Compact System of Wavelength-Tunable Femtosecond Soliton Pulse Generation Using Optical Fibers

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***Abstract*—Using passively mode-locked femtosecond (fs) fiber laser and polarization maintaining fibers, the compact system of wavelength-tunable femtosecond (fs) fundamental soliton pulse generation is realized. The monocolored soliton pulse, not multicolored ones, with the ideal sech^2 shape is generated, and its wavelength can be linearly shifted by varying merely the fiber-input power in the wide wavelength region of 1.56–1.78 μm for 75-m fiber. The soliton pulses of less than 200 fs are generated with the high conversion efficiency of 75%–85%. This system can be widely used as a portable and practical wavelength-tunable fs optical pulse sources.**

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

I. INTRODUCTION

THE WAVELENGTH-TUNABLE femtosecond (fs) optical pulse sources are very useful in the field of opto-electronics, nonlinear optics, optical chemistry, and ultrafast spectroscopy. They have been realized using solid state lasers or dye lasers with many optical elements so far. In the systems using those lasers, it is necessary to control the optical elements with very high precision through complicated adjustment in order to get the stable operation and tune the wavelength of the laser pulse, and the whole system is rather large.

Recently, passively mode-locked fs fiber lasers of very compact size have been demonstrated and received great attention [1]–[5]. In these lasers, since all of the optical paths are constructed with the fibers, the control of the optics is not necessary, but the wavelength of the fs laser pulse is not widely tunable.

In 1987, it was observed that when the short optical pulses are input into the fibers, the new optical pulse components are generated at the longer wavelength side [6], [7], due to the high-energy density along the fiber and results in a large nonlinear effect. Then a few groups have investigated these phenomena [8]–]12]. In those experiments, however, the multiple or broadened spectra have been generated and the spectral shapes have been usually complicated.

In this study, the wavelength tunable fs soliton pulses with the ideal sech^2 shapes are generated by using the fs Er-doped fiber laser and the polarization maintaining fibers. It is found that by varying merely the fiber-input power from the fs laser, the wavelength of the fs soliton pulse is shifted almost linearly in the wide region of 1.56–1.78 μm for the fiber of 75-m length and the conversion efficiency from the input pump pulse to the soliton pulse is as high as 75%–85%. To our knowledge, this is the first wavelength tunable fs soliton pulse generation system using only fibers in which the monocolored soliton pulse, not the multicolored ones, is generated. Since the system is composed of the very compact fs fiber laser and the fine fiber, it is much more compact and stable than other wavelength tunable fs pulse systems and almost maintenance-free.

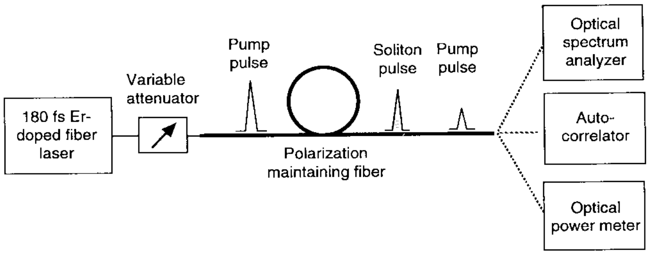

Fig. 1. Experimental setup of wavelength tunable fs soliton pulse generation.

The principle of this wavelength-tunable soliton pulse generation is as follows [7]. When the short optical pulse with the high peak power is input into the fibers, the Stokes pulse is created through the Raman scattering effect at the longer wavelength side of the pump pulse spectrum. If the wavelength of the Stokes pulse is in the anomalous dispersion region, the pulse narrowing occurs owing to the soliton pulse compression effect and the fundamental soliton pulse is generated. If the pulsewidth is short enough, the soliton self-frequency shift occurs and the center wavelength is shifted toward the longer wavelength side as the pulse propagates [13]. Since the magnitude of the Raman effect is dependent on the fiber length and fiber-input power, the wavelength of the soliton pulse can be varied by changing these parameters.

The experimental setup used in this study is shown in Fig. 1. The passively mode-locked Er-doped fiber laser (IMRA Femtolite 780 Model FA 1550/30SA) is used as the pump pulse source. In this laser, the saturable absorber is used to induce the passive mode-locking [5]. The fs pulses are generated at the repetition rate of 48 MHz. Fig. 2 shows the autocorrelation trace and the optical spectrum of the output pulses from the Er-doped fiber laser. The time width of the

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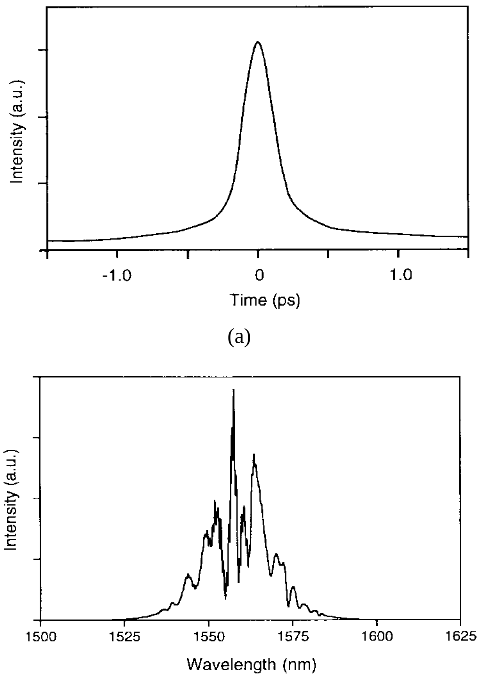

(a)

(b)

Fig. 2. (a) Autocorrelation trace and (b) optical spectrum of the output pulse from the Er-doped fiber laser.

autocorrelation trace is 280 fs at full-width at half-maximum (FWHM). The autocorrelation trace is nearly fitted to that of the sech^2 pulse and the pulsewidth is estimated to be 180 fs. The spectrum shape of the laser pulse has a few peaks and the laser pulse is not the transform limited one. The center wavelength of the laser pulse is 1556 nm and the spectrum width is about 35 nm at FWHM. As for the fibers, the diameter reduced type polarization maintaining fibers (3M FS-PM-7811), in which the mode-field diameter is 5.5 μm, are used in order to get the large nonlinear optical effects.

The output of the fiber laser is passed through the variable optical attenuator, which is constructed with the half-wave plate and polarization beam splitter and the throughput power is changed by rotating the wave plate. The maximum fiber-input power is 11.2 mW and the corresponding pulse peak power is 1296 W. Then the direction of the polarization is adjusted to the birefringent axis of the fiber. The extinction ratio of the output beam is about 500:1.

At the output of the fibers, the optical spectrum is measured with the optical spectrum analyzer (Anritsu MS9710B). The temporal waveforms are observed with the autocorrelator. The powers of the soliton pulses are measured with the diffraction grating and optical power meter.

In Fig. 3, the observed spectra of the fiber output are shown at the fiber length of 75 m and the fiber-input power of 9 mW. When the fiber-input power is increased above 3 mW, the pump pulse is broken into two pulses and the soliton pulse is generated at the longer wavelength side. Owing to the soliton self-frequency shift, the center wavelength of the soliton pulse is shifted toward the longer wavelength side as the pulse propagates. In this figure, the ideal sech^2-shaped soliton pulse spectrum is clearly observed at 1715 nm. The spectral width is about 17.5 nm at FWHM. Since the pump pulse is not the perfect soliton, a part of the pump pulse is not converted into the soliton pulse. The spectral components at the wavelength of 1556 nm is that of the residual pump pulse which is not converted into the soliton pulse.

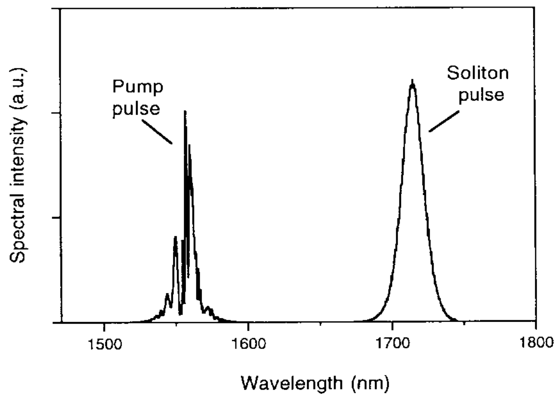

Fig. 3. Spectra of output beam from the 75-m fiber when the fiber-input power is 9 mW.

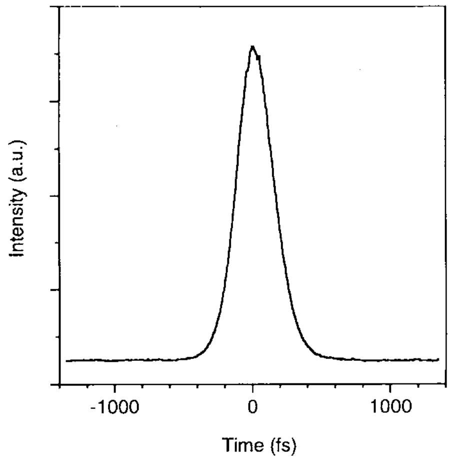

Fig. 4. Autocorrelation trace of soliton pulse. The fiber length is 75 m and the fiber-input power is 9 mW.

Fig. 4 shows the autocorrelation trace of the soliton pulse when the fiber length is 75 m and fiber-input power is 9 mW. The pedestal free good trace is observed and this trace is well fitted to that of the sech^2 pulse. The time width of the autocorrelation trace is 315 fs at FWHM, and the pulsewidth is obtained as 315 fs $\times$ 0.648 $=$ 204 fs. The corresponding time-bandwidth product is 0.367, and this value is almost in agreement with that of the transform-limited sech^2 pulse.

In Fig. 5, the wavelength shifts of the soliton pulses are shown as a function of the fiber-input power at the fiber lengths of 75 and 30 m. As the fiber-input power is increased beyond the threshold value of about 3 mW, the wavelength shift is almost linearly increased. The pulse spectra keep the ideal sech^2-shapes above the threshold fiber-input power. The maximum wavelength is 1775 nm when the fiber length is 75 m and the fiber-input power is 11.2 mW. The tuning wavelength range is about 220 nm, while it is a few tens of nm for one set of optical components in the case of the solid state lasers. From this figure, we can see that the wavelength

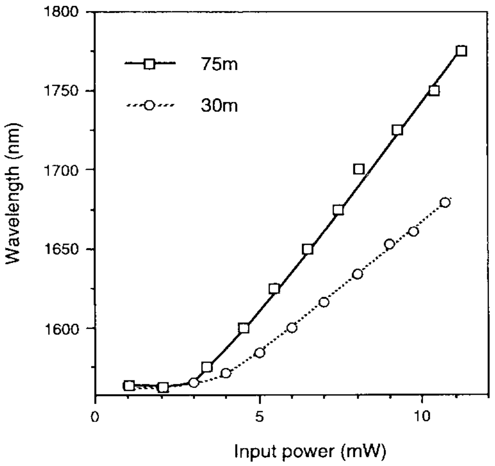

Fig. 5. Characteristics of wavelength shift in terms of the fiber-input power for 75- and 30-m fibers.

of the soliton pulse can be almost linearly and continuously controlled by varying the fiber-input power. The threshold fiber-input power is almost the same for any fiber lengths, which is considered as the threshold power of stimulated Raman scattering in the fibers used in this experiment.

The power of the soliton pulses linearly increases as the fiber-input power increases in our present fiber-input power region. At the fiber length of 75 m and fiber-input power of 11.2 mW, the power of the soliton pulse is 8.5 mW. The conversion efficiency from the input pump pulse to the soliton pulse is 76%. The observed maximum conversion efficiency is 85% when the fiber-input power is 5.5 mW.

The magnitudes of the wavelength shifts for 30-m fiber are about 57% of those for 75-m fiber at the same fiber-input power. The dependence of the wavelength shift on the fiber length is under study.

When the fiber-input power is 9.0 mW, the spectrum widths of the soliton pulses are 17.3 nm for 75-m fiber and 20.3 nm for 30-m fiber. The corresponding pulsewidths are 203 and 153 fs. As the fiber length is increased, the spectral width is decreased and the temporal pulsewidth is increased.

In conclusion, the wavelength tunable fs monocolored soliton pulses with the ideal sech^2 shapes are generated in the wide wavelength region of 1.56–1.78 μm with fs fiber laser and polarization maintaining fibers, and the magnitude of the wavelength shift is almost linearly changed with the fiber-input power.

It is expected from our present experimental results that if the fiber-input power and the fiber length are increased more, the magnitude of the wavelength shift is increased up to 300–400 nm. Moreover, since the obtained soliton pulses have large peak power of a few hundred watts, the wavelength-tunable optical pulses can be generated in the region of 780 nm to 1 μm using the second-harmonic generation.

Since this wavelength tunable fs pulse generation system is very compact, it is expected to be used widely in various fields such as optical chemistry and ultrafast spectroscopy.

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