Fig. 2(a). The polarization direction of the soliton pulse is parallel to the x axis. The wavelength components at 1556 nm are that of the pump pulse along the y axis and the residual pump pulse along the x axis, which is not converted into the soliton pulse.

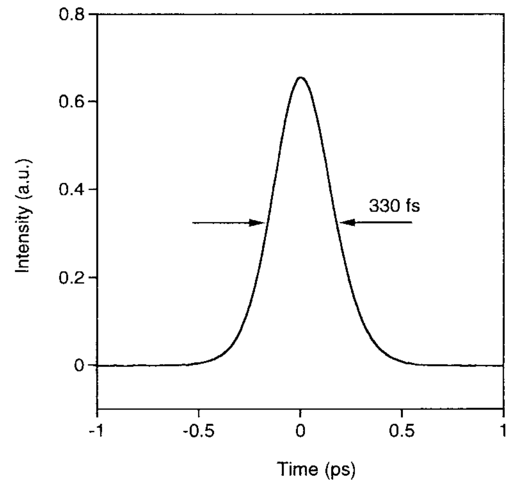

Fig. 3. Autocorrelation trace of horizontally polarized soliton pulse at 1652 nm when $\theta = 20.5°$. The fiber length is 110 m and the input power is 11.2 mW.

As θ is increased, the polarization direction is gradually inclined from x axis and P_x is gradually decreased. Thus, the wavelength of the soliton pulse in x axis, λ_x, is gradually decreased. On the other hand, the second soliton pulse is created at the longer wavelength side of the pump pulse spectrum as shown in Fig. 2(b). The polarization direction of this second soliton is parallel to the y axis. Then wavelengths of the two soliton pulses gradually approach as θ is increased as shown in Fig. 2(c). We can see that the spectral shapes of the two soliton pulses are clearly $\rm sech^2$ shapes and the spectral widths of the two pulses are almost equal as 15 nm. When $\theta = 22.5°$, P_x is equal to P_y and the wavelengths of the two soliton pulses agree precisely as shown in Fig. 2(d). Then the wavelengths of the two soliton pulses are reversed and when θ is approached to near 45°, the monocolored soliton pulse is generated, in which the polarization direction is parallel to y axis.

Fig. 3 shows the autocorrelation trace of the generated soliton pulse when the input power is 11.2 mW and $\theta = 20.5°$. In this condition, the wavelength of the horizontally polarized soliton pulse λ_x is 1654 nm and that of the vertically polarized soliton λ_y is 1613 nm. In the measurement of the autocorrelation trace of the horizontally polarized soliton pulse, the other vertically polarized one is removed using the polarization beam splitter. In Fig. 3, we can see that the pedestal free clear pulse is observed. The autocorrelation trace is well fitted to that of the $\rm sech^2$ pulse. The time width of the autocorrelation trace is 330 fs at FWHM, and the pulsewidth is estimated to be 210 fs. The pulsewidth is almost independent of the input power and θ. The time-bandwidth product is 0.32 and it is almost in agreement with that of the transform-limited $\rm sech^2$ pulse. The pulse energy is about 100 pJ and it is almost

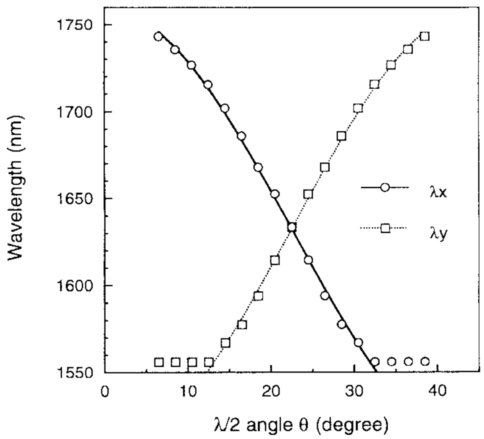

Fig. 4. Characteristics of wavelength shift in terms of the angle of the $\lambda/2$ plate θ. The fiber length is 110 m and the input power is 11.2 mW.

equal to that of the $N = 1$ soliton pulse. The pulsewidth of the vertically polarized soliton pulse is almost equal to that of the horizontally polarized one.

Fig. 4 shows the wavelength of the soliton pulse as a function of the angle of the $\lambda/2$ plate θ when the input power is 11.2 mW. The open circles are the measured wavelengths of the horizontally polarized soliton pulses and the open squares are those of the vertically polarized ones. The wavelength of the soliton pulse is linearly changed with respect to the power of the polarized components. The two-colored soliton pulses are simultaneously generated in the region of 1.56–1.70 μm. The observed magnitudes of the wavelength shifts are almost in agreement with the estimated ones using the theory in [6].

The wavelengths of the two-colored soliton pulses can be relatively shifted as the fiber-input power is changed by using the variable attenuator. Thus the sets of the wavelengths of two-colored soliton pulses can be selected by changing the power and the polarization direction of the fiber input pulses. The magnitude of wavelength shift is monotonically increased as the fiber length is increased. Using much longer fiber and much higher power, a much broader region of wavelength tuning can be obtained.

In this system, the two soliton pulses come out from the fiber at different times. The time difference depends on the magnitude of the birefringence of the PM fiber and the wavelength difference between the two soliton pulses. Considering the magnitude of birefringence of the PM fibers used in this experiment, the time difference between the two soliton pulses is estimated to be about 370 ps when the wavelengths of the two soliton pulses are equal. Using the pin-photo diode and the sampling oscilloscope, the time difference between the two soliton pulses is measured as about 330 ps and is in close agreement with the estimated value. The temporal waveforms are observed stably and clearly and the magnitude of timing jitter is considered to be not so large.

In conclusion, the compact system of wavelength-tunable two colored fs soliton pulse generation is successfully demonstrated for the first time. The arbitrary set of the two wavelengths can be obtained in the wavelength region of 1.56–1.70 μm for 110-m fiber by changing the power and the polarization direction of the fiber-input pulses. The generated two-colored soliton pulses are almost the transform-limited ones and their pulsewidths are about 200 fs.

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