Dispersion engineered small area photonic crystal fibers for Supercontinuum generation

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Abstract

An overview of the effects leading to Supercontinuum (SC) emission is given and the required properties of the photonic crystal fibers (PCF) leading do SC generation are mentioned. A possible geometry for a hexagonally structured PCF obtained by a systematic parameter-scan is presented.

1 Introduction

The generation of new frequencies in a nonlinear medium requires high intensities for substantial excitation of the nonlinear polarization. High intensities can be produced by tight focusing of a laser beam but the smaller the spot, the larger the resulting divergence and hence the smaller the length over which the intensity is high. Small area PCFs offer a solution to this problem. Because the area of a mode in a fiber is constant over its whole length, there is no divergence. The inclusion of air in the cladding leads to a high index contrast ($\triangle n$=n$_{core}$-n$_{clad}$) which allows the construction of fibers with relatively small area and so the product of intensity times length is directly proportional to fiberlength. The interaction length can therefore be increased sufficiently to compensate for the fact that silica has a small nonlinear index n$_2$=3*10^{-16} cm$^2/W$ [12] (as compared to n$_2$=2.6*10^{-15} cm$^2/W$ for SF57 glass [11] or even n$_2$=4.2*10^{-14} cm$^2/W$ for chalcogenide-glass [2]).
A second property of PCFs that makes them ideal for SC generation is their tunable dispersion characteristics. Whereas it is generally desirable to prevent the pulses from broadening over as long a distance as possible (zero dispersion) there are nonlinear effects that require phase matching (parametric processes) and consequently a specific dispersion relation.
The general equation governing the propagation of short pulses in a lossless fiber is [1]

$$\frac{\partial A}{\partial z} = i\sum_{k\geq 2}\frac{i^k\beta_k}{k!}\frac{\partial^k A}{\partial t^k} + i\gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial t}\right)\left[A\int_{-\infty}^{t} R(t') \mid A(t-t') \mid^2 dt'\right] \tag{1}$$

where A is the slowly varying amplitude (in units of $\sqrt{W}$) of the mode along the fiber. The first term on the right accounts for dispersion of order higher than one. β_k stands for $\frac{\partial^k\beta}{\partial\omega^k}$. The first order term does not appear because a coordinate frame was chosen that moves with the velocity of the pulse [1] (group velocity v_g=1/β_1).

The second term on the right takes the nonlinear processes into account. R includes the effects of instantaneous and delayed Raman scattering

$$R(t) = f\delta(t) + (1 - f)r(t) \tag{2}$$

where δ(t) is Dirac's delta (instantaneous electronic response [1]) and r(t) is an empirically determined impuls response of the delayed Raman effect (optical phonon response [1]). The relative weight of these two contributions is represented by the factor $f \in [0, 1]$. Brillouine scattering (BS) is important for long pulses or CW mode and is directed in the backward direction [1]. BS is not included in this model. The dispersion terms (first term in equation (1)), if acting isolated, leave the modulus of the pulse spectrum unchanged while introducing phase modulation. This conforms with the fact, that linear effects do not generate new frequencies. They only change the shape of the pulse in the time domain. If the pulse length $T_p \gg 10fs$ the nonlinear term can be simplified to [1]

$$\left(\frac{\partial A}{\partial z}\right)_{NL} = i\gamma\left(| A |^2 A + \frac{i}{\omega_0}\frac{\partial}{\partial t}(| A |^2 A) - T_r A\frac{\partial | A |^2}{\partial t}\right) \tag{3}$$

The first term accounts for self phase modulation which, if acting alone, leads to a broadening of the pulse spectrum but leaves the shape of the pulse unaffected. The second term is responsible for self-steepening and shock formation while the last term represents the delayed Raman response which leads to self-frequency shift and intrapulse Raman scattering. The impact of the nonlinear term is, in addition to the amplitude A, also determined by the nonlinear parameter

$$\gamma = n_2\omega/cA_{eff} \tag{4}$$

where n_2 is the nonlinear index of refraction of the material, ω is the center frequency of the pulse and A_{eff} is the area of the mode. To achieve high nonlinear response from a fiber it is therefore necessary to choose the mode diameter as small as possible.
All effects together lead to a very complex evolution of the pulses in time as well as in frequency space which can only be tackled numerically.

2 Mechanism of SC generation

The widest spectra are obtained when the wavelength of the pump pulses is close to the zero dispersion wavelength of the fiber [7]. Pumping in the normal dispersion region where D<0 (D=-$\frac{\lambda}{c}\frac{\partial^2 n}{\partial\lambda^2}$), leads to self-modulation that broadens the pulse spectrum and dispersion changes the pulse shape. The closer the pump wavelength is to the ZW the broader the produced spectrum gets until a part of it comes to lie in the anomalous dispersion regime where D>0. This part evolves towards higher order solitons which in turn decay into first order solitons because of higher order dispersion (≥ 3), intrapulse Raman scattering and self-steepening. Four-wave mixing and Raman scattering finally contribute to the formation of a broad supercontinuum [8]. The resulting spectrum is very sensitive to changes in fiber and pulse parameters.
If there are two zero dispersion wavelengths in the vicinity of the pump wavelength, a qualitatively different behaviour emerges. If the fiber is pumped in the anomalous regime in between the two ZWs, there appears light at two bands just outside the anomalous regime. These bands are very

insensitive to changes in parameters and input noise. The prime mechanism in this mode is initial self-phase-modulation and subsequent four-wave mixing [9].

3 Fibers on the market

There are essentially two classes of nonlinear fibers commercially available: Multimode fibers with honeycomb structure and single mode fibers in conventional hexagonal geometry. The single mode type is straightforward to fabricate and is easier to couple because the light is guided only in the center of the fiber and not in the cladding nodes as can be the case with the honeycomb structure [7].

4 Used software

To calculate the dispersion relations of the PCFs the multipole method was used [6]. The beampropagation method [4] proved to be unstable in the fully vectorial calculations. As Fig. 1 shows, the plane-wave expansion technique [3] which does ignore the losses is of no use either. These calculations are for a fiber of $\Lambda = 1\mu m$ and $d/\Lambda = 0.35$ and include only waveguide dispersion. The deviation between the plane-wave and the multipole method becomes substantial as the wavelength gets larger and the losses increase [5].

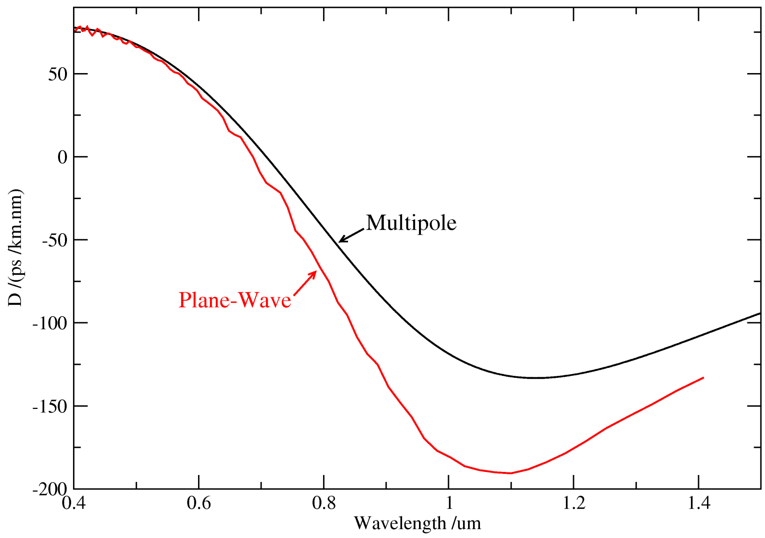

Figure 1: Plane-wave and multipole method in comparison

However, the use of the multipole method restricted the investigations to hexagonal designs with circular holes. All following calculations refer to fibers with the geometry shown in Fig. 2 and more or less rings.

The evolution of the pulses was simulated by the splitstep method in which the linear and the nonlinear part of the equation are solved independently for small steps and the resulting effects are added.

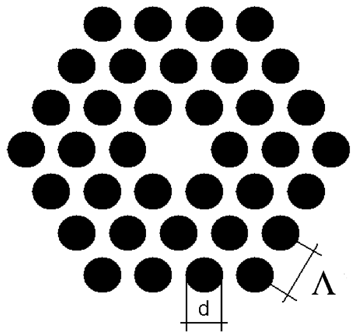

Figure 2: Hexagonal geometry used in calculations

5 Dispersion of a downscaled large core-area fiber

To check whether a downscaled version of an existing large core-area fiber [5] could have suitable dispersion properties, the dispersion for different Λ is computed. Fig. 3 shows the results.

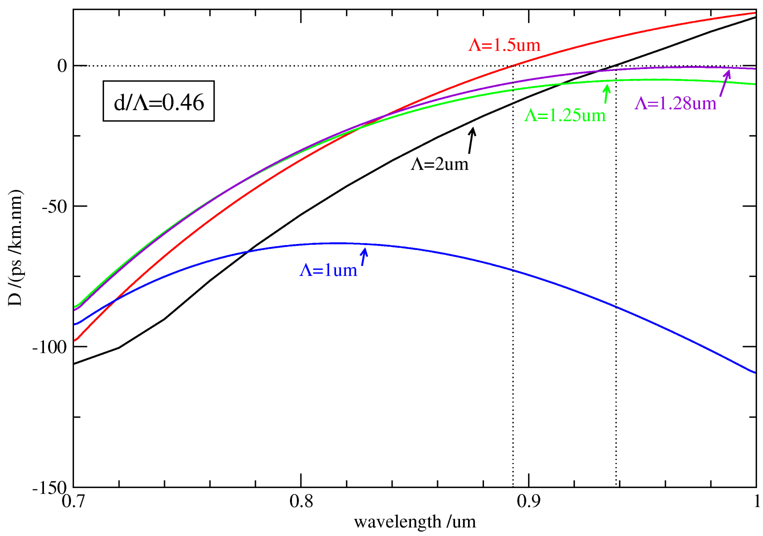

Figure 3: Dispersion for a fiber with $d/\Lambda = 0.46$ for different Λ

With decreasing Λ the ZW first gets smaller but at a certain point, about Λ=1.28 (Fig. 3), vanishes. Below this Λ the fiber has no anomalous dispersion regime. For this fiber the corresponding wavelength is above 800 nm which means that pumping at this wavelength is only possible in the normal dispersion regime.

6 Systematic search

A good approximation [10] to the total dispersion of a PCF is $D_{tot} = D_{wgd} + D_{mat}$ where the waveguide dispersion is calculated for n=constant while the material dispersion is calculated with the Sellmeier equations. To verify this assertion Fig. 4 shows calculations where the sum of waveguide dispersion and material dispersion is compared to the exact dispersion (exact means that the variable material index is included in the calculation of the waveguide dispersion).

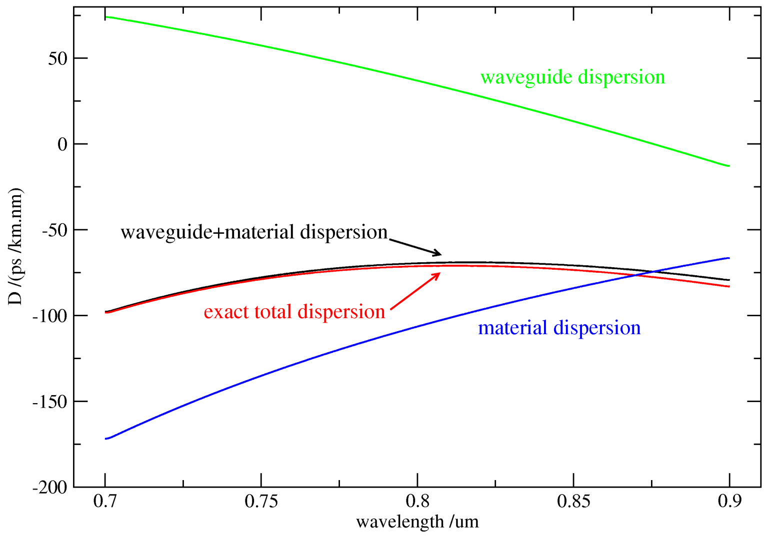

Figure 4: $D_{wgd} + D_{mat}$ vs. D_{exact}

In order to find a fiber geometry that has zero dispersion near the pump wavelength (800 nm Ti-Sapphire laser), an automated search was performed. In a first step, the waveguide dispersion for a one-parameter family of hexagonal solid core fibers was calculated by the multipole method. The parameter d/Λ was varied, while Λ was kept constant at $1\mu m$. Then the scaling relation

$$D(\lambda)_{scaled} = fD(f\lambda)_{ref} \tag{5}$$

was applied where $f = \Lambda_{ref}/\Lambda$. This results in a two-parameter family of dispersion relations, depending on Λ and d/Λ.

The final step was to optimize D_{tot} subject to a suitable criterion. Least squares approximation to zero over the intervall [700 nm, 900 nm] yielded the following dispersion (Fig. 5).

In this case we have two ZWs, one below and one above 800 nm which should lead to the stable sidebands described above. To test this, a numerical calculation of a pulse through a fiber with ZWs at 750 nm and 850 nm was performed. The maximum dispersion was chosen to be 15 $ps/km.nm$ which is higher than in the above result but can be realised [9] (the concern in the parameter search was not the two-ZW case but minimum dispersion around 800 nm). A 700 pJ pulse of 40 fs was launched into a fiber of varying length L and $\gamma = 0.15/(Wm)$. Fig. 6 shows that the spectrum gets indeed broader and the wavelengths of the inner etches remain aproximately constant.

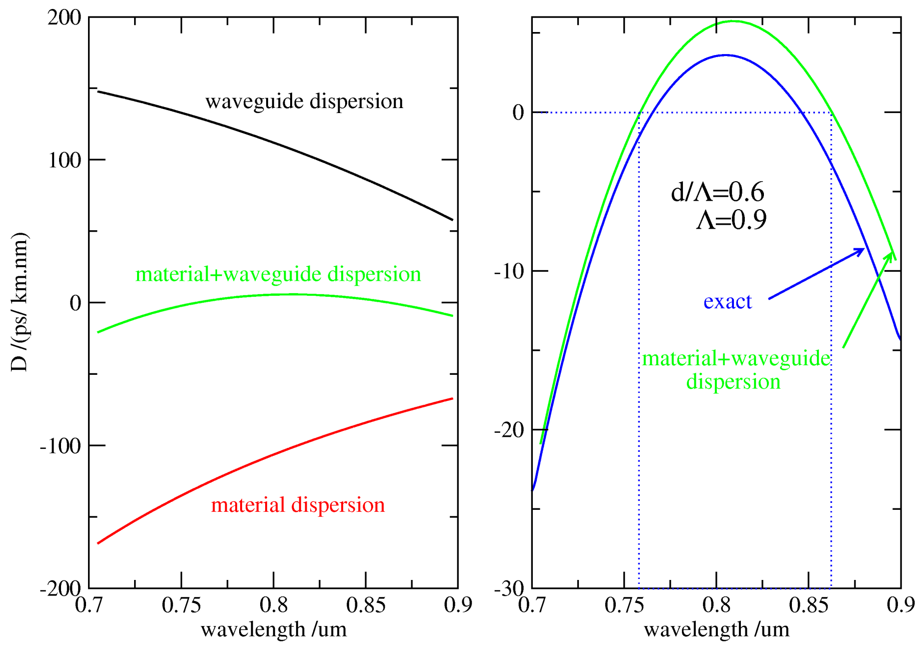

Figure 5: Optimized dispersion relation

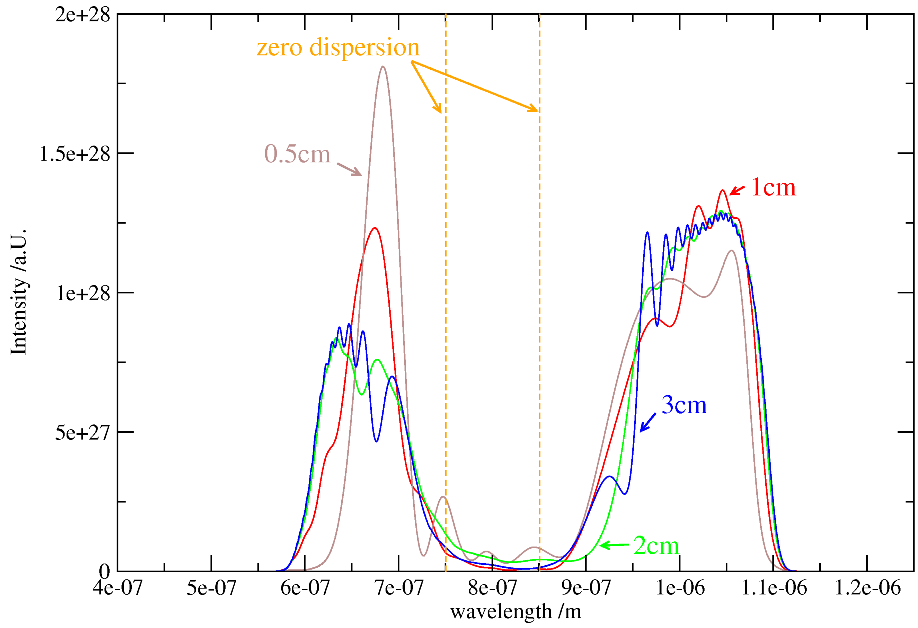

Figure 6: Output spectra for L=0.5cm, 1cm, 2cm and 3cm

7 Outlook

The next step will be the variation of the fiber geometry to more exotic cases. In particular a symmetry breaking will be included to introduce polarization maintenance and thus to reduce the required power levels.

8 Summary

The main mechanisms involved in SC generation were mentioned. The possibility of simple hexagonal PCFs for the generation of SC was investigated. Pumping of d/Λ =0.46 fibers near the ZW is possible only in the normal dispersion region. For suitably chosen d/Λ, pumping between two ZW seems possible thus allowing the generation of stable sidebands in the normal dispersion region.

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