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Dispersion Engineered Cob-Web Photonic Crystal Fibers for Efficient Supercontinuum Generation

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Abstract: Highly nonlinear cob-web photonic crystal fibers are engineered to have dispersion profiles for efficient direct degenerate four-wave mixing and optimized supercontinuum generation with low-power picosecond pulses. This process is robust to fiber irregularities.

OCIS codes: (060.0060); (190.0190); (060.4370).

1 Introduction

The small mode-field diameters of highly nonlinear photonic crystal fibers (PCFs) and their unusual dispersion properties make them a convenient medium for supercontinuum generation (SCG). Using femtosecond (fs) pulses, a supercontinuum (SC) spanning 400-1500nm has been generated in a PCF [1]. The wide SC was later explained to be a result of self-phase modulation (SPM), direct degenerate four-wave-mixing (FWM) [2] and fission of higher order solitons [3]. The complexity of high-power fs lasers can be avoided, since SCG is also achievable in PCFs with low-power picosecond (ps) pulses through parametric four-wave mixing (FWM) combined with stimulated Raman scattering (SRS) [4]. Due to direct degenerate FWM, additional Stokes and anti-Stokes spectral lines can be efficiently generated directly from the pump. These Stokes and anti-Stokes spectral lines can broaden and merge with the spectrum around the pump, provided that the PCF has a proper dispersion profile. In this way, the power transferred to the Stokes and anti-Stokes lines is not lost. Previous results on engineering a theoretical dispersion profile showed numerically that a 800nm wide (within 20dB) SC spectrum can be generated in a PCF with low-power ps pulses [5].

Here we consider a PCF with a cob-web structure, for which we calculate the dispersion profile using a full vectorial mode solver [6], and optimize it for SCG with optimum efficiency and robustness. We sweep the structural parameters of the cob-web PCF until the separation between the direct degenerate FWM Stokes and anti-Stokes wavelengths and the pump, as well as the direct degenerate FWM gain bandwidth, are optimized. We then numerically verify, how the optimized cob-web PCF allows to generate a broader SC, which is robust to fluctuations in the fiber parameters along the fiber, such as variations of hole size and glass-wall width, typically found in a real cob-web PCF.

2 Structural dispersion engineering of a cob-web PCF.

The direct degenerate FWM phase mismatch for a polynomium fitted dispersion profile, is given by[7]

$$\Delta\beta = 2\left[\gamma(1-f_R)I_p + \Omega^2\beta_2/2! + \Omega^4\beta_4/4! + \Omega^6\beta_6/6! + \ldots\right] \tag{1}$$

Here $\Omega = \omega_p - \omega_s = \omega_{as} - \omega_p$, where ω_p, ω_s, and ω_{as}, are the pump, Stokes and anti-Stokes frequencies, $\beta_{2..6}$ are dispersion coefficients, γ is the nonlinear coefficient, f_R is the fractional contribution of the Raman effect, and I_p is the pump power. The gain of the direct degenerate FWM process around the pump is[7]

$$g = \sqrt{[(1-f_R)\gamma I_p]^2 - \Delta\beta^2/4} \tag{2}$$

The cob-web PCF (see inset of Fig. 1) has three parameters through which the dispersion can be engineered: the core diameter d, pitch size Λ, and wall thickness δ. Figure 1 shows dispersion profiles for different core radii with fixed

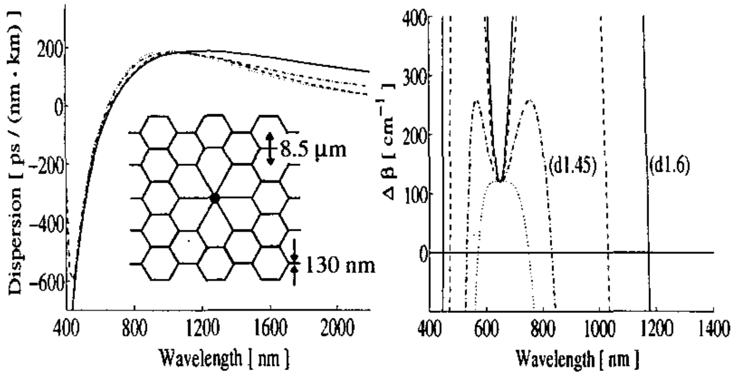

Fig. 1. Left: dispersion profiles of cob-web PCFs with pitch Λ=8.5μm, wall thickness δ=130nm, and core diameter d=1600nm (solid line), 1500nm (dashed), 1450nm (dash-dotted), and 1400nm (dotted). Right: Corresponding phase mismatch for pump wavelength λ_p=647nm and peak pump power I_p=400W.

pitch and wall thickness, calculated using a full-vectorial plane-wave method [6]. The phase mismatch curves in Fig. 1 are calculated using Eq. (1). We see that the direct degenerate FWM Stokes and anti-Stokes wavelengths (λ_s and λ_{as}, for which $\Delta\beta$=0) are moving closer to the pump λ_p and that the slope of the phase-mismatch curves around them is reduced when the core diameter is reduced. The dependency of λ_s and λ_{as} and the corresponding gain bandwidths Δg_s and Δg_{as} on the core diameter are shown in Fig. 2. When decreasing the core diameter, the gain bandwidth increases until the variations of the Stokes and anti-Stokes wavelengths saturate around a core diameter of 1400nm, after which the bandwidth again decreases.

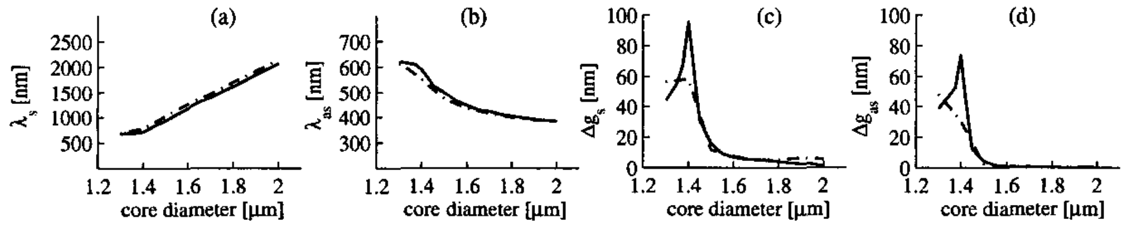

Fig. 2. (a,b): direct degenerate FWM Stokes and anti-Stokes wavelengths λ_s and λ_{as} versus core diameter of a cobweb PCF with pitch Λ=8.5μm and wall thickness δ=130nm (solid) and 150nm (dash-dot). (c,d): corresponding gain band widths Δg_s and Δg_{as}. As in Fig. 1, λ_p=647nm and I_p=400W.

As was recently reported λ_s and λ_{as} should be just so close to the pump that merging with the main spectral part is achieved within the length of the PCF, before the influence of loss and temporal walk-off eliminates the efficiency of nonlinear processes, and thus the SCG process [5]. If λ_s and λ_{as} are further away, merging is not achieved, and if they are closer, the resulting SC spectrum becomes narrower. At the same time the larger the gain bandwidth is the more robust the FWM and thus the SCG process is to fluctuations in the fiber parameters [5]. For the cob-web PCF considered in Figs. 1-2, this means that the optimum core diameter is around d=1450nm at the peak of the bandwidth, before saturation of λ_s and λ_{as} sets in. We simulated SCG in a cob-web PCF with δ=130nm and d=1450 and 1600nm, using the standard SCG model (and included a loss of 0.1dB/m)[4, 5]. The resulting spectra are shown in Fig. 3. Indeed we see that for d=1600nm (the PCF used in [4]) λ_s and λ_{as} are too far from λ_p for merging to occur. However, for the optimum core diameter d=1450nm, merging occurs and the formation of a much broader SC is observed.

Due to the complex structure of PCFs, fluctuations in its parameters, and thus its dispersion profile, can be anticipated. We included random variations in the phase-mismatch, the group-velocity mismatch, and all dispersion coefficients with a relative strength (or variance) of ρ=10%, which appears to be realistic in real PCFs [5, 8]. Fig. 3 again confirms the much improved robustness of the SC spectrum in the optimum cob-web structure with d=1450nm due to the much broader FWM gain bandwidth.

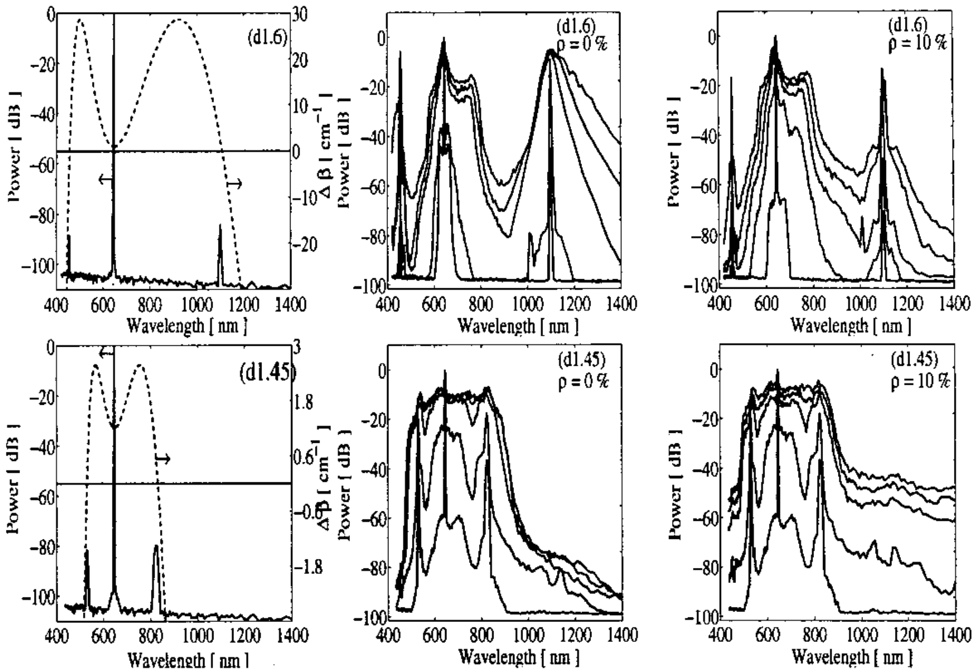

Fig. 3. Dispersion profiles d1.6 (top row) and d1.45 (bottom row). Left column: phase mismatch $\Delta\beta$ for direct degenerate FWM (dashed line) and spectrum at L=10cm (solid line). Middle and right columns: spectrum at L=20cm, 30cm, 1m, 2m, and 3.7m (counting upwards). Middle column: spectrum under no influence of structural fluctuations (ρ=0). Right row: spectrum under influence of structural fluctuations with strength ρ=10%.

3 Conclusion

We have shown that careful engineering of the structural parameters of a cob-web PCF to optimize its dispersion, can significantly increase the width of the SC spectrum generated by low-power ps pulses. Furthermore, robustness with respect to structural fluctuations is found to be tolerable.

For a wall thickness of 130nm and a pitch of 8.5μm, the optimum core diameter was found to be around 1450nm. In fact, the coupling losses are not significantly changed for core diameters between 1450nm and 2μm, so the improvement by a factor of two in SC bandwidth we have shown is indeed a true improvement. Results using a smaller pitch will also be reported.

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