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1.0 μm band supercontinuum light as WDM pulse source generated by using photonic crystal fibers

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Abstract: This paper describes a supercontinuum (SC) generation in 1.0 μm band using photonic crystal fibers. To generate the SC, we have utilized two photonic crystal fibers with length of 1 km and 300 m, and an optical band pass filter inserted between them. We have obtained a 10 GHz, 1.0 μm band WDM pulse source with a large spectral bandwidth of 4.22 THz. The SC can be applied to WDM pulse source for 1.0 μm band large-capacity transmission and the obtained SC has the potential to realize terabit/s WDM signal pulse generation.

Keywords: photonic crystal fiber, WDM pulse generation, supercontinuum

Classification: Photonics devices, circuits, and systems

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1 Introduction

The rapid increase in broadband Internet services has provided motivation for the development of a high-capacity optical transmission system. One way to increase transmission system capacity is to develop a new wavelength band. When we construct a WDM transmission system in the new wavelength band, it's better if we can construct a WDM light source with a simple configuration. A spectrally sliced optical pulse generation utilizing supercontinuum (SC) is an attractive method to obtain a number of WDM signal pulse and to construct an ultralarge-capacity photonic network. Morioka *et al.* reported the generation of more than 40 WDM signal pulse streams at 6.3 Gbit/s over 1530–1570 nm [1]. A new optical communication band at 1.0 μm region is promising for development since 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 [2]. Photonic crystal fiber (PCF) has great potential as a transmission fiber in 1.0 μm band because PCF can be single mode for any wavelength [3]. A PCF is also suitable as a nonlinear fiber for realizing spectral broadening in the 1.0 μm band, because PCF can provide high nonlinearity and low dispersion in the 1.0 μm band. There have been some reports describing supercontinuum generation in the 1.0 μm band using centimeter- and meter-long PCFs [4, 5]. The reported broadened spectrum is not designed for WDM signal pulse generation and the repetition rates of the pulses used in these experiments are in the kHz to MHz region. To realize optical spectral broadening for application to WDM signal generation, we have to use an optical pulse train with a higher repetition rate of GHz order. In this case, a long and low loss PCF is required for the spectral broadening because the peak power of the optical pulse is reduced by increasing the repetition rate. However, no such spectral broadening experiment in the 1.0 μm band has yet been reported.

In this paper, we describe a novel wideband and high repletion rate optical pulse generator in the 1.0 μm band that utilizes the nonlinearity of the long, low loss PCFs we fabricated. The optical spectrum of a 10 GHz pulse train emitted from a mode-locked Yb fiber laser operating in the 1.0 μm band [6] is broadened to more than 1.53 THz (5.7 nm) by using a 1 km-long PCF. By tuning the emission wavelength of the mode-locked fiber laser, we obtained a broadened optical spectral range from 1051 to 1085 nm. Moreover, we incorporated an optical band-pass filter (OBPF) and a 300 m-long PCF after the 1 km-long PCF to obtain a broader bandwidth, which resulted in further

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spectral broadening to 4.22 THz (16.6 nm).

2 Spectral broadening using 1 km PCF

To generate wideband 10 GHz pulses in the 1.0 μm band, we used a harmonically mode-locked Yb fiber ring laser operating in the 1.0 μm band as a seed pulse source. The repetition rate of the pulse laser was stabilized at 10 GHz by using phase-locked loop (PLL) technology. The emission wavelength was tuned from 1054 to 1080 nm by inserting a tunable 3-nm-bandwidth OBPF in the ring cavity. The pulse width and optical frequency bandwidth of the laser output at the emission wavelength of 1080 nm were 10.5 ps and 44 GHz (0.17 nm), respectively, giving a time-bandwidth product of 0.46. The optical pulse from the laser was amplified to a peak power of 13 W by using a YDFA and was injected into a 1-km long PCF. The spectral bandwidth of the pulse was broadened by the nonlinearity of the PCF (mainly by self-phase modulation: SPM). 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 efficiently. The zero dispersion wavelength λ_0 of the PCF was 1092 nm, and we used the PCF in the normal dispersion range below λ_0 to reduce the noise due to modulation instability [7]. The mode field diameter of the PCF is 4.8 μm at 1064 nm. We measured optical spectra at a 1 km PCF output for mode-locked fiber laser emission wavelengths (λ_{laser}) of 1054, 1060, 1068 and 1080 nm. Figure 1 shows the obtained optical spectra. It can be seen that the −10 dB bandwidth of the optical spectrum is broadened to 5.7–10.0 nm (1.53–2.60 THz), and we can obtain a broadened optical spectrum for any wavelength region from 1051 to 1085 nm by tuning the emission wavelength of the mode-locked fiber laser.

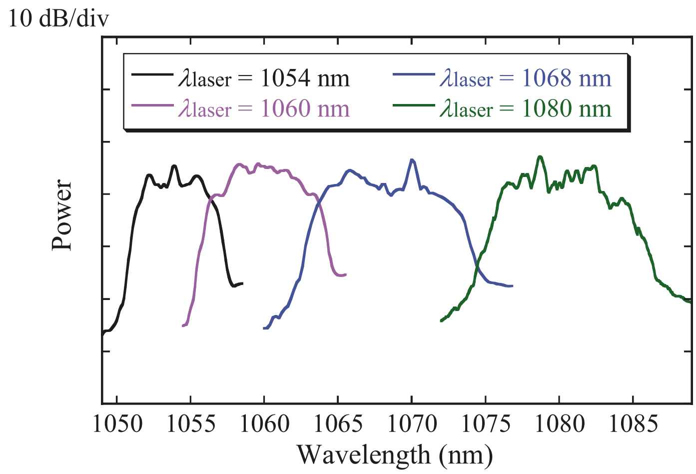

Fig. 1. Optical spectra of SC after 1 km PCF.

3 Further spectral broadening by adding OBPF and 300 m PCF

A SC with broader optical spectrum is preferable in terms of increasing the number of WDM pulse wavelengths. However, when we increased the input

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pulse power into the 1 km PCF furthermore, the intensity noise of the pulse was considerably increased. So we adopted another method to realize further spectral broadening, that is, we added an optical bandpass filter and an incremental 300 m-long PCF. Figure 2 shows the experimental setup. In this experiment the emission wavelength of the mode-locked fiber laser was set at 1080 nm. The output of the 1 km PCF was filtered out by using an OBPF with a center wavelength of 1077.5 nm and a −3 dB bandwidth of 0.7 nm. The optical pulse width of the 10 GHz optical pulse train at the OBPF output was 5.2 ps, which is approximately half of the mode-locked fiber laser output. After the OBPF, the optical pulse was amplified to a peak power of 25 W by using a YDFA, and then injected into a 300-m long PCF, where the spectrum was broadened further. The addition of the filter and PCF corresponds to the regeneration of a broader optical spectrum by using an optical pulse with a smaller pulse width. This two-stage spectral broadening method is preferable because the use of a pulse with a smaller pulse width and nonlinear fiber with a shorter fiber length are desirable in terms of realizing spectral broadening while avoiding the pulse degradation. We sliced the broadened optical spectrum using a tunable OBPF with a bandwidth of 0.7 nm, and obtained a 10 GHz optical pulse train with an arbitrary wavelength.

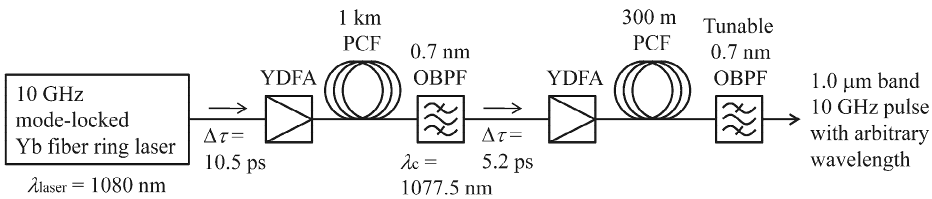

Fig. 2. Experimental setup for further spectral broadening of 10 GHz pulse.

Figure 3 shows the optical spectra measured at the output of a 1 km PCF, and a 1 km + 300 m PCF. By adding the OBPF and the 300 m PCF, the −10 dB bandwidth of the 10 GHz optical pulse was broadened from 9.0 nm (2.29 THz) to 16.6 nm (4.22 THz). By using a 1.0 μm band AWG filter instead of the tunable 0.7 nm OBPF after the 300 m PCF, we can simultaneously obtain multi-channel 10 GHz optical pulses operating in the 1.0 μm band. When we fully utilize the broadened optical spectrum of 4.22 THz, we can generate 1.7 terabit/s WDM signals by setting the 10 Gbit/s signal channel separation at 50 GHz and by simultaneously using polarization multiplexing. The inset in Fig. 3 shows an autocorrelation trace of the 10 GHz optical pulse at the output of the OBPF (center wavelength: 1073.5 nm) after the 300 m PCF, where the FWHM of the trace and the corresponding pulse width are 5.1 and 3.6 ps, respectively. Since the optical pulse width is compressed from 10.5 to 3.6 ps and the resulting duty ratio of the 10 GHz optical pulse shown in Fig. 3 is only 3.6%, it is possible to utilize the 10 GHz pulse to generate an optical time division multiplexing (OTDM) signal and realize a higher transmission rate.

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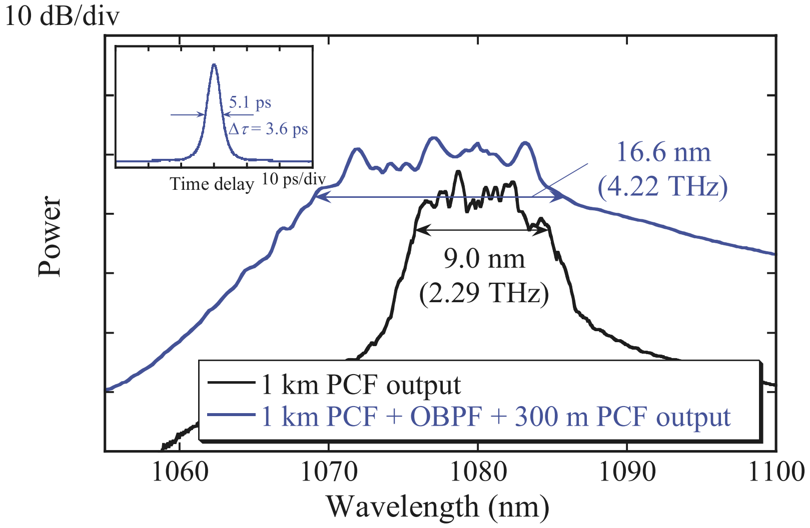

Fig. 3. Optical spectra (The inset shows autocorrelation trace).

4 Conclusion

This paper described the SC generation in 1.0 μm band using photonic crystal fibers. The optical spectrum of a 10 GHz optical pulse train emitted by a 1.0 μm band mode-locked Yb fiber laser was broadened to 4.22 THz by using the nonlinearity of two (1 km- and 300 m-long) PCFs with a 0.7 nm-bandwidth OBPF inserted between them. This result reveals the potential for realizing a multi-channel signal pulse source in a WDM transmission system operating in the 1.0 μm band.

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