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The Effect of Input Azimuth of Cross-Phase-Modulated Soliton Pulses on Supercontinuum Generation in a Dispersion-Flattened/Decreasing Fiber with Low Birefringence

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SUMMARY It is found that the supercontinuum spectrum is generated from cross-phase modulated soliton pulses which are propagated through a dispersion-flattened/decreasing fiber with low birefringence. The cross-phase modulation is achieved by exciting two orthogonally polarized modes in a birefringent fiber and the effect of input azimuth of linearly polarized pulses is discussed theoretically and numerically.

key words: *nonlinear wave propagation, supercontinuum spectrum, optical soliton, cross-phase modulation, dispersion-flattened/decreasing and birefringent fiber*

1. Introduction

Generation of supercontinuum (SC) in optical fibers is very attractive for large-capacity.

Optical communication systems since SC can produce short optical pulses over a broad spectral range of more than a few hundred nm [1]. It is well known that a high-quality and broad SC spectrum is generated by self-phase modulation (SPM) in optical fibers with a dispersion-flattened and dispersion-decreasing characteristic [2]–[4]. For such a dispersion-flattened/decreasing fiber (DFDF) whose group-velocity dispersion (GVD) not only decreases with the fiber length but also has a convex shape with respect to the central wavelength analysis and design of SC pulse generation have been discussed theoretically and experimentally [5]. In contrast, cross-phase modulation (XPM) induces pulse compression and leads to SC generation in the anomalous GVD region of a polarization maintaining (birefringent) fiber that is not a DFDF [6]. Due to interaction between the orthogonally polarized components of a single beam, XPM coupling enhances the phase modulation of light induced in highly nonlinear dispersion-shifted fibers with birefringence.

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We report here the generation of a broad and flat supercontinuum in a conventional low-birefringent telecommunication fiber whose flattened profile of GVD decreases along the fiber length [7]. For example, a special fiber like DFDF with a low birefringence is taken into account in analysis. The effect of XPM preferentially takes place by exciting two orthogonally polarized optical pulses at the input end of the fiber [8]. The wave-vector mismatch (WVM) between these pulses that occurs in due course of XPM can be neglected because of soliton trapping [9]. It is required for soliton pulses to interact through the process of XPM that the modal birefringence of DFDF be less than 10^{-6} for typical fiber parameters.

Under such conditions, when the input azimuth of linearly polarized pulse is between 0° and 45° with respect to the fast axis (x axis) of the birefringent fiber, the output intensity which is found by superimposing the two orthogonal components at the same azimuth as the input, exhibits a flat SC spectrum. Due to the interplay of XPM and GVD without wave-vector mismatch, a SC spectrum as broad as 340 nm is obtained in a low-birefringent DFDF.

2. Analytical Model for SC Generation

Figure 1 shows a simulation model of SC spectrum generation by utilizing XPM in a DFDF. In the inset, the principal axes, i.e., the fast and slow (x and y) ones at the input end of a birefringent fiber are also shown. As seen the figure, θ_{xy} denotes an polarization angle of input azimuth measured from the fast (x) axis.

An ultrashort optical pulse generated from a mode-locked Er^{3+} doped fiber ring laser (ML-EDFRL) is a sech^2 type transform limited (TL) pulse with a pulse duration of 3.5 ps and a center wavelength of 1.55 μm. The optical pulses were amplified to a peak power of few watts with Er^{3+} doped fiber amplifier (EDFA). The

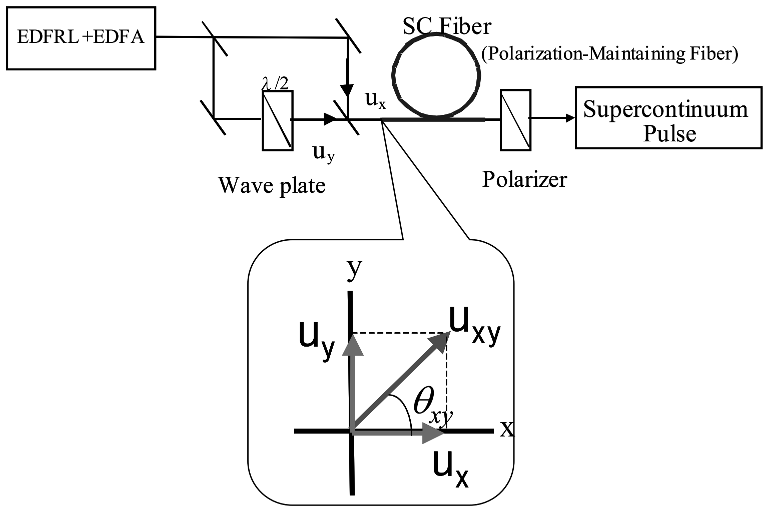

Fig. 1 Simulation model of SC spectrum generation by utilizing XPM in a DFDF with low birefringence.

$\lambda/2$ wave plate in Fig. 1 is required to generate two orthogonally polarized fundamental soliton pulses at the input end of SC fiber (polarization-maintaining fiber). Then, the polarizer is used to detect the optical pulses at arbitrary azimuths for inspection of an ultra-wide supercontinuum spectrum. For numerical analysis, the coupled nonlinear Shrödinger equations are numerically solved by the help of a split-step Fourier analysis [8]. In the equations, the effects of higher-order dispersion, as well as nonlinearities of self-phase modulation (SPM), cross-phase modulation (XPM) (coupling between orthogonally polarized waves of the same frequency), self steepening and stimulated Raman scattering (SRS) are included. The generalized Raman scattering susceptibility can be approximated in the harmonic oscillator model for molecular vibrations [10]. The rigorous numerical analysis of SC generation over a broad spectral range of more than a few hundred nm becomes possible using the Lorentzian model.

The fiber used for numerical simulation is a W-type profile of refractive index distribution whose GVD characteristic is assumed to vary along the length of the fiber [4]. For a W-type fiber, general propagation properties and dispersion curves have already been reported elsewhere. The test fiber with a dispersion-flattened characteristic is anomalous-dispersion at the input end, zero-dispersion at the distance of 2.184 km, and normal-dispersion at the output end. It is also found that the wavelength-dispersion characteristic of a W-type fiber is more symmetrical at the center wavelength λ_0 compared to a bulk SiO_2 fiber. This fact results in the calculated SC spectrum in symmetry with respect to λ_0. At center wavelength ($\lambda_0 = 1.55\,\mu$m) zero-dispersion is observed at the distance of 2.184 km. An adiabatic soliton compression occurs in due course of optical propagation along the fiber. In a DFDF, it is pointed out that the soliton order N=1 is maintained throughout the propagation of the optical pulse due to adiabatic compression [11], [12]. This means that even if the dispersion characteristics of the wave guide changes, and then the optical pulse becomes narrow and its peak power increase while the pulse propagates down the DFDF, the behavior of soliton order N=1 is held in the spatial evolution. Therefore, because of the compression of optical pulse, the nonlinear effects like SPM and XPM dominates over the dispersion effect. The optical pulses which propagate down the anomalous-dispersion and reach the normal-dispersion region are affected by spectrum broadening [8].

3. Numerical Results and Discussion

The enlargement of the SC spectral width due to XPM coupling can then be evaluated quantitatively. The two orthogonally polarized pulses are sech^2 type transform limited (TL) and fundamental soliton (N=1). It is noted that the total incident power is defined as a sum of two pulses i.e., twice the peak power P_0 which satisfies the fundamental soliton condition in XPM regime. The analytical model of the two orthogonally polarized pulses is realized by inserting a half-wave plate in one arm of the optical beam paths and combining the split beams at the input end of the fiber [8]. The GVD profile of the W-type fiber under test represents the characteristics of the DFDF and is shown in Table 1 together with the optical soliton parameters. In the numerical simulations, P_0=2.3 W (N=1 soliton order), T_0=1.986 ps (t_p is 3.5 ps) and λ_0=1.55 μm are used with other parameters listed in Table1. It was found that the condition of soliton trapping is satified when the modal birefringence is approximately less than 10^{-6}, based on the criterion given by Agrawal's book [11]. In addition, it is reminded that time delay between the input fields ux and uy orthogonally polarized solitons

Table 1 SC fiber parameters at input end and optical soliton parameters of incident light.

Center wavelength λ_0	1.55 [μm]
Pulse width t_p	3.5 [ps]
Peak power P_{0x}, P_{0y}	2.3 [W]
Soliton order N	1.0
Effective core area $A_{\rm eff}$	50 [μm^2]
Nonlinear refractive index n_2	3.0×10^{-20} [m^2/W]
Modal birefringence Δn_{xy}	5×10^{-7}

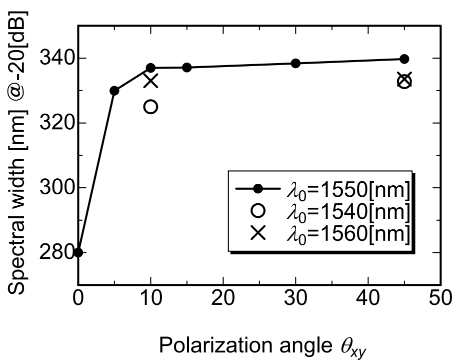

Fig. 2 SC spectral width plotted as a function of polarization angle θ_{xy}.

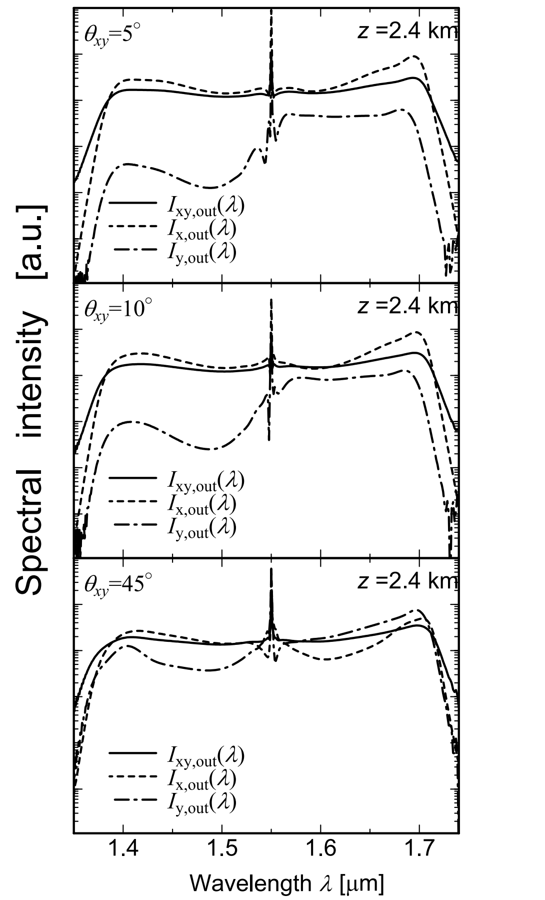

Fig. 3 Calculated spectral intensities of soliton pulses $I_{x,\rm out}$ (dashed line), $I_{y,\rm out}$ (dotted-chain line) and $I_{xy,\rm out}$ (solid line) at the exit end (z = 2.4 km) of a DFDF at some polarization angles of θ_{xy} = 5°, 10°, 45°.

depends on modal birefringence ($|n_{0x} - n_{0y}| = \Delta n_{xy}$) because the time delay is given by $\Delta t_{xy} = \Delta n_{xy} \cdot k'_0 \cdot z$ where $k'_0 (= k'_{0x} = k'_{0y})$ is group-velocity at the incident central wavelength and z is the propagation distance. For $\Delta n_{xy} \leq 10^{-6}, \Delta t_{xy} \leq 27.84$ ps is obtained at z=2.4 km of a DFDF in which XPM between orthogonally polarized solitons occurs due to soliton trapping [8]. Therefore, SC generation induced by XPM effect is supported under the requirement of soliton trapping, i.e., in a DFDF with $\Delta n_{xy} = 5 \times 10^{-7}$ where time delay of approximately 14 ps is much smaller than the critical value of $\Delta t_{xy} = 27.84$ ps.

It is noted here that modulation instability occurs in such a low-birefringent optical fiber. Owing to Agrawal's book [11], however, in the cause of nonlinear length L_{NL} is larger than the beat length L_B, solitons remain stable whether the optical pulse is launched close to the slow on the fast axis [11] because the induced refractive index changes due to optical Kerr effect does not exceed the modal birefringence when $L_{NL} > L_B$. For numerical examples of Table 1, $L_{NL} = 1/(\gamma P_0) = 178.9$ m, and $L_B = 2\pi/(\Delta n_{xy} k_0) = 2.147$ m. This means that the optical soliton is stable in a DFDF with low birefringence. Under such a condition, we calculated the SC spectrum in the polarization angle of $0° \leq \theta_{xy} \leq 45°$ since the dependence of input azimuth between 45° and 90° on SC generation holds in the case of neglecting modulation instability.

In Fig. 2, the numerical results of SC spectrum at the output end of the fiber (z=2.4 km) is plotted at some polarization angles (=θ_{xy}). Here, it is assumed that the polarizer is set at the same angle (θ_{xy}) of input azimuth to obtain the maximum output intensity composed of the x and y polarizations. At $\theta_{xy} < 10°$, the SC spectral width decreases with a decrease of θ_{xy}. However, when $\theta_{xy} \geq 10°$ the spectral width increases slowly with increasing θ_{xy}. Moreover, the SC spectrum generated by the different wavelengths of incident light is also shown in the figure. The numerical results for λ_0 = 1540 nm and 1560 nm are depicted by a circle (◯) and a cross (×), respectively, at the polarization angles θ_{xy} = 10° and 45°. It is seen from the figure that the SC spectrum becomes slightly narrower as the input wavelength is less than or greater than the central wavelength λ_0. Moreover, the dependence of the incident wavelength on the spectrum broadening appears noticeable when the angle θ_{xy} is small. In order to gain insights into XPM induced SC spectrum the spectrum distributions of soliton pulses are shown for different input azimuths of θ_{xy} = 5°, 10° and 45° at λ_0 = 1550 nm in Fig. 3. In Fig. 4, those of θ_{xy} = 10° and 45° at different input wavelengths of λ_0 = 1540 nm

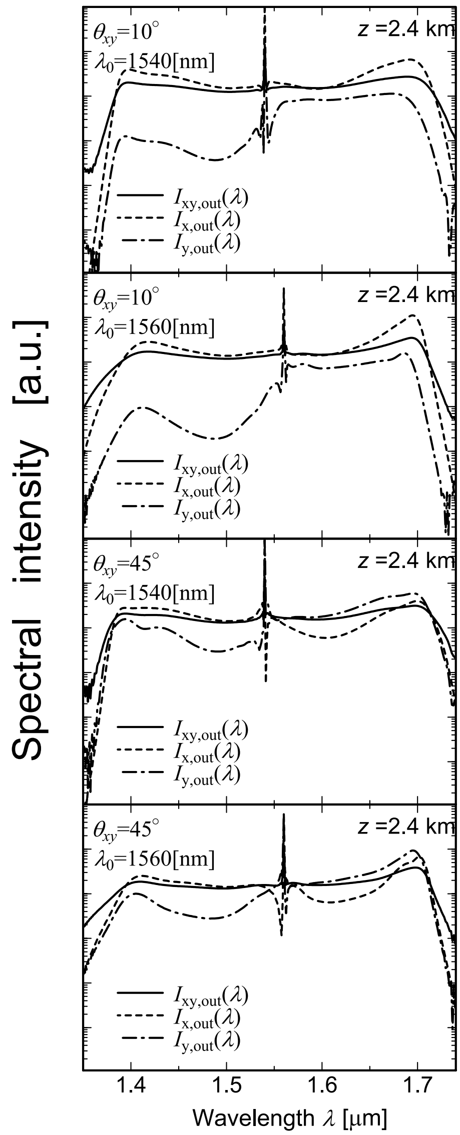

Fig. 4 Calculated spectral intensities of soliton pulses $I_{x,\mathrm{out}}$ (dashed line), $I_{y,\mathrm{out}}$ (dotted-chain line) and $I_{xy,\mathrm{out}}$ (solid line) at the exit end ($z = 2.4\,\mathrm{km}$) of a DFDF at 10° and 45° when the incident wavelengths of 1540 nm and 1560 nm are employed instead of $\lambda_0 = 1550\,\mathrm{nm}$.

and 1560 nm are also shown for comparison. In order to gain insights into SC spectrum broadening, the spectral distributions of soliton pulses are shown for different input azimuths of $\theta_{xy} = 5°$, 10° and 45° in Fig. 3. In each figure, the output intensities at the fast axis (x-axis), slow axis (y-axis) and the incident azimuth (θ_{xy}) are denoted by $I_{x,out}$ (dashed line), $I_{y,out}$ (dotted-chain line), and $I_{xy,out}$ (solid line), respectively. It is apparent that $I_{x,out}$ (dashed line) represents a rather symmetric distribution, independent of θ_{xy} whereas $I_{y,out}$ (dotted-chain line) deforms in a shorter wavelength region as θ_{xy} decreases. However, the superimposed spectral intensity $I_{xy,out}$ (solid line) in logarithmic scale behaves similarly, irrespective of θ_{xy}. This means that the complementary fashions of $I_{x,out}$ and $I_{y,out}$ are cancelled out at a shorter wavelength region. Then, for a broad and flat SC spectrum, it is necessary to coincide the axis of a polarizer with the input azimuth of linearly polarized soliton pulse. As mentioned above, when a mismatch of the incident wavelength and the center wavelength λ_0 happens at small angles of θ_{xy}, the spectrum distributions $I_{x,out}$ and $I_{y,out}$ tend to be deformed and asymmetric with respect to wavelength. However, it is possible to reduce the effect of wavelength mismatch by superimposing $I_{x,out}$ and $I_{y,out}$ with the help of a polarizer.

4. Conclusions

We have demonstrated theoretically the enlarged supercontinuum (SC) generation by utilizing cross-phase modulation (XPM) of orthogonally polarized soliton pulses propagated through a dispersion flattened/decreasing fiber (DFDF). For analysis of SC generation from XPM coupling, it is assumed that the soliton trapping between the two orthogonal polarization components occurs in a low-birefringent fiber of $\Delta n_{xy} \leq 10^{-6}$. Due to the interplay of XPM and GVD in a DFDF with low birefringence, a SC spectrum as broad as 340 nm was obtained by superimposing the two orthogonal polarization components on the input azimuths $\theta_{xy} \geq 10°$.

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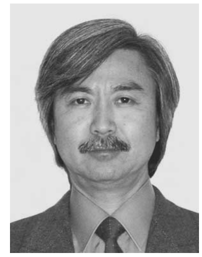

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