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1.0 μm band supercontinuum generation using photonic crystal fiber and its application as multi-wavelength pulse source

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Abstract: A 1.0 μm-band supercontinuum (SC) with a flat spectral bandwidth of 6.0 nm is generated using a seed pulse source consisting of a CW light source, a phase modulator and a dispersion medium. And we use a photonic crystal fiber (PCF) as the nonlinear medium. PCF can be designed to realize high nonlinearity and low dispersion in the 1.0 μm band. Moreover, we showed that we could fine-tune the optical spectrum of the SC by changing the modulation index $\Delta\theta$ of the phase modulator in the seed pulse source. We also describe the application of the supercontinuum as a multi-wavelength pulse source in the 1.0 μm band.

Keywords: photonic crystal fiber, supercontinuum, multi-wavelength pulse source

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Internet traffic is increasing rapidly, and considerable attention has been paid to the construction of a high-speed network such as a 100 G Ethernet. A new optical communication band in the 1.0 μm region is attractive for high speed networks because we can use an ytterbium (Yb^{3+}) doped fiber amplifier (YDFA) to obtain sufficient amplification gain and compensate for the loss of the transmission fiber. Moreover, it is attractive in terms of realizing a large capacity transmission because the 1.0 μm band has a capacity of 27 THz which is more than twice that of the C band + L band, which is 11.5 THz. And photonic crystal fiber (PCF) has great potential as transmission fiber in the 1.0 μm band because PCF can be single mode for any wavelength [1]. A PCF is also suitable as a nonlinear fiber for realizing spectral broadening in the 1.0 μm band, because PCF can provide both high nonlinearity and low dispersion in the 1.0 μm band [2]. We obtained a 10 GHz optical pulse train emitted by a 1.0 μm band mode-locked Yb fiber laser and revealed the potential for realizing a multi-channel signal pulse source in a WDM transmission system operation in the 1.0 μm band [3].

In this paper, we describe the generation of a flat supercontinuum (SC) using a seed pulse source consisting of a CW light source, a phase modulator and a dispersion medium. And we examined its use as a multi-wavelength pulse source.

2 Optical seed pulse generator using phase modulator and dispersion medium

Figure 1 (a) shows the experimental setup we used to generate wideband 10 GHz pulses in the 1.0 μm band. The CW light emitted from an external cavity laser (ECL) operating at 1080 nm was coupled into a $LiNbO_3$ phase modulator (PM) and a 10 GHz sinusoidal phase modulation was applied to the CW light. The sinusoidally phase-modulated light can be converted into an optical pulse train by applying group delay dispersion (GVD) to the light [4, 5]. As a GVD device, we used a linearly chirped fiber Bragg grating (CFBG) with a −1 dB bandwidth of 20 nm and a dispersion parameter D of 60 ps/nm. We employed this method to obtain a 10 GHz optical pulse train with a low duty ratio. The waveform of the light after the GVD medium is expressed as

$$P(t) = P_{\mathrm{CW}} \cdot \left| \sum_{-\infty}^{+\infty} \left[J_n(\Delta\theta) \times \exp\left[i\left(2\pi^2 n^2 f_{\mathrm{m}}{}^2 B_2 - 2\pi n f_{\mathrm{m}} t \right) \right] \right] \right|^2 \quad (1)$$

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Here, $P_{\rm CW}$ is the power of the original CW light, J_n is a Bessel function of the first kind. n is an integer, and B_2 is the total GVD of the dispersive medium (not in unit length). In Eq. (1), we disregarded the excess losses of the phase modulator and the dispersive medium. Eq. (1) shows that the waveform of the optical pulse is determined by just three parameters, namely the phase modulation frequency $f_{\rm m}$, the modulation index $\Delta\theta$, and the total group velocity dispersion B_2. As these three parameters can be stabilized easily, we can obtain stable optical pulses using this method. For this reason, this optical pulse generation method is suitable for generating the seed pulses needed to obtain a stable SC [6].

The waveforms of the optical pulses for $\Delta\theta$ values of 8.11, 8.62, and 9.20 are shown in Figure 1 (b). The pulse widths were 4.7, 4.2, and 3.8 ps, respectively, and they agree with calculated results obtained under the same conditions. We can fine-tune the pulse width by slightly changing $\Delta\theta$.

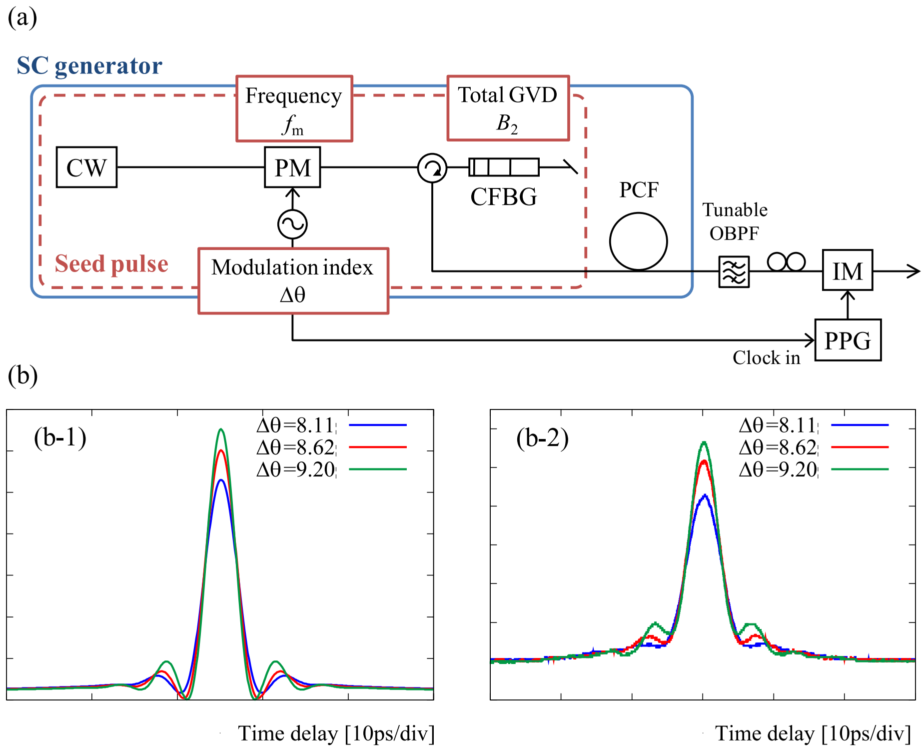

Fig. 1. (a) Experimental setup for generating wideband 10 GHz optical pulses in 1.0 μm band.
(b) Waveforms of 10 GHz seed pulses.
(b-1) Calculation results. (b-2) Measured auto-correlation traces.

3 Supercontinuum generation using 1.6 km PCF

Next, the optical pulse was amplified to an average power of 31 dBm by using YDFA, and was injected into a 1.6 km-long PCF that we fabricated. The PCF had 60 holes and the structural parameter d/Λ was 0.5. Here, d and Λ denote the hole diameter and pitch, respectively, and Λ was 5.7 μm.

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The mode field diameter (MFD) at 1080 nm was around 4.0 μm. The spectral bandwidth of the pulse was broadened by the nonlinearity of the PCF and an SC was obtained. The PCF we used had a low loss of 1.3 dB/km at 1080 nm. This low loss enables us to extend the effective length L_{eff} and utilize the nonlinearity of the fiber efficiency. The dispersion parameter D of the PCF was -10 ps/(nm·km) at 1080 nm.

Figure 3 shows the optical spectra we obtained for $\Delta\theta$ values of 8.11, 8.62, and 9.20. We obtained the best SC light with a flattened spectrum and a -10 dB bandwidth of 6.0 nm at $\Delta\theta = 8.62$. Compared with the SC spectrum at $\Delta\theta = 8.62$, the spectral bandwidth is smaller at $\Delta\theta = 8.11$ and the spectral flatness is worse at $\Delta\theta = 9.20$. As shown in Figure 2, the seed pulse waveforms for the three modulation indices are very similar. However,

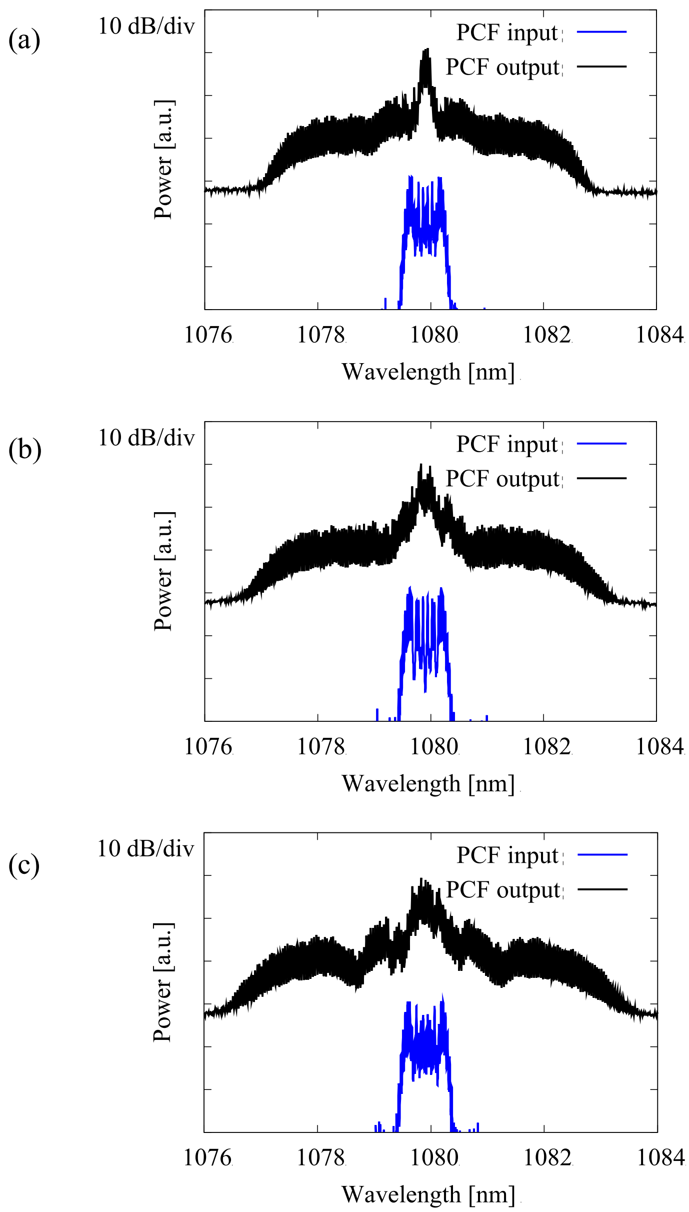

Fig. 2. Optical spectra before and after 1.6 km PCF. (a) $\Delta\theta = 8.11$. (b) $\Delta\theta = 8.62$. (c) $\Delta\theta = 9.20$.

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as shown in Figure 3, the difference between the optical spectra of the SC lights for these modulation indices is relatively large. This indicates that we can optimize the optical spectrum of the SC light by fine-tuning the phase modulation index $\Delta\theta$ which would be difficult if we used a mode-lock laser as a seed pulse source.

4 Application as multi-wavelength pulse source

The SC light generated at $\Delta\theta = 8.62$ was coupled into a tunable optical band-pass filter (OBPF) with a 0.7 nm bandwidth, and we obtained 10 GHz optical pulses at arbitrary wavelengths of 1078, 1079, 1080, 1081, and 1082 nm. To observe the quality of the generated optical pulses, we inserted a $LiNbO_3$ intensity modulator (IM) and applied intensity modulation with a 10 Gbit/s $2^{15} - 1$ PRBS signal to the 10 GHz pulse train. Figure 3 shows the average received power at a BER of 10^{-9} measured at the above five wavelengths. The dashed line shows the result of a back-to-back measurement. The power penalty was below 1.2 dB. We confirmed that the eye opening was clear at every wavelength. The source has the potential to realize stable multi-wavelength pulse generation.

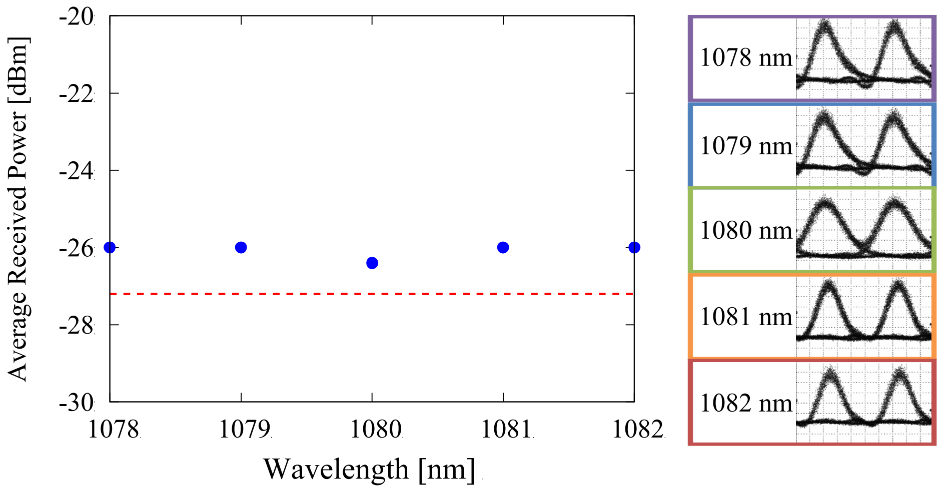

Fig. 3. Average received power of 10 Gbit/s signal at BER $= 10^{-9}$.

5 Conclusion

We described 1.0 μm band SC generation using a simple and compact seed pulse source with a phase modulator and a dispersion medium. Using this seed pulse source, we obtained an SC with a flat optical spectrum. Moreover, we showed that we could fine-tune the optical spectrum of the SC by changing the modulation index $\Delta\theta$ of the phase modulator in the seed pulse source. We also showed that we could realize a stable multi-wavelength pulse source in the 1.0 μm band with this SC generation method.

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