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Route to broadband blue-light generation in microstructured fibers

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We explore theoretically the possibility of generating broadband blue light by copropagating a short soliton pump pulse and a broader signal pulse in a microstructured fiber with a zero-dispersion wavelength located between the center wavelength of the pump and the signal pulses. We show that the unique properties of microstructured fibers should allow for broadening of the signal pulse's spectrum by as much as a factor of 50 through the conjugate action of cross-phase modulation and a soliton self-frequency shift. The physical mechanism that leads to this large spectral broadening is analyzed by use of an extended nonlinear Schrödinger equation. © 2005 Optical Society of America

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Blue light sources with large bandwidths are of considerable interest for many applications such as spectroscopy, data storage, and biomedical analysis. In this Letter we propose a scheme for efficient generation of blue light with a −20-dB bandwidth that exceeds 100 nm. The technique consists of copropagating a short pump pulse and a signal pulse in a narrow-core microstructured fiber (MF) with a zero-dispersion wavelength (λ_{ZD}) located between the pump and the signal center wavelengths. The spectrum of the signal pulse is considerably broadened along the MF owing to cross-phase modulation (XPM) induced by the short pump pulse on the broader signal. We show that the soliton self-frequency shift (SSFS) enhances the broadening of the signal spectrum that results from XPM. The dispersion profile of the MF is also found to be crucial, as it allows for cascaded XPM to occur, leading to the extension of the signal spectrum toward even shorter wavelengths. The energy of the pulses is kept low to limit other nonlinear effects that may deplete the pump pulse and thereby decrease the XPM efficiency. The technique permits generation of blue light with better efficiency than that obtained with phase-matched dispersive wave amplification in MFs.[1] Also, the method presented here differs from supercontinuum (SC) generation, which uses two pumps in MFs where the pump pulses are much broader (nanoseconds) and highly energetic (millijoules) and the spectrum at blue wavelengths is shown to result from four-wave mixing.[2]

XPM can lead to efficient spectral broadening, as the nonlinear phase shift induced by a strong pump pulse in a weaker signal pulse is twice that which results from self-phase modulation.[3] For instance, XPM was recently shown to play an important role in a SC generated with short pulses.[4] For efficient interaction, pump and signal pulses should travel at the same group velocity (GV). If the GVs of the pump and the signal pulses differ, the pulses walk off from each other, preventing further interaction.[4] One way to equalize the GVs of the pump and the signal pulses is to have their center wavelengths (λ_{center}) on different sides of λ_{ZD}. However, even in that case, the XPM-induced spectral broadening of the signal is eventually limited by the dispersion at the signal wavelength, such that further propagation does not produce any additional broadening.[5] One can take advantage of the Raman response of MFs and its effect on short optical pulses, i.e., the SSFS. Indeed, a short soliton pulse with high enough power will experience a SSFS that induces a progressive redshift of λ_{center} with propagation.[6] Inasmuch as λ_{center} of the pulse shifts toward longer wavelengths, the GV of the pulse decreases as a result of fiber dispersion. Therefore the pump pulse can interact with the new XPM-induced spectral components of the signal, which, in turn, allows for cascaded XPM to occur and for enhanced spectral broadening.

We model the propagation of the pulses by using the extended nonlinear Schrödinger equation.[4,7] The air-filling fraction of the honeycomblike structure of the MF was chosen to be 95%, with a core diameter of 1.5 μm, yielding λ_{ZD} located at 650 nm. This ensures that, for pump and signal wavelengths located at 900 and 450 nm, respectively, the GVs of the two pulses are close to each other. The width of the hyperbolic-secant pump pulse is taken to be 27 fs. The large separation between the pump wavelength and λ_{ZD} prevents the generation of phase-matched dispersive waves.[8] The signal pulse is assumed to be Gaussian, with pulse duration $T_{FWHM}=200$ fs and peak power P_p of 5.6 W, corresponding to a −20-dB spectral bandwidth of ~2.5 nm. The signal pulse can, e.g., be obtained by frequency doubling the pump pulse. The low energy and broad temporal width of the signal pulse are chosen on purpose to loosen the constraint on the frequency doubling. A dichroic mirror and a delay line may be introduced into the setup to tune separately the characteristics of both pulses.

If the pump pulse is launched alone into the fiber, its spectrum shifts because of the SSFS, as shown in Fig. 1(a). When only the signal pulse propagates along the MF, it experiences dispersion, and no spectral broadening is observed [see Fig. 1(b)]. However, when the signal pulse is copropagated with the pump

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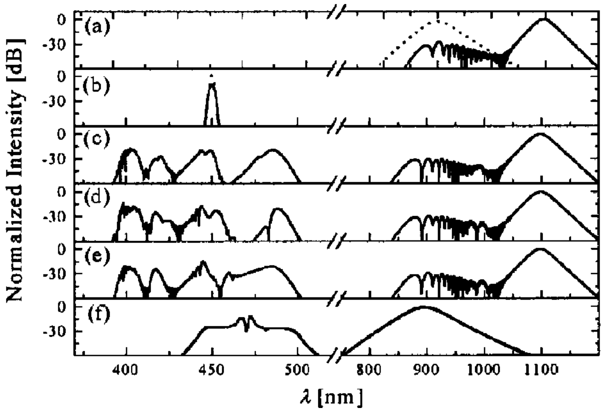

Fig. 1. Spectrum of (a) pump, (b) signal, (c) signal and pump, (d) negatively chirped signal and pump, (e) positively chirped signal and pump, and (f) signal and pump without the Raman term. Pump: $P_p=1.7$ kW and $T_{\mathrm{FWHM}}=27$ fs; signal: $P_p=5.6$ W and $T_{\mathrm{FWHM}}=200$ fs. Dotted curve, input spectrum. $L_{\mathrm{Fiber}}=80$ cm.

pulse, its −20-dB spectral bandwidth is enhanced by as much as a factor of 55 after 100 cm of propagation (see Fig. 2). This substantial broadening results from the XPM induced by the pump pulse experiencing the SSFS. In the early stage of propagation, the spectrum of the signal expands toward the red. After ~15 cm, blueshifted wavelength components appear in the spectrum, whereas the red side of the spectrum remains nearly unchanged. We note that the SC extending down to 390 nm has been generated with a single pump.[8] However, the pulse energy required is much higher, and the extent of the blue wavelength is limited by the high dispersion value of silica. Here the spectrum of the blue light extends to 380 nm, with very low pump–signal energy. Increasing the pump–signal energy and (or) the fiber length results in an even broader bandwidth.

The physical effects that are responsible for broadening the signal spectrum can be analyzed from the simulated spectrograms presented in Fig. 3 and the relative time delay between the pump and the signal pulses versus propagation length shown in Fig. 4(a). For a full understanding of the process it is also useful to plot the wavelength components on the signal side whose GV equals that of the soliton [see Fig. 4(b)]. The GV of the soliton experiencing the SSFS changes with propagation and was obtained from the simulations. The wavelengths on the signal side traveling with the same GV were subsequently calculated from the propagation constant of the fiber. The soliton initially travels with a faster GV than the signal pulse, which, consequently, trails behind the soliton [Figs. 3(b) and 4(a)]. The XPM-induced blue components move with a faster velocity than the soliton. This limits the blue spectral broadening, whereas the XPM-induced red components move at roughly the same GV as the soliton, allowing for further cascaded XPM toward the red wavelengths. This explains the strong redshift of the signal spectrum during the early propagation stage. With further propagation, the GV of the soliton experiencing the SSFS decreases, and it is therefore caught back by the signal pulse [Figs. 3(c) and 4(a)]. The situation is then opposite that of the early stage, and the XPM-induced blueshift is dominant. The red part of the signal spectrum remains nearly unchanged as the mismatch between the GV of the red components of the signal and the GV of the soliton grows constantly.

To emphasize the decisive role of the SSFS, the propagation of the pump and signal pulses along an 80-cm-long MF was simulated with [Fig. 1(c)] and without [Fig. 1(f)] the Raman term included. When the Raman term was omitted, $\lambda_{\mathrm{center}}$ of the pump and signal were set to 900 and 467.7 nm, ensuring an exact GV match for the MF chosen. It is clear from Figs. 1(c)–1(f) that the SSFS improves the spectral broadening considerably. The −20-dB bandwidth of the output signal spectrum is doubled (151.4 THz) when the pump pulse experiences the SSFS compared with the bandwidth when the signal and the pump travel together along the entire fiber length (76 THz). We also investigated the effect of linear initial negative (−5) and positive (+5) chirp on the resultant signal spectrum, as frequency-doubled pulses may be chirped. The bandwidth of the blue light is relatively unaffected [Figs. 1(d) and 1(e)]. The most noteworthy effect is on the flatness on the red side of the signal

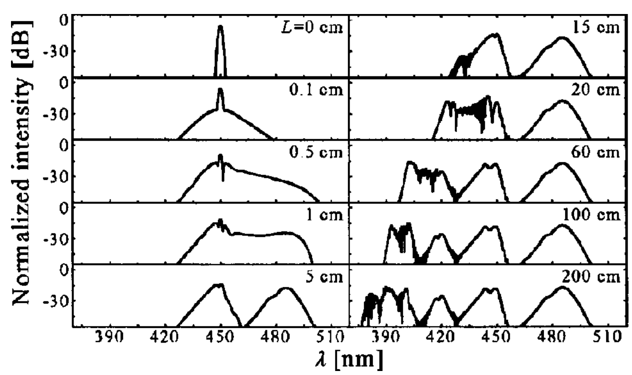

Fig. 2. Evolution of the signal spectrum versus propagation. The pump and signal parameters are identical to those of Fig. 1. The input delay between the pump and the signal pulses is set to 0.

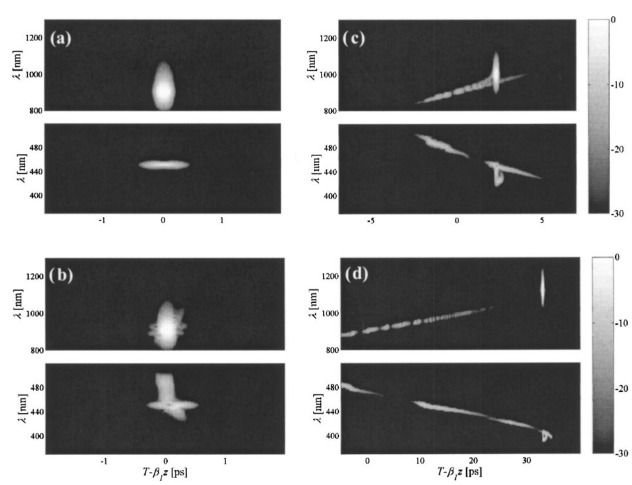

Fig. 3. Spectrogram of the signal pulse after (a) 0, (b) 1, (c) 20, and (d) 100 cm of propagation. The pump and signal parameters are identical to those of Fig. 1.

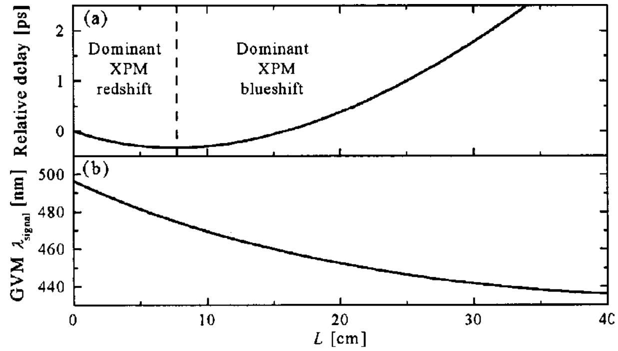

Fig. 4. (a) Evolution of the relative delay between the pump and the signal pulses versus propagation. (b) Calculated wavelength that is GV matched with the pump along propagation.

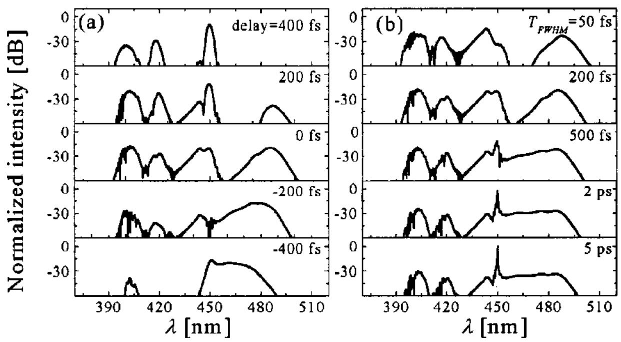

Fig. 5. Influence of (a) initial delay and (b) initial signal pulse duration on the signal spectrum. The delay between the pump and the signal pulses is set to 0 in (b). The pump parameters are identical to those of Fig. 1. $L_{\mathrm{Fiber}}=80$ cm.

spectrum because initial chirp affects the relative delay between the two pulses in the early propagation stage as a result of dispersion. With further propagation, the initial chirp is negligible compared with the chirp accumulated from the dispersion experienced by the signal pulse, which explains the minor effect on the blue side of the signal spectrum.

Initial delay between the pump and the signal pulses is expected to affect the output spectrum of the signal pulse.[9] The effect of the initial delay on the output signal spectrum was simulated. The results are plotted in Fig. 5(a). If the signal pulse is originally delayed with respect to the pump pulse, it interacts mainly with the trailing edge of the pump pulse experiencing the SSFS. This induces mostly blue spectral broadening. As the initial delay is reduced, the spectrum of the signal pulse appears also to broaden toward the red. The signal pulse then also interacts with the leading edge of the pump pulse, thereby inducing a redshift in the signal spectrum. The largest spectral broadening in excess of 100 nm is obtained when the pump and the signal pulses coincide at the input of the MF.

We subsequently simulated the output spectrum of the signal pulse for an increasing initial pulse duration, as illustrated in Fig. 5(b). The energy of the input signal pulse was kept constant and equal to 2 pJ. The variation of the input pulse's duration on the −60-dB bandwidth of the signal's output spectrum is minor. However, the −20-dB bandwidth was found to be strongly reduced for longer pulses. In particular, for pulses of the order of 1 ps, the remainder of the input signal appears as a peak well above the new spectral components generated through XPM. Furthermore, the pulse duration substantially affects the flatness of the spectrum on the red side. This is so because, for longer signal pulses, the soliton never completely walks off from the signal pulse in the early propagation stage as it does for short signal pulses. Note also that the spectra of the pump pulse in Fig. 5 are identical to the one shown in Fig. 1(a), confirming that XPM induced by the signal on the pump is negligible.

In conclusion, we have investigated the possibility of generating broadband blue light in MFs by copropagating a short pump pulse with a broader signal pulse. The substantial broadening of the signal spectrum results from XPM. Dispersion and SSFS are crucial in the process. The technique is applicable for generating broadband light centered at any wavelength, provided that $\lambda_{\mathrm{center}}$ of the pump and signal pulses are carefully selected and the dispersion profile of the MF is properly chosen. Finally, we point out that the technique should also allow for generation of broadband light at the infrared wavelengths by use of a MF with two λ_{ZD}.

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References

1. K. M. Hilligsøe, H. N. Paulsen, J. Thøgersen, S. R. Keiding, and J. J. Larsen, J. Opt. Soc. Am. B **20**, 1887 (2003).
2. P. Champert, V. Couderc, P. Leproux, S. Février, V. Tombelaine, L. Labonté, P. Roy, C. Froehly, and P. Nérin, Opt. Express **12**, 4366 (2004), http://www.opticsexpress.org.
3. G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. (Academic, San Diego, Calif., 2001).
4. G. Genty, M. Lehtonen, and H. Ludvigsen, Opt. Express **12**, 4614 (2004), http://www.opticsexpress.org.
5. L. Helczynski, D. Anderson, B. Hall, M. Lisak, and H. Sunnerud, J. Opt. Soc. Am. B **19**, 448 (2002).
6. F. M. Mitschke and L. F. Mollenauer, Opt. Lett. **11**, 659 (1986).
7. K. J. Blow and D. Wood, IEEE J. Quantum Electron. **25**, 2665 (1989).
8. G. Genty, M. Lehtonen, H. Ludvigsen, J. Broeng, and M. Kaivola, Opt. Express **10**, 1083 (2002), http://www.opticsexpress.org.
9. G. P. Agrawal, P. L. Baldeck, and R. R. Alfano, Phys. Rev. A **40**, 5063 (1989).