Spectra and Phases of Supercontinuum Pulses Generated in Tapered Fiber and Photonic-Crystal-Fiber with Low Dispersion

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(Received June 23, 2011)

Recently, optical pulses propagating through a tapered fiber (TF) immersed in heavy water (D_2O) or photonic crystal fiber (PCF) of a special design were reported to yield a broad and flat supercontinuum (SC) spectrum because the fiber dispersion characteristics are of low dispersion around 1000 nm. This study was undertaken to investigate spectral intensities and phase distributions of SC pulses generated in low-dispersion fibers. Results show that highly nonlinear PCF with group velocity dispersion (GVD) distributions having an extremum value and zero dispersion around 1000 nm is useful at short fiber length for applications in which the phase distribution is a concern.

Key Words: Nonlinear fiber optics, Supercontinuum generation, Tapered fiber, Heavy water (D_2O), Photonic crystal fiber (PCF)

1. Introduction

A tapered conventional communication fiber (TF) with thin clad diameter of a few micrometers, when immersed in heavy water (D_2O), is known to have an altered effective index of the fiber cross section. For that reason, it produces a low group velocity dispersion (GVD) in a wide range around 1000 nm.[1–3] A photonic crystal fiber (PCF) that yields similar characteristics was developed. It has repeated holes in a clad of silica fiber with an interval of approximately the optical wavelength.[4–6] By injecting an ultra-short pulse into these fibers, the SC pulses are generated efficiently. Those SC pulses accompany phase distribution as a function of wavelength. Therefore, the SC pulse conditions cannot be used simultaneously over the entire range of the SC wavelength. Detailed information related to the phases is indispensable for the efficient use of SC pulses. Nevertheless, few studies have examined this problem. We experimentally investigated spectral intensities and phase distributions of SC pulses generated in low-dispersion fibers.[7]

2. Experiment

Our experimental setup is presented in Fig. 1. The TF structure used in our studies is presented in Fig. 2. The TF is made from single mode fiber (SMF-28) with a heat-drawing device for producing fiber couplers. After fabrication, the TF was encased in the glass tube. The taper region and waist of the TF are exposed to room air or to D_2O. Two PCFs with low dispersion at the incident light wavelength were examined. The two PCFs are NL-4.7-1030 (PCF1) and NL-1050-zero-2 (PCF2) of 0.15 m and 1 m length, respectively, produced by NKT Photonics A/S. Figure 3 presents the calculated GVD characteristics of the waist of TF (gray broken and solid lines)[3,7] and two PCFs (black broken and solid lines).[5–7] The mode-field diameter (MFD) of PCF1 and PCF2 was 3.8 μm and 2.2 μm at 1060 nm, respectively. The nonlinear coeffi-

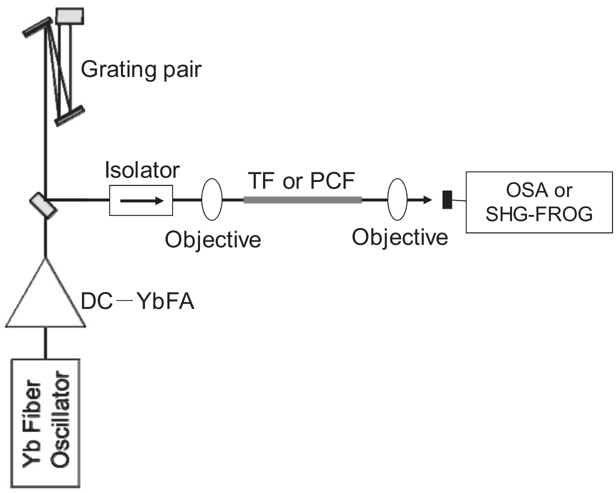

Fig. 1 Experimental setup including Grating pair (1000 lines/mm) and double-clad Yb fiber amplifier (DC-YbFA) system.[8]

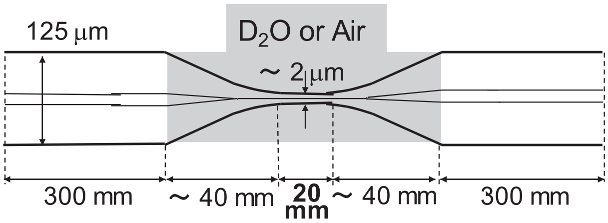

Fig. 2 Structure of a TF.[7)]

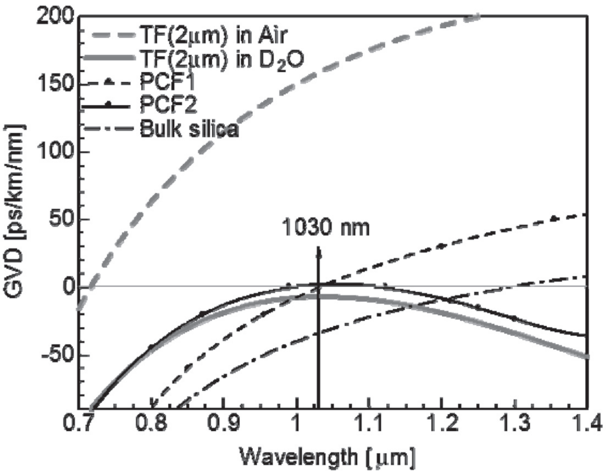

Fig. 3 GVD curves for the waist of TF immersed in air (or heavy water (D_2O)), PCF (PCF1; NL-4.7-1030, PCF2; NL-1050-zero-2, made by NKT Photonics A/S) and bulk silica.[7)]

cient γ of PCF1 and PCF2 was 12 $(Wkm)^{-1}$ and 37 $(Wkm)^{-1}$ at 1060 nm, respectively. The incident light was produced by an ytterbium (Yb) fiber oscillator at the repetition rate of 100 MHz. The incident ultra-short pulses were amplified to several watts of average power by a double-clad Yb fiber amplifier (DC-YbFA). The incident power of these pulses was varied by changing the pump power of the amplifier. For this experimental set up, the temporal pulse shape is constant over the whole power range, which is already reported in Ref. 8. For the TF, these incident pulses at the center wavelength of 1030 nm are compensated by using a grating pair so that the transform limited pulse width is 220 fs after passing through the single mode fiber of 30 cm. In the case of the PCFs, the incident light pulse width is 170 fs at the center wavelength of 1035 nm, which is transform limited pulse. The spectral intensity as a function of wavelengths of the output pulse was measured using an optical spectrum analyzer (OSA). The phase was calculated as a function of wavelengths from a high-speed recording spectrogram using second harmonic generation – frequency resolved optical gating (SHG-FROG) method.[9)] The thickness of the SHG crystal (BBO) in the FROG device was 300 μm, which is sufficiently thin to enable FROG measurements within a range of 130 nm.

3. Results and discussion

3.1 SC generated using TF

Spectral intensities obtained using OSA and phase distributions calculated using SHG-FROG traces generated through TF are portrayed in Fig. 4. The phase as a function of wavelength is shown within a range of 130 nm, which is limited by the SHG crystal.[10)] Gray lines show TF results in air. Black lines show those in D_2O. The average power of input pulses in each was 3 W (coupling efficiency of 38%). The retrieval FROG error was found to be 0.0294 for air and 0.0211 for heavy water, respectively. It had wide SC spectral intensities generated using TF. Lower performance of TF in generating SCs might be attributable to shortening of the low-dispersion part, which brought about the short length of the waist (20 mm) and GVD of 40-mm-long taper region connecting normal fiber (300 mm). Although a slight difference of spectral shape and width is apparent for the two environments, results show that the difference between the maximum and minimum phases (maximum phase difference) in D_2O is less than that in air, which might be attributable to the lower GVD around the wavelength of incident light in D_2O, as presented in Fig. 3.

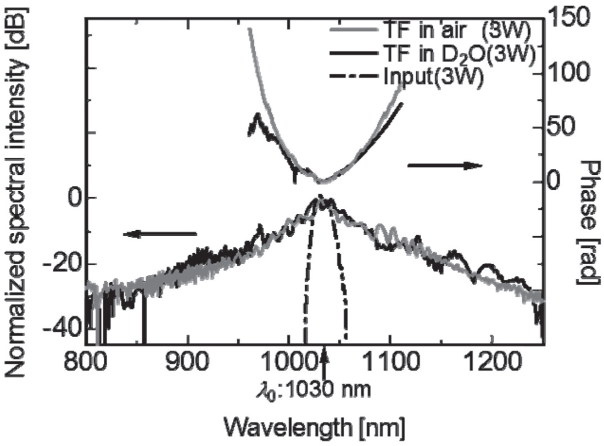

Fig. 4 Spectral intensities (measured using OSA) and phase distributions (calculated using SHG-FROG traces (within a range of 130 nm)) of supercontinuum pulses generated through TF in air and TF in D_2O.

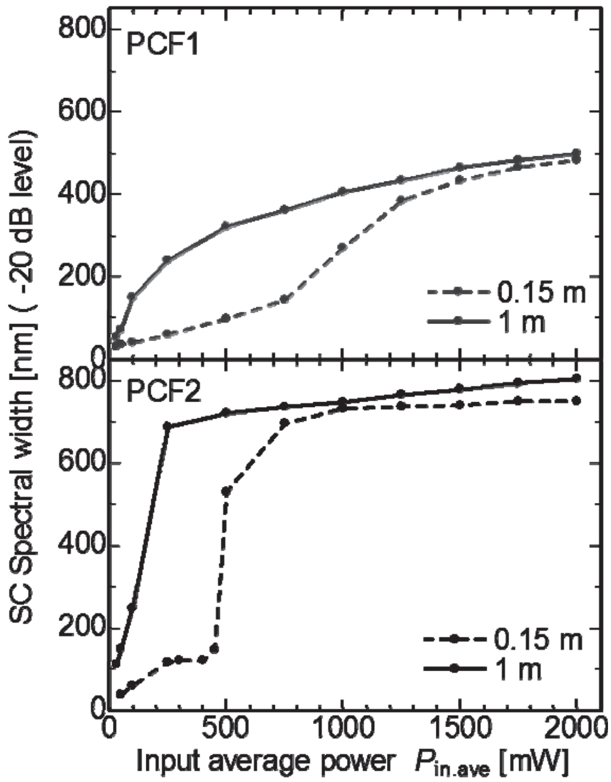

Fig. 5 SC spectral width (at the −20dB level) as a function of input average power.

3.2 SC generated using PCF

3.2.1 Dependence of SC Spectral width on input power

The SC spectral intensities generated using TF in the previous section were narrow. Because of the short length of the TF waist, however, it is difficult to prepare a TF with a long waist. Therefore, we examined PCF, which can make use only of that waist of TF with low-dispersion that is sufficiently long. The spectral width of SC at the −20dB level versus input average power is presented in Fig. 5. Gray lines represent PCF1 in the upper figure of Fig. 5; black lines show PCF2 in the lower figure of Fig. 5. Solid lines show data for a fiber length of 1 m. Broken lines show data for the fiber length of 0.15 m. The coupling efficiencies were, respectively, 20% for PCF1 and 14% for PCF2. Compared to the TF performance (Fig. 4), the width of SC spectra generated through PCF is wider with lower input power. The longer fiber (1 m) in both PCFs generates SC at lower input power because of the greater length of nonlinear interaction, as we had expected. With increase of the input power, the SC width using PCF1 (upper figure of Fig. 5) was increased uniformly, as shown in Ref. 4 which is described about PCF with GVD dispersion crossing zero. On the other hand, in the case of using PCF2 (lower figure of Fig. 5) with GVD distributions having an extremum value of zero dispersion, the SC spectrum appearing on the short wavelength side and long wavelength side from the center wavelength enhanced SC spectral width, as shown in Ref. 6. The zero dispersion wavelength of PCF1 is near the incident center wavelength and coupling efficiency of PCF1 is better than that of PCF2, nevertheless we infer that the PCF2 is better at generating SC pulses. Because the nonlinear coefficient γ of PCF2 is about three times higher than that of PCF1 and GVD distribution of PCF2 yields low normal dispersion at a wide range around the incident central wavelength (Fig. 3).

3.2.2 Spectral intensities and phase distributions of SC pulses

Figure 6 presents detailed results related to spectral intensities of SC pulses measured using OSA. Figure 7 shows calculated phase distributions around the wavelength of incident light obtained using SHG-FROG. Gray and black lines respectively present results for PCF1 and PCF2. Solid lines show data for a fiber with 1 m length with average input power of 250 mW (coupling efficiencies were 20% for PCF1 and 14% for PCF2). Broken lines show data for a fiber with 0.15 m length with average input power of 750 mW (coupling efficiency was 12%). The retrieval FROG error was found to be 0.0222 for PCF1, 0.0172 for PCF2 1 m and 0.0078 for PCF2 0.15 m, respectively. Examination of two spectral intensities of black and gray solid lines suggests as follows. Especially, in the case of using PCF2 with GVD distributions having an extremum value of zero dispersion, the SC spectrum appearing on the short wavelength and long wavelength side from the center wavelength enhanced SC spectral width,[6] as stated in section 3.2.1. Because the PCF2 generates a wide SC spectrum efficiently at lower power than PCF1 with GVD distributions crossing zero dispersion.

In addition, comparison of phase distributions of these two lines shows that PCF2 yields a greater maximum phase difference because of the high nonlinearity, but this distribution behaves roughly as a parabolic function of frequency. The latter property might be useful to compensate the dispersion. Comparison of phase distributions of the black solid (1 m, 250 mW) and broken lines (0.15 m, 750 mW) shows a smaller maximum phase difference for the shorter fiber.

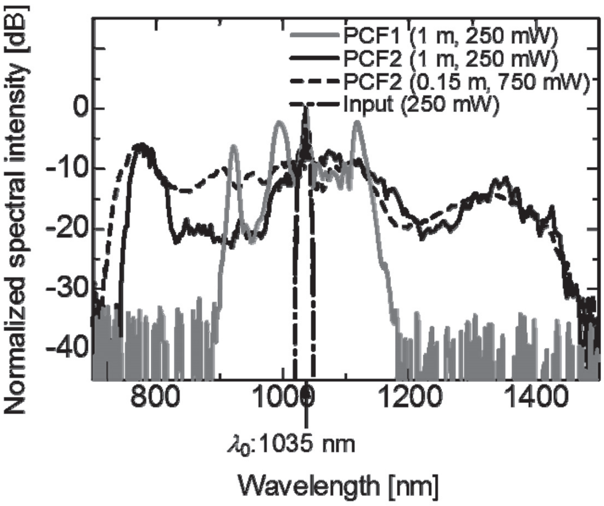

Fig. 6 Spectral intensities of supercontinuum pulses generated through PCF as a function of wavelength, measured using the optical spectrum analyzer (OSA).

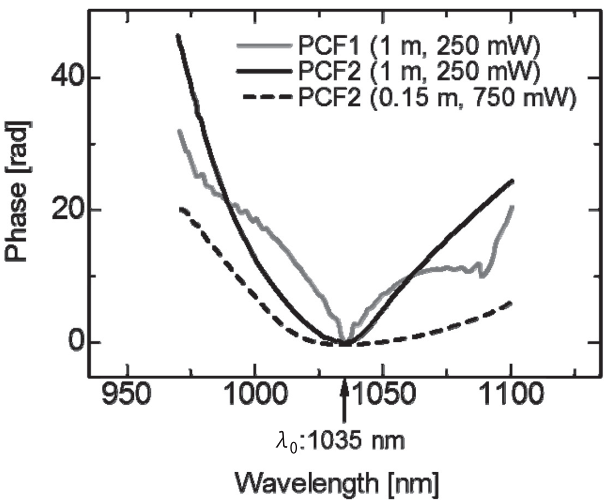

Fig. 7 Phase distributions of supercontinuum pulses generated through PCF. Calculated using SHG-FROG traces (within a range of 130 nm).

4. Conclusions

We examined spectral intensities and phase distributions of SC pulses generated by two TFs, one TF was exposed to air and the other TF to D_2O. Although the two spectral intensities for these two TFs do not differ greatly from each other, the maximum difference of phases is smaller in the D_2O environment. We also examined two PCFs with low dispersion for their performance in generating SC pulses. Results show that the PCF with highly nonlinear coefficient and with GVD as a function of wavelength having an extremum value of zero dispersion generates SC pulses at lower power of the input pulse more efficiently than PCF with lowly nonlinear coefficient and with GVD crossing zero dispersion. Furthermore, the phase distribution of PCF with GVD distributions having an extremum value of zero dispersion behaves roughly as a parabolic function of frequency. The same PCF with shorter length of 0.15 m provides sufficiently wide SC spectra of 650 nm at the −20dB level with a smaller maximum phase difference of 20 rad in the range 130 nm. Results show that, for applications where the phase distribution is a concern, highly nonlinear PCF with GVD as a function of wavelength having an extremum value of zero dispersion is useful for short fiber lengths.

Acknowledgments

The authors thank Prof. Katsumi Morishita at the Osaka Electro-Communication University for setting a device for producing the TF and Dr. Masaaki Imai, Professor Emeritus of Muroran Institute of Technology for his valuable comments. A part of this research was supported by a Grant-in-Aid for Scientific Research (C) (No. 21560038).

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