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Improving efficiency of supercontinuum generation in photonic crystal fibers by direct degenerate four-wave-mixing

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Abstract: The efficiency of supercontinuum generation in photonic crystal fibers is significantly improved by designing the dispersion to allow widely separated spectral lines generated by degenerate four-wave-mixing directly from the pump to broaden and merge.

Introduction.
Photonic crystal fibers (PCFs) [1] and tapered fibers [2] are promising sources for efficient supercontinuum generation (SCG) due to their unusual dispersion properties and high effective nonlinearities. These fibers have similar dispersion and nonlinearity characteristics and they have the advantage that their dispersion may be modified by a proper design of the cladding structure [3], and by changing the degree of tapering [2], respectively. Using femtosecond pulses a supercontinuum (SC) spanning one octave has been generated in a PCF, whereas impressive two octave SC has been obtained in a tapered fiber. The latter two octave wide SC was later explained to be a result of self-phase modulation (SPM) and direct degenerate four-wave-mixing (FWM) [4].

However complex high power femtosecond lasers are not necessary, - SCG may be achieved with picosecond and even nanosecond pulses. Thus Coen et al. generated a one octave SC in a PCF using subkilowatt picosecond pulses and showed that the primary mechanism was the combined effect of stimulated Raman scattering (SRS) and parametric FWM, allowing the Raman shifted components to interact efficiently with the pump [5]. Here we show how direct degenerate FWM can be used to significantly improve the efficiency of SCG with subkilowatt picosecond pulses in PCFs, if the dispersion is properly designed.

Improving efficiency of SCG with picosecond pulses in PCFs using degenerate FWM.
We study the SCG process numerically using the well known coupled nonlinear Schrödinger equations that describe the evolution of the x- and y-polarization components of the field for pulses with a spectral width up to 1/3 of the pump frequency [5]. This model accounts for SPM, cross-phase-modulation, FWM, and SRS. An initial random phase noise seeding of one photon per mode is included.

We consider the same PCF and numerical and experimental data as in [5], kindly provided by S. Coen. Thus we pump along the slow axis with 30ps pulses of 1p=400W peak power and pump wavelength λp=647nm. Our PCF has core area Acore=1.94μm², dispersion D(λp)=−30ps/(nm km), zero dispersion wavelength λzd=875nm, n2=3×10⁻¹² m²/W, and birefringence n₁-n₂=1.9×10⁻⁶. The dispersion is expanded around the pump to include β₂=7.0ps²/km, β₃=5.1x10⁵ps³/km, β₄=−4.9x10⁶ps⁴/km, β₅=1.2x10⁷ ps⁵/km, β₆=−1.8x10¹⁰ps⁶/km, and β₇=1.2x10¹³ ps⁷/km. A uniform loss of 0.1dB/m is used and the effective area is approximated with the core area, giving the nonlinearity parameter γ=2πn₂/(λₚAcore)=0.15(Wm)⁻¹.

Fig. 1 a) Phase-mismatch δp and spectrum of the slow axis polarization component at L=17.4cm. b) Same spectrum at L=4.3cm, 2.6m, and 3.7m.

We use the standard split-step Fourier method with 2¹⁷ points in a time window of T=236ps. In our longest
simulation out to \( L = 3.7 \) m the photon number is conserved to within 5\% of its initial value. Due to our large spectral window (405 nm → 1613 nm) we see in Fig.1(a) the emergence of FWM Stokes and anti-Stokes waves at the wavelengths \( \lambda_S = 1100 \) nm and \( \lambda_{as} = 458 \) nm for which the phase matching condition \( \Delta \beta = \beta_s + \beta_p - 2 \beta_0 + \gamma_p = 0 \) is satisfied. The spectral window presented in [5] was narrower and thus \( \lambda_p \) and \( \lambda_{as} \) were not observed. We find the maximum FWM parametric gain to be twice the maximum SRS gain, which explains why the FWM Stokes and anti-Stokes components appear before the SRS components.

The loss and walk-off of the PCF gives the maximum distance \( L_{\text{max}} \) over which nonlinear processes, and thus the SCG process, are efficient. From Fig.1(b) we see that after the FWM Stokes and anti-Stokes components are generated they broaden much in the same way as the central part of the spectrum around the pump. The merging of the spectral parts around \( \lambda_{as} \), \( \lambda_p \), and \( \lambda_S \) would create an ultra broad spectrum as observed in tapered fibers with femtosecond pulses [2,4]. However, in this particular case the FWM Stokes and anti-Stokes lines are too far away for a merging to take place within the maximum length \( L_{\text{max}} \), i.e., before nonlinear effects become negligible.

The wavelengths \( \lambda_s \) and \( \lambda_{as} \) can be adjusted to be closer to the pump wavelength \( \lambda_p \) by a proper design of the dispersion. This will enable the FWM Stokes and anti-Stokes lines to broaden enough to allow a final merging. To show the effect we modify \( \beta_0 \), \( \beta_s \), and \( \beta_p \) to \( \beta_0 = 1.0 \) ps \(^2\)/km, \( \beta_s = -2.5 \times 10^6 \) ps \(^4\)/km, and \( \beta_p = -3.25 \times 10^6 \) ps \(^4\)/km. The phase-matching condition \( \Delta \beta = 0 \) then gives \( \lambda_s = 850 \) nm and \( \lambda_{as} = 530 \) nm. The effect on the dispersion profile is to down-shift the zero dispersion wavelength to \( \lambda_p = 660 \) nm and reduce the normal dispersion to \( D(\lambda_p) = -4.35 \) ps/(nm·km), as shown in Fig.2.

The numerical results shown in Fig.3 confirm our hypothesis. The FWM Stokes and anti-Stokes lines are still widely separated, but now generated close enough to the pump to broaden and merge. The resulting ultrabroad SC is flat within 20 dB and spans 510 nm (at -40 dB from the flat part) in contrast to the original 230 nm observed in [5].

![Fig.2 Original dispersion [5] (solid line) and our modified dispersion (dashed line).](image)

![Fig.3 a) Phase-mismatch \( \Delta \beta \) and spectrum of the slow axis polarization component at \( L = 17.4 \) cm. b) Same spectrum at \( L = 8.7 \) cm, 43 cm, and 2.154 m.](image)

**Conclusion:**
We have numerically considered SCG in birefringent PCFs using sub-kilowatt picosecond pulses. Our results show that by properly designing the dispersion properties and using the simultaneous broadening and final merging of widely separated pump and FWM Stokes and anti-Stokes lines the SCG efficiency can be significantly improved. Further investigations will involve the robustness of the process towards variations in the birefringence along the PCF. This work was supported by the Danish Technical Research Council (Grant no. 26-00-0355) and the Graduate School in Nonlinear Science (The Danish Research Agency).

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