# Width and Wavelength-Tunable Optical Pulse Train Generation Based on Four-Wave Mixing in Highly Nonlinear Photonic Crystal Fiber

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***Abstract*—We demonstrate both width and wavelength-tunable optical pulse train generation based on four-wave mixing in highly nonlinear photonic crystal fiber. By tuning the delay time between two pulse trains, the pulsewidth of the generated pulse train is continuously tuned. By tuning the wavelength of one of the pulse trains, the wavelength of the generated pulse train is also continuously tuned. In our experiment, the pulsewidth of a 5-GHz repetition rate pulse train is tuned from 88 to 19 ps and the pulsewidth of a 10-GHz pulse train is tuned from 39 to 19 ps. The 3-dB wavelength tuning range is about 70 nm.**

***Index Terms*—Four-wave mixing (FWM), nonlinear optics, optical fiber communication.**

## I. Introduction

ROBUST optical pulse train sources, capable of producing width-tunable and wavelength-tunable pulses with high repetition rate and high extinction ratio are important sources for many applications, such as high-speed optical communication, all-optical reshaping, optical sampling, ultrafast optoelectronics, ultrafast spectroscopy, and optical chemistry, etc. Passive and active mode-locking of fiber lasers are very useful techniques for generating ultrashort pulses [1], [2]. In order to tune the wavelength of the pulse, an intracavity tunable bandpass filter (BPF) can be used in the laser cavity over the gain spectral width of the gain medium. Wavelength tunability can be extended beyond the gain bandwidth of the gain medium through various nonlinear processes in optical fibers such as supercontinuum generation [3], [4], soliton self-frequency shift [1], [5], and optical parametric amplification (OPA) [6]. By launching high intensity picosecond pulses into optical fibers near the zero-dispersion wavelength region, one can generate an extremely broad and flat supercontinuum, which can be sliced using a suitable BPF to provide picosecond pulses over a wide spectral range [3]. A wavelength-tunable soliton is generated when a soliton pulse is launched into an anomalous dispersion fiber due to the intrapulse stimulated Raman scattering, which transfers energy from the higher frequency components of the soliton to its low frequency ones [7]. Another scheme launches high-power picosecond pulse into a highly nonlinear fiber, in which the low-power signal is amplified by OPA and the pulse pattern is copied from the input pulse train. Wavelength-tunable pulses are generated by changing the wavelength of the low power signal [6]. However, the width of optical pulse trains generated by the nonlinear processes cannot be tuned continuously.

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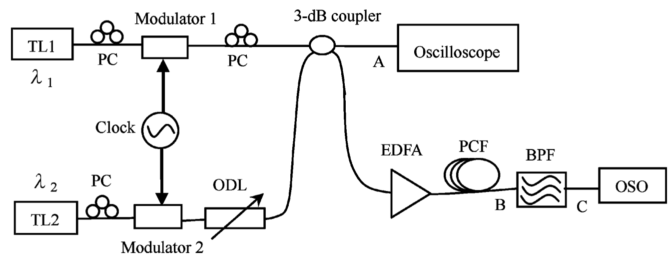


Fig. 1. Experimental setup.

Besides wavelength tunability, another desirable feature of pulses is width (duration) tunability, which critically influences the performance of optical transmission systems. Shorter pulses have the potential to be transmitted a longer distance with the same bit rate because the effect of dispersion will not be as serious. Recently, width tunable pulse generation based on four-wave mixing (FWM) in a 1-km length of highly nonlinear fiber has been reported [8]. The narrowest pulsewidth obtained for 10-Gb/s signal is around 20 ps. However, the long length of the fiber will be sensitive to the changes in the environment, and wavelength tunability is not studied in [8]. In this letter, we report both width and wavelength-tunable optical pulse train generation based on FWM in a highly nonlinear photonic crystal fiber (PCF), which has a very small dispersion slope near the zero-dispersion wavelength.

## II. Experimental Setup

The schematic of the wavelength and width tunable pulse train generation is shown in Fig. 1, which is based on FWM between two width-fixed pulse trains in a highly nonlinear PCF. Two pulse trains with fixed pulsewidths are generated first by modulating the output from two tunable lasers (TL1 at wavelength $\lambda_1 = 1550.5$ nm and TL2 at wavelength $\lambda_2 = 1543.1$ nm) with two electrooptic intensity modulators. The outputs of two pulse pattern generators (PPGs) are synchronized clocks at radio frequency (RF), which are used to drive the modulators and control the repetition rate of both pulse trains. The optical powers after the two modulators are measured to be both around $-8$ dBm. One modulator is connected to a polarization controller, which is used to optimize the conversion efficiency of FWM in the highly nonlinear PCF.

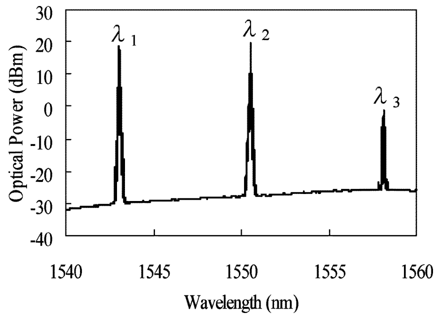


Fig. 2. Optical spectrum at point $B$ with the wavelengths of the original pulse trains at 1550.5 and 1543.1 nm and the new wavelength generated by FWM at 1558.1 nm.

The other modulator is connected to a tunable optical delay line (ODL), which is used to control the delay time between the two pulse trains. The two pulse trains are combined by a 3-dB coupler and amplified by a high power erbium-doped fiber amplifier, which has a saturation power about $+27$ dBm. A photodector and an oscilloscope are used to observe the combined waveform of the two pulses at another port of the 3-dB coupler. The amplified optical pulses are launched into a highly nonlinear PCF of length 20 m. The nonlinear coefficient of the PCF is about 30.6 $W^{-1} \cdot km^{-1}$, its zero-dispersion wavelength is around 1550 nm and the dispersion slope near the zero-dispersion wavelength is very small (of the order of $10^{-4}$ ps/nm$^2 \cdot$km). The total insertion loss of the PCF is around 1 dB. The peak powers at $\lambda_1$ and $\lambda_2$ launched into the PCF are both approximately $+20$ dBm.

After passing through the highly nonlinear PCF, a new pulse train at wavelength $\lambda_3$ is generated due to the FWM in the PCF. An optical BPF with a bandwidth of 0.5 nm and center wavelength at $\lambda_3$ is used to filter out the generated pulse train. After the optical filter, a 500-GHz optical sampling oscilloscope (OSO) is used to observe the shape and the width of the generated pulse train at $\lambda_3$. A clock output from a PPG is used to trigger the OSO. The time resolution of the OSO is 800-femtoseconds.

## III. Results and Discussion

The optical spectrum after FWM happens in the PCF is observed at point $B$ and is shown in Fig. 2. Two wavelengths are generated on both sides of $\lambda_1$ and $\lambda_2$ based on the FWM. Only the generated wavelength on the right side and the two original wavelengths $\lambda_1$ and $\lambda_2$ are shown in Fig. 2. The peak power at the generated wavelength $\lambda_3 = 1558.1$ nm is approximately $-1$ dBm, which is larger than the power of the original pulse trains. The spectra at $\lambda_1$, $\lambda_2$, and $\lambda_3$ are all broadened as expected because they are high repetition rate pulse trains. The waveform observed at point $A$, the waveform at point $C$, and the spectrums at point $C$ for different delay times of 80, 100, 120, 140, and 160 ps when the repetition rate for the pulse train is 5 GHz are shown in Fig. 3. When the overlap between the two pulse trains is smaller (i.e., when the delay between them is larger), the width of the generated pulses at $\lambda_3$ becomes narrower, as seen in Fig. 3(b). When the width of the generated pulses is smaller, the spectrum of the pulses becomes broader, as shown in Fig. 3(c). The noise observed in Fig. 3(b) was mainly

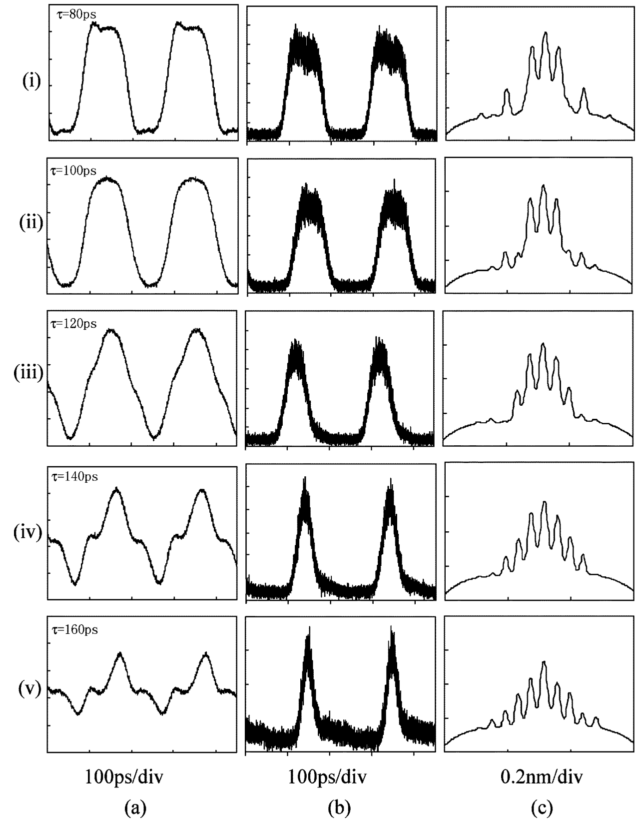


Fig. 3. (a) Combined waveform of the two pulse trains at point $A$, (b) waveform of the generated pulse train at $C$, and (c) spectrum at point $C$ for 5-GHz clock, all as a function of various optical delay times $\tau$ as shown in (i) to (v).

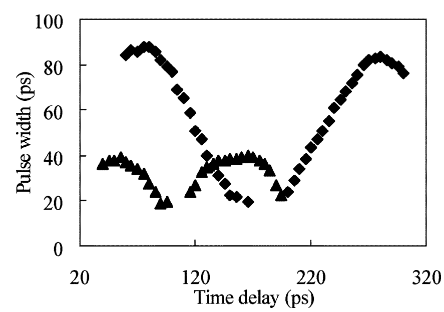


Fig. 4. Width of the pulses at $\lambda_3$ versus the delay time. ◆: 5-GHz clock. ▲: 10-GHz clock.

due to the OSO which was specified to have a typical optical signal-to-noise ratio of about 10 dB for an input optical power of 10 mW, and the optical power from our laser incident on the OSO was less than 1 mW, resulting in noisy waveforms.

The delay time between the two width-fixed pulse trains can be tuned continuously by changing the delay time which depends on the length of the ODL. As a result, different width pulses are generated. The pulsewidth of the generated pulses versus optical delay time $\tau$ of the ODL for both 5- and 10-GHz repetition rates of the pulse trains are shown in Fig. 4. The pulsewidth of the generated pulse train at $\lambda_3$ can be tuned from 88 to 19 ps by tuning the delay time $\tau$ of the ODL from 80 to 160 ps for the 5-GHz RF clock. When the RF clock is 10 GHz, the pulsewidth at $\lambda_3$ can be tuned from 39 to 19 ps by varying the delay time $\tau$ of the ODL from 55 to 95 ps. When the delay time $\tau$ continues to increase, the width of the pulse at $\lambda_3$ stops

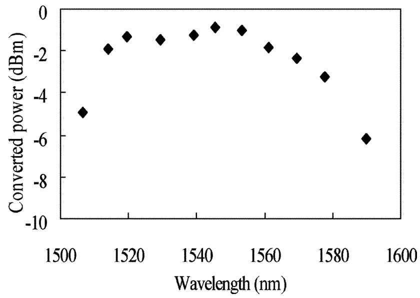


Fig. 5. Wavelength-tunable range for $\tau = 80$ ps.

decreasing. The minimum pulsewidth is limited by the rise time and fall time of the modulators. When the delay time further increases the pulsewidth begins to increase. This is because the pulse in one of the pulse trains starts to overlap with the following pulse in the other pulse train when the ODL is sufficiently long. The pulsewidth changes periodically by changing the delay time $\tau$ of the ODL. For 5-GHz RF clock, the period in which the pulsewidth changes is about 200 ps. For 10-GHz RF clock, the pulsewidth changes periodically every 100 ps.

We also investigated the wavelength tunability of the generated pulse train. The optical power launched into the PCF is fixed at 20 dBm at both $\lambda_1$ and $\lambda_2$. The wavelength of one pulse train is fixed at 1550.58 nm. The wavelength of the other pulse train is varied to get a wavelength-tunable pulse at $\lambda_3$. The average power of the generated pulse versus its wavelength $\lambda_3$ for one case $\tau = 80$ ps is shown in Fig. 5 since the pulsewidth is dependent on the optical delay $\tau$ as shown in Fig. 4. The maximum average power we can get is around $-1$ dBm. The tuning range is defined as the wavelength difference when the optical power drops by 3 dB from the maximum, which is about 70 nm (from 1510 to 1580 nm). The maximum average power for different values of $\tau$ is obviously different but the 3-dB wavelength tuning range was observed to be unchanged. Such a large tuning range is due to the small dispersion slope of the PCF around the zero-dispersion wavelength [9]. This condition follows from the following reasoning.

The bandwidth of the FWM depends on the nonlinearity-assisted phase matching of the propagation vector. Consider the phase matching parameter $\boldsymbol{\kappa}$ in FWM

$$\kappa = \Delta k_{\rm NL} + \Delta\beta \tag{1}$$

where $\Delta k_{\rm NL}$ is the nonlinear phase mismatch. The pump wavelengths are near the zero-dispersion wavelength. $\Delta\beta = \beta_{n1} + \beta_{n2} - \beta_{p1} - \beta_{p2}$ is the linear phase mismatch, where $\beta_{n1}$, $\beta_{n2}$, $\beta_{p1}$, and $\beta_{p2}$ are the propagation constants of two generated pulses and the two original pulse trains, respectively. $\Delta\beta$ can be written approximately as [10]

$$\Delta\beta = \frac{\lambda_0^4}{(2\pi c)^2} S_0[(\omega_{p1}-\omega_0)+(\omega_{p2}-\omega_0)](\omega_{n1}-\omega_{p1})(\omega_{n1}-\omega_{p2}) \tag{2}$$

where $\omega_{p1}$ and $\omega_{p2}$ are the angular frequencies of the original pulse trains, respectively, $\omega_0$ is the zero-dispersion angular frequency of the PCF, $\omega_{n1}$ is the angular frequency of the generated pulses, $S_0 = \partial D/\partial\lambda$ is the dispersion slope of the PCF, $D$ is the chromatic dispersion near the zero dispersion wavelength $\lambda_0$, and $c$ is the velocity of light in vacuum.

For a constant phase mismatch range ($a < \Delta\beta < b$), the power of the generated pulse will be in a certain range, for example, the power variation will be less than 3 dB. The wavelength $\omega_{n1}$ can be calculated from (2) by replacing $\Delta\beta$ with $\Delta\beta = a$ and then with $\Delta\beta = b$. As a result the tuning range will be $\Delta\omega_{n1} = \omega_{n1}|_{\Delta\beta=a} - \omega_{n1}|_{\Delta\beta=b}$. The tuning range will be larger when the dispersion slope $S_0$ is small, as can be deduced from (2). The dispersion slope for our fiber is small and estimated to be 0.0004 ps/(nm$^2 \cdot$ km), which results in a large tunable range. The chirping introduced by the electrooptical modulator, therefore, has little effect on the pulses because of the small dispersion-slope and the short length of PCF.

## IV. Conclusion

Both width and wavelength-tunable optical pulse train generation have been demonstrated in this letter. The generated pulsewidth is tuned by varying the delay time between the two pulse trains, which have fixed pulsewidth. The pulse wavelength is varied by keeping the wavelength of one of the original pulse trains fixed, while the wavelength of the other pulse train is changed. The pulsewidth is tunable continuously from 88 to 19 ps for a 5-GHz RF clock and tunable continuously from 39 to 19 ps for a 10-GHz RF clock. The 3-dB wavelength tuning range is about 70 nm.

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