Design of Photonic Crystal Fibers for Optical Parametric Amplification

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Abstract: The possibility of achieving broadband, high-gain optical parametric amplifiers with photonic crystal fibers is investigated. Simulations point out that it is possible to obtain broadband parametric gain by designing optimal fiber chromatic second and fourth order dispersion. The influence of fiber parameters on parametric amplification is discussed.

1. Introduction

Optical parametric amplifiers (OPA), exhibit a low noise level, due to the absence of amplified spontaneous emission, offer a large and flexible bandwidth, and a fast response time, as the amplification mechanism is not based on any electronic state transition. The features of OPA make them appealing for DWDM and CWDM amplification, where large amplifier bandwidths can be achieved with a small pump number and low pump power, as well as for optical signal processing, due to idler generation (e.g. for wavelength conversion, regeneration) [1]. The efficiency of parametric amplification, based on degenerate FWM effect between pump and signal waves, depends only on phase-matching conditions between pump and signals, which are related to customizable fiber characteristics, such as fiber chromatic dispersion and nonlinearity.

Photonic Crystal Fibers (PCF) permit, to a much greater extent than conventional optical fibers, an almost independent tailoring of fiber effective area and chromatic dispersion properties [2]. The design and manufacturing of fibers with optimized dispersion and nonlinearity profiles can then lead to the implementation of broadband amplifiers, operating with a very low input power and a short fiber length.

2. Simulations

The tailoring of fiber dispersion in PCF along with the nonlinear properties of the fiber can lead to the implementation of broadband OPA providing high gain with a low input pump power. Actually, the phase-matching for pump and signal waves is given, to fourth order, by:

$$\mathbf{k} = \beta_2 \Delta\lambda^2 + \beta_4 \Delta\lambda^4 / 12 + 2\gamma P_0 \tag{1}$$

where $\Delta\lambda=\lambda_s-\lambda_{pump}$; $\boldsymbol{k}$ depends, for given input pump power P_0, on second and fourth order dispersion only.

The efficiency of parametric gain is maximum for $\boldsymbol{k=0}$, and in turn the maximum gain depends on fiber nonlinear properties $g_{max}=\gamma P_0$.

An optimal design of the fiber chromatic dispersion $D=-(2\pi c/\lambda^2)\cdot\beta_2$ and the fourth order dispersion β_4 at the pump frequency permits, for a given P_0, to minimize the phase matching conditions for a wide range of channel wavelengths, and then to maximize the amplification bandwidth B [3,4]. In particular, **k** keeps low within a large signal wavelength interval if $\beta_2<0$, $\beta_4>0$, and β_2 at pump wavelength satisfies the condition

$$\beta_2 = -\sqrt{\tfrac{2}{3}\gamma P_0 \beta_4} \tag{2}$$

If the fiber is properly designed and β_2 correctly chosen, then the amplification bandwidth is essentially limited by the extent of β_4, and given by

During the fiber design stage, then, a geometry is sought with β_4 *i)* positive and *ii)* small, then the optimum β_2 is

$$B = 2\sqrt{2}\left(\frac{3\gamma P_0}{\beta_4}\right)^{1/4} \tag{3}$$

found by varying the fiber parameters, until attaining the configuration with the largest amplifier bandwidth.

The numerical method used in simulating the PCF structures was developed by [5] is based on a plane wave expansion of the transverse magnetic field vector **H**(x,y) in the PCF cross-section, neglecting fiber losses.. The propagation constant $\beta(\omega)$ (or equivalently the effective index) for a given frequency ω is found through integration of the differential equation specified in [5] for each Fourier component of magnetic field vector. Periodic boundary conditions are imposed on the optical fiber cross-section edge, and the related matrix boundary value problem is solved providing $\beta(\omega)$ of modes as eigenvalues and **H**(x,y) as eigenvectors. By numerical derivatives and fit of $\beta(\omega)$, the fiber chromatic dispersion D and higher order dispersion terms are then calculated.

The introduction of Sellmeier equation to take into account the refractive index variation versus frequency allows to calculate the effects of waveguide and material dispersion, leading to an exact calculation of the overall higher-order fiber chromatic dispersion.

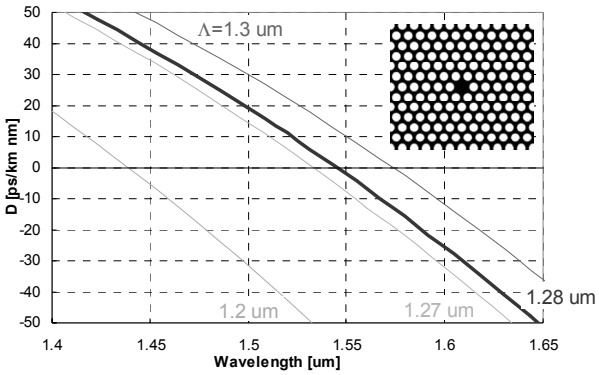

Fig.1. Fiber dispersion versus wavelength for varying pitch values (inset: scheme of simulated PCF)

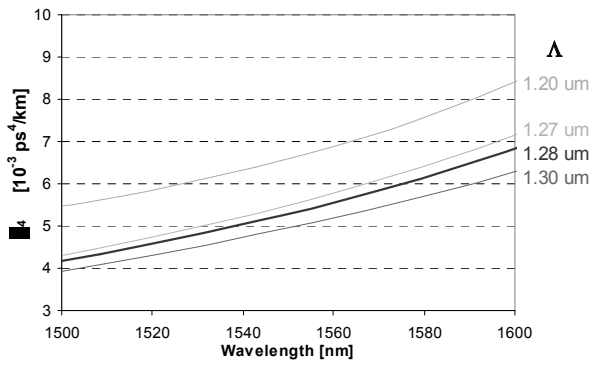

Fig.2. Fiber fourth order dispersion b4 versus. wavelength, for varying pitch values

3. Results

The general structure of a simulated PCF is reported in inset of Fig. 1. The fiber cladding is given by a hexagonal close packed (HCP) structure of air holes of diameter *d* and pitch Λ (white circles) surrounding a solid core of pure silica.

A set of different PCFs with the geometrical structure of the image have been simulated, with varying pitch (Λ) and *d*/Λ parameter, in order to analyze the dependence of dispersion properties on the geometry. Results of simulations showing the chromatic dispersion D and the fourth order dispersion β_4 versus wavelength λ, for different values of pitch Λ, are reported in Fig. 1 and Fig. 2 respectively. The *d*/Λ parameter has been kept constant in simulations, and equal to *d*/Λ=0.72. The graphs outline some of the relevant properties found out with the analysis: PCFs with HCP geometry possess positive β_4 values around 1550 nm (see Fig. 2), which is the base requirement for broadband parametric amplification. Secondly, from calculations it was found that a higher air filling fraction (or higher *d*/Λ) corresponds to a higher value of β_4 (and GVD slope). Thus in order to obtain wider amplification bandwidths (small β_4) PCFs with smaller holes must be used.

Our simulations showed that the variation of β_4 with respect to Λ for a fixed *d*/Λ is such that smaller β_4 are attained for higher Λ values (low non-linearity). This relation then highlights a trade-off between large bandwidth (small β_4) and high gain (small Λ) for such fiber geometries.

Another major issue emerged from our simulations is given by the high sensitivity of the zero-dispersion wavelength λ_0 to the fiber geometrical parameters (both Λ and *d*/Λ). For instance, as it can be seen from Fig. 1, a variation in fiber pitch of only 0.08 μm reflects into a shift in λ_0 of more than 100 nm. This could pose sensible limiting constraints to the repeatability of λ_0 in case of an industrial fiber manufacturing process.

Following the design stage directions, a set of PCF with the studied HCP geometry and slightly different parameters has been physically designed, stacked and manufactured at the University of Bath. The scanning electron microscope (SEM) image of one of the manufactured fibers is shown in inset of Fig. 5; the fiber pitch value is Λ=1.3 μm and *d*/Λ=0.79. Simulations of on-off parametric gain have been carried out, for the scheme indicated in Fig. 3, with the effective area and nonlinear coefficient arising from the measurements of the actual fibers (Aeff=1.95μm, γ= 63 $W^{-1}Km^{-1}$), taking into account the effects of fourth order dispersion. The calculated gain resulting from the fiber of Fig. 5 inset is reported in Fig. 4. The amplifier is obtained by using 100m-long fiber spool and an input co-propagating pump power of 30mW. The resulting on-off gain is found to be 16dB, exhibiting a 3-dB amplification bandwidth wider than 23 dB, from 1560nm to 1583nm for a pump at 1550nm, and excellent flatness behaviour. Note that the small core diameter and the *d*/Λ arise from measurements, while the dispersion properties are supposed to give the optimal relation as in Eq. (2) between β_2 and β_4 at the pump wavelength.

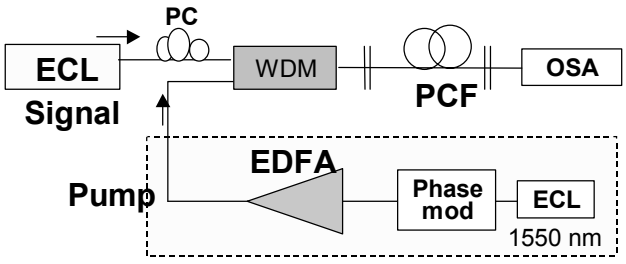

Fig.3. Experimental set-up used in stimulated Brillouin scattering measurements (and for parametric gain simulations)

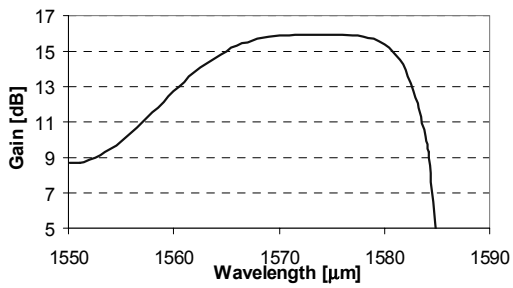

Fig.4. Amplifier on-off gain versus wavelength . (simulations, pump at 1550 nm).

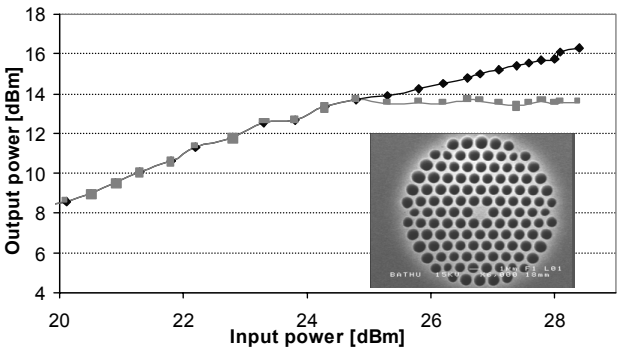

Fig.5. Output pump power versus input pump power for non-modulated pump (grey line) and phase-modulated pump (black line). Inset: SEM picture of a manufactured fiber.

Experiments aimed at assessing the on-off amplifier gain make use of the implemented set-up reported in Fig. 3. The input signal is provided by an external cavity laser (ECL), whose polarization is controlled via a fiber polarization controller (PC) multiplexed through a WDM coupler to the optical pump, given by a second ECL, phase-modulated in order to avoid Stimulated Brillouin Scattering (SBS), and amplified by an Erbium-doped fiber amplifier (EDFA). The main issue in measuring sensible parametric gain arises from high sensitivity of λ_0 to fiber drawing parameters, which makes difficult to match phase-matching condition within the pump wavelength range (given by EDFA 1530-1560nm). Experiments are being carried out presently.

Measurements to identify the Brillouin threshold level have also been carried out. The results reported in Fig. 5 are referred to the fiber showed in the inset. While phase-modulated pump source at 1550nm does not experience SBS (for input powers up to 19.5 dBm) in the 100m long PCF due to its large line-width, SBS has been observed in case of non-modulated pump, thus limiting the input power to about 16 dBm, and the output power to 13.5 dBm. The coupling efficiency has been estimated to be at around 15%, giving about 9 dB of coupling losses, which are also depending on the input pump power. The calculated fiber absorption coefficient is hence about 30 dB/km.

4. Conclusions

In conclusion, the analysis carried out led to the design of an optimized PCF for implementing broadband OPA. The study showed that it is possible to construct PCF with HCP geometry having the correct values of β_2 and β_4; however, calculations pointed out a trade-off between small values (large bandwidth) and small core (high non-linearity). Furthermore, the fiber zero-dispersion wavelength has showed to be very sensitive with respect to small fiber parameters variations (d/λ and Λ). Simulations also showed that fibers with lower dispersion slope are achievable by designing larger core PCF, while d/λ has a much smaller influence on dispersion slope. Fibers for implementing broadband OPA have been designed, and system simulations indicate 23nm-wide amplification bandwidth employing just one pump wavelength at low input power.

Measurement carried out at University of Bath (UK) on manufactured fibers confirm the high sensitivity of λ_0 to small fiber geometrical variations.

Measurements assessing the threshold for stimulated Brillouin scattering have also been carried out, showing that for non-modulated narrow-linewidth pumps the maximum output power from the fiber is 13.5 dBm, attained at a threshold input power of about 16 dBm.

4. Acknoledgment

In this work the numerical model implemented by Tom Hedley (University of Bath, UK) was used. The photonic crystal fibers used were manufactured by Dr Nicolas Joly (University of Bath, UK).

5. References

1. Hansryd, J., Andrekson, P. A., Westlund, M., Li, J., and Hedekvist, P. O., "Fiber-based optical parametric amplifiers and their applications IEEE Journal of Selected Topics in Quantum Electronics, **8**, 506-520 (2002).
2 William H. Reeves, J. C. Knight, P. St. J. Russell, P. J. Roberts, "Demonstration of ultra-flattened dispersion in photonic crystal fibers", Opt. Expr., **10,** 609-613 (2002)
3. M. E. Marhic, N. Kagi, T.-K. Chiang, L. G. Kazovsky, "Broadband fiber optical parametric amplifiers", Opt.Lett. **21,** 573-575 (1996).
4. C. Floridia, M.L. Sundheimer, L. S. Menezes, A.S.L. Gomes, "Optimization of spectrally flat and broadband single-pump fiber optic parametric amplifiers," Opt. Comm. **223,** 381-388 (2003).
5. J. M. Pottage, David Bird, T. D. Hedley, J. C. Knight, T. A. Birks, P. St. J. Russell, P. J. Roberts, "Robust photonic band gaps for hollow core guidance in PCF made from high index glass",Opt Expr. **11,** 2854-2861 (2003).