# 0.78–0.90-$\mu$m Wavelength-Tunable Femtosecond Soliton Pulse Generation Using Photonic Crystal Fiber

Norihiko Nishizawa, *Member, IEEE*, Youta Ito, and Toshio Goto, *Fellow, IEEE*

***Abstract*—Compact system of 780–900-nm wavelength tunable femtosecond soliton pulse generation is demonstrated for the first time using fiber laser, periodically poled $LiNbO_3$, and photonic crystal fiber (PCF). The wavelength of generated soliton pulse can be shifted almost linearly by varying the fiber input power. The temporal width of the generated soliton pulse is as short as 55 fs. As the results of numerical analysis, it is expected that the wavelength of the soliton pulse is shifted above 1.1 $\mu$m using much higher power or longer PCF. This system is constructed with almost all the fiber devices and it is compact and useful for practical applications.**

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

## I. Introduction

ULTRASHORT pulse source is important light source for a lot of applications, such as ultrafast optoelectronics, ultrafast spectroscopy, etc. So far, as the ultrashort pulse source, the solid state laser, dye laser, and optical parametric oscillator have been mainly used. However, it is not easy to handle them and they need huge systems.

A few years ago, the passively mode-locked ultrashort fiber laser has been demonstrated [1]. It is compact, a stable light source, and useful for practical applications. The wavelength of the output pulses, however, can not be changed in the wide wavelength region.

Recently, we have demonstrated the compact system of wavelength tunable femtosecond soliton pulse generation [2], [3]. In this system, 100–200 fs transform-limited soliton pulse is generated. The wavelength of the soliton pulse can be shifted continuously at wide wavelength region of 1.55–2.15 $\mu$m by merely varying the fiber input power [2]–[4]. In this system, ultrahigh-speed wavelength tuning of the femtosecond soliton pulse can be demonstrated using intensity modulator [5]. Using the dispersion-shifted fiber, in addition to the wavelength tunable soliton pulse, the wavelength tunable antistokes pulse can be generated which is shifted toward the shorter wavelength side as the fiber input power is increased [6]. Recently, 1.1–2.1-$\mu$m ultrawidely broadened super continuum has been generated using the highly nonlinear dispersion-shifted fibers [7].

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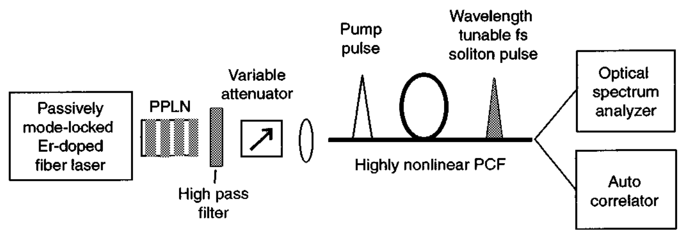


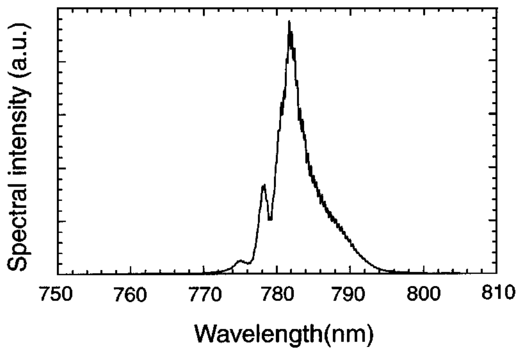

Fig. 1. Experimental setup of wavelength-tunable femtosecond soliton pulse generation using PCF.

In order to generate the wavelength-tunable soliton pulse, it is necessary to use the anomalous dispersive fiber to obtain the effect of soliton self-frequency shift (SSFS) [8]. Using the photonic crystal fiber, the anomalous dispersion can be obtained over wide wavelength region [9]. The soliton pulse propagation and widely broadened super continuum generation at wavelength around 800 nm were demonstrated using microstructure optical fibers [10]. Recently, wavelength tunable soliton pulse generation has been demonstrated at wavelength region of 1.3–1.65 $\mu$m using tapered PCF [11]. For the application of the two-photon microscope, optical memory, etc., it is important to generate the wavelength tunable soliton pulse at wavelength region below 1 $\mu$m.

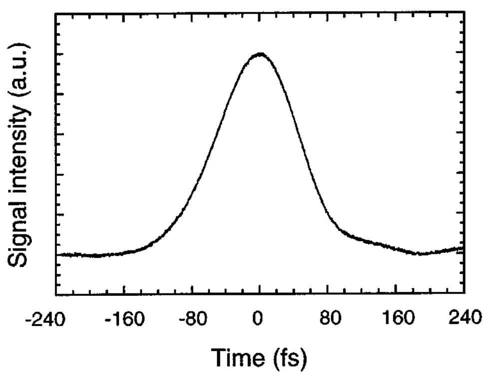
In this letter, we have demonstrated the compact system of wavelength-tunable femtosecond soliton pulse generation at wavelength of 780–900 nm for the first time using ultrashort pulse fiber laser, quasi-phase-matched SHG crystal, and PCF. The temporal width of the soliton pulse is as short as 55 fs. The center wavelength of the generated soliton pulse is shifted continuously toward the longer wavelength side as the fiber input power is increased. Since the system is constructed with almost all the optical fiber devices, it is compact and useful for practical application.

## II. Experimental Setup

Fig. 1 shows the scheme of experimental setup. As the pump pulse source, a passively mode-locked Er-doped fiber laser (IMRA femtolight) is used. It generates 110 fs $\mathrm{sech}^2$ like pulses at repetition frequency of 48 MHz. The center wavelength of the pulse spectrum is 1.56 $\mu$m. The output pulse is focused into the 1-mm-thick periodically poled $LiNbO_3$ (PPLN) and the ultrashort pulse at wavelength of 780 nm is generated through the quasi-phase matched second harmonic generation (SHG).




(a)




(b)

Fig. 2. (a) Optical spectrum and (b) autocorrelation trace of the SHG pulse at output of PPLN.

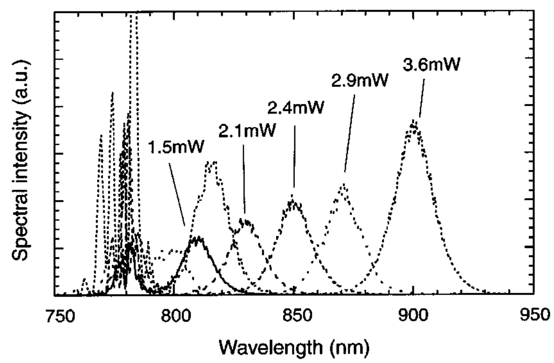



Fig. 3. Optical spectra of generated wavelength-tunable femtosecond soliton pulse as the fiber input power is changed.

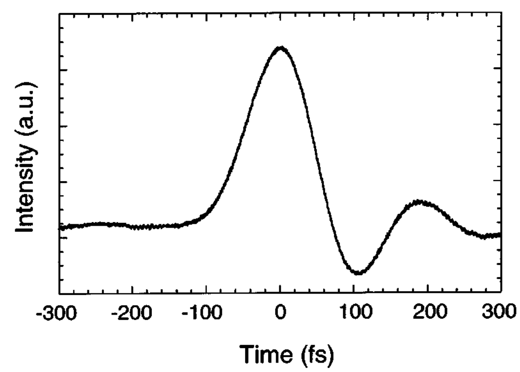



Fig. 4. Observed autocorrelation trace of generated soliton pulse in 60 cm of PCF when the fiber input power is 3.5 mW.

The output pulse is passed through the high pass filter and only the SHG pulse is picked out.

As the Raman shift fiber, 60 cm of highly nonlinear type PCF (Crystal Fiber CF-1.7ACD) is used. The diameter of the core is as small as 1.7 $\mu$m and nonlinear effect can be obtained effectively. The core is surrounded by the large air holes and the zero-dispersion wavelength is set to be around 690 nm.

The SHG pulse is passed through the variable attenuator and then is coupled into the PCF using the objective lens. Since the wavelength of the SHG pulse is in the anomalous dispersion region, the soliton effect can be obtained at this wavelength. Owing to the effect of soliton self-frequency shift (SSFS) [8], the wavelength-tunable femtosecond soliton pulse is generated in the PCF. The output of the PCF is observed using the optical spectrum analyzer (Anritsu MS9710B) and two-photon absorption type auto-correlator (Femtochrome FR-103PD).

## III. Results and Discussion

Fig. 2 shows the observed optical spectrum and the autocorrelation trace of the SHG pulse at the output of PPLN. For the optical spectrum, the center wavelength is 782 nm and the spectral width is 4 nm at full-width at half-maximum (FWHM). Since the spectrum of the fundamental pump pulse from fiber laser is broadened due to the effect of Raman scattering, the spectrum shape is slightly asymmetric. For the auto-correlation trace of the SHG pulse, almost pedestal free clear trace is observed. The temporal width is about 115 fs at FWHM and the corresponding pulse width is 71 fs under assumption of the sech$^2$ pulse.

Fig. 3 shows the optical spectra of the output pulses from PCF. As the fiber input power is increased, the pulse breakup occurs and the wavelength-tunable soliton pulse is generated at the longer wavelength side of the pump pulse. As the fiber input power is increased, the center wavelength of the generated soliton pulse is shifted toward the longer wavelength side continuously due to the effect of SSFS [8]. The observed maximum wavelength of the soliton pulse is 900 nm when the fiber input power is 3.56 mW. The spectral shape of the soliton pulse is almost sech$^2$ one. The spectral width is almost constant to be 18 nm. The observed maximum conversion efficiency from SHG pulse into soliton pulse is as high as 70%. When the fiber input power is increased above 3.1 mW, the second soliton pulse is generated from the residual pump pulse which is not converted into the initially generated soliton pulse.

Fig. 4 shows the auto-correlation trace of the generated soliton pulse. The detection time constant of the auto-correlator (Femtochrome FR-103PD) is set to be 10 fs. Almost pedestal free clear trace is observed. Owing to the effect of response time of the photodetection and amplifier system in auto-correlator, the relaxation oscillation arises at the trailing edge of the observed auto-correlation trace. The temporal width of the autocorrelation trace is 90 fs at FWHM and the estimated pulse width is as short as 55 fs under assumption of the sech$^2$ pulse. The corresponding time-bandwidth product is 0.37 and it is almost near to that of the transform limited sech$^2$ pulse, which is 0.315.

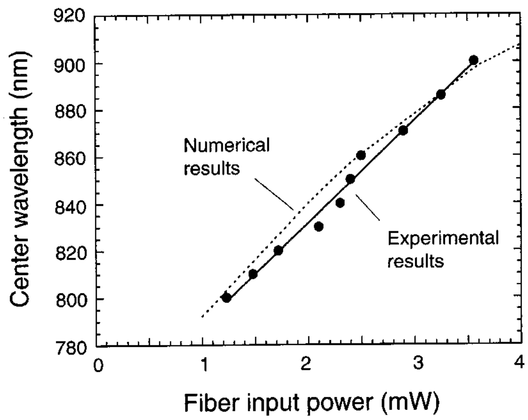



Fig. 5. Characteristics of wavelength shift of generated soliton pulse as a function of fiber input power, where circles are experimental results and dotted line shows the numerical ones.

The characteristics of the wavelength-tunable soliton pulse are analyzed numerically using the strict nonlinear Schrödinger equation [12]. The characteristics of chromatic dispersion in PCF are almost similar to those in solid silica strand surrounded by air [9]. Thus, the clad of the PCF is assumed to be air and the dispersion characteristics of the PCF is estimated using the dispersion equations.

Fig. 5 shows the characteristics of the wavelength shift of soliton pulse in terms of the fiber input power. The circles show the experimental results and dotted line is the numerical ones. In the numerical analysis, the transform-limited $\mathrm{sech}^2$ pulse is assumed for the SHG pulse. The numerical results are almost in agreement with the experimental ones. The wavelength of the soliton pulse is shifted continuously and almost linearly as the fiber input power is increased up to 4 mW. Then the efficiency of the wavelength shift of soliton pulse is gradually decreased as the fiber input power is increased and finally the wavelength shift is saturated around 1.15 $\mu$m.

For the fiber length, the wavelength shift is increased monotonously as the fiber length is increased and is gradually saturated. The reason for the saturation of the wavelength shift of soliton pulse is considered to be the effect of increment of the absolute value of second-order dispersion.

## IV. Conclusion

In conclusion, the wavelength-tunable femtosecond soliton pulse is generated at wavelength of 780–900 nm using ultrashort pulse fiber laser, PPLN, and PCF. The wavelength of the soliton pulse is shifted continuously toward the longer wavelength side as the fiber input power is increased. The temporal width of the generated soliton pulse is about 55 fs. The characteristics of the generated soliton pulse are analyzed numerically using the strict nonlinear Schrödinger equation. The numerical results are almost in agreement with the experimental ones. As the results of numerical analysis, it is expected that the wavelength of the soliton pulse is shifted above 1.1 $\mu$m using much higher input power or longer PCF. The system is constructed with almost all the optical fiber devices and it is compact and useful for practical applications.

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## References


[1] M. E. Fermann, L.-M. Yang, M. L. Stock, and M. J. Andrejco, "Environmentally stable Kerr-type mode-locked erbium fiber laser producing 360 fs pulses," *Opt. Lett.*, vol. 19, pp. 43–45, 1994.

[2] N. Nishizawa and T. Goto, "Compact system of wavelength tunable femtosecond soliton pulse generation using optical fibers," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 325–327, Mar. 1999.

[3] ——, "Widely wavelength tunable ultrashort pulse generation using polarization maintaining optical fibers," *IEEE J. Select. Topics Quantum Electron.*, vol. 7, pp. 518–524, July–Sept. 2001.

[4] M. E. Fermann, A. Galvanauskas, M. J. Stock, K. K. Wong, and D. Harter, "Ultrawide tunable Er soliton fiber laser amplified in Yb-doped fiber," *Opt. Lett.*, vol. 24, pp. 1428–1430, Oct. 1999.

[5] T. Hori, N. Nishizawa, H. Nagai, M. Yoshida, and T. Goto, "Electronically controlled high-speed wavelength-tunable femtosecond soliton pulse generation using acoustooptic modulator," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 13–15, Jan. 2001.

[6] N. Nishizawa, R. Okamura, and T. Goto, "Widely wavelength tunable ultrashort soliton pulse and anti-stokes pulse generation for wavelengths of 1.32–1.75 $\mu$m," *Jpn. J. Appl. Phys.*, vol. 39, pp. L409–L411, 2000.

[7] N. Nishizawa and T. Goto, "Widely broadened super continuum generation using highly nonlinear dispersion shifted fibers and femtosecond fiber laser," *Jpn. J. Appl. Phys.*, vol. 40, pp. L365–L367, 2001.

[8] F. M. Mitschke and L. F. Mollenauer, "Discovery of the soliton self-frequency shift," *Opt. Lett.*, vol. 11, pp. 659–661, 1986.

[9] J. C. Knight, J. Arriaga, T. A. Birks, A. Ortigosa-Blanch, W. J. Wadsworth, and P. St. J. Russell, "Anomalous dispersion in photonic crystal fiber," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 807–809, July 2000.

[10] J. K. Ranka, R. S. Windeler, and A. J. Stentz, "Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm," *Opt. Lett.*, vol. 25, pp. 25–27, 2000.

[11] X. Liu, C. Xu, W. H. Knox, J. K. Chanadalia, B. J. Eggleton, S. G. Kosinski, and R. S. Windeler, "Soliton self-frequency shift in a short tapered air-silica microstructure fiber," *Opt. Lett.*, vol. 26, pp. 358–360, 2001.

[12] N. Nishizawa, R. Okamura, and T. Goto, "Analysis of widely wavelength tunable femtosecond soliton pulse generation using optical fibers," *Jpn. J. Appl. Phys.*, vol. 38, pp. 4768–4771, 1999.