Four-Wave Mixing in Photonic Crystal Fibres for Wavelength Conversion in Optical Networks

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Abstract: Four-Wave Mixing is one of the few all-optical techniques which provides fully transparent wavelength conversion. Here, we demonstrate Four-Wave Mixing generation in a band of up to 20 nm centred at the zero dispersion wavelength of a photonic crystal fibre (1560 nm). A stable efficiency around -35 dB is maintained across the band using a pump power of 10 dBm. The experimental results are in good agreement with the theoretical results.

1. Introduction.

Photonic crystal fibre (PCF) technology has recently witnessed a great evolution and is of great interest for fibre device applications because of the wide range of novel optical properties that it offers. Its structure can provide a much higher effective nonlinearity than a conventional fibre. As a result of that, many non-linear effects in this kind of fibres have been demonstrated, such as four-wave mixing (FWM), cross-phase modulation (XPM), stimulated and spontaneous Brillouin scattering effect [1].

Photonic crystal fibre is made from a single material (for example, undoped silica), whose waveguiding mechanism is defined by a regular array of empty holes running along the length of the fibre, arranged around a central core. To obtain a PCF with small mode area and hence high effective non-linearity, a structure with larger air holes and a small hole-to-hole spacing must be used.

The Four-Wave Mixing effect generates a wavelength-shifted signal and therefore may be used for wavelength conversion in all-optical networks. This technique provides total transparency of the transmitted information as well as the possibility of simultaneous conversion of a band of optical channels present in the WDM bandwidth using a single converter.

The use of PCFs results in improvements, when compared to dispersion shifted fibres (DSFs) or highly non-linear DSFs, that can be obtained in terms of reduced device lengths and (or) power requirements as a result of the high effective non-linearity of the fibre, making them a more realistic proposition for real-world telecommunications applications. Soliton self-frequency shift [2], wavelength conversion [3] and a dispersion-compensation fibre [4] are some examples of typical real-world applications. Previous DSF experiments have shown -16 dB efficiency with a 6 nm conversion bandwidth [5,6], while FWM using a holey fibre provides similar efficiency though over an increased bandwidth of 10 nm [7].

In this work, we have observed four-wave mixing using a 9.4 m long Photonic Crystal Fibre. The two main parameters analysed in detail are conversion efficiency and conversion bandwidth. Both are extremely important. The former defines the highest possible power efficiency of the wavelength converter. The latter directly influences the wavelength band where the converter may be used, which is an important cost saving factor considering that fewer converters must be used to provide wavelength conversion capability in a pre-determined transmission band.

2. Theory

The optical fibre cannot always be considered as linear transmission channel. The higher the injected power and the further the transmission distance, the faster the non-linear effects begin to emerge. When an optical high-power signal is launched into a fibre, the linearity of the optical response is lost giving rise to diverse non-linear effects. One such non-linear effect, which is due to the third-order electric susceptibility, is called the optical Kerr effect. Four-wave mixing (FWM) is a type of optical Kerr effect and occurs when light of two or more different wavelengths is launched into a fibre. Generally speaking, FWM occurs when light of three different wavelengths is launched into a fiber, giving rise to a new wavelength. Figure 1 (a) shows a schematic diagram of four-wave mixing in the frequency domain.

The frequency of the new wave (or converted wave – $f_{\text{converted}}$) is determined by $f_{\text{converted}} = f_{p1} + f_{p2} - f_s$ where f_s is the frequency of the signal and f_{p1} and f_{p2} are the pumping frequencies.

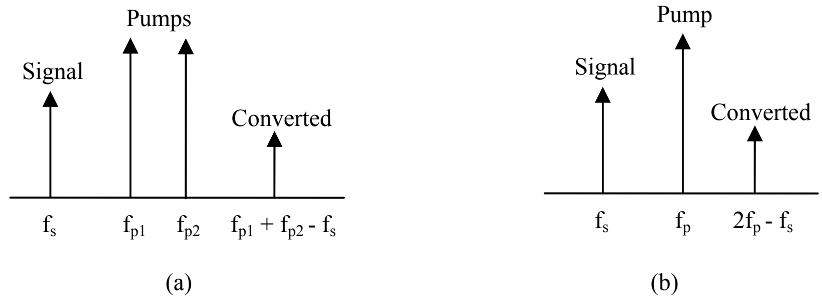

Figure 1 – (a) Non-degenerate Four-wave Mixing (b) Degenerated Four-Wave Mixing

When the frequencies of the two pumping waves are identical (f_{p1} = fp_2 = f_p), the more specific term "degenerated four-wave mixing" (DFWM) is used, and the equation for this case may be written as $f_{\text{converted}} = 2\, f_p - f_s$. Figure 1 (b) shows a diagram of degenerated four-wave mixing in the frequency domain.

One usually is interested in degenerated case since it has more advantages. To achieve high conversion efficiency over a broad bandwidth the pump wavelength must coincide with the zero-dispersion wavelength of the fibre. The conversion efficiency (ξ) is given by [7]

$$\xi = \frac{P_{converted}}{P_s} = (\gamma L_{eff} P_p)^2 \eta e^{-\alpha L} \quad (1)$$

where L is fibre length, α is the attenuation coefficient, γ *is* the non-linear coefficient of the fibre, P_p and P_s are the optical power of the pump and input signal waves, respectively. L_{eff} is the effective interaction length and is obtained by $L_{eff} = (1-e^{-\alpha L})/\alpha$ [7].

η is the four-wave mixing process efficiency and is given by [7]

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left[1 + 4\frac{e^{-\alpha L}}{(1-e^{-\alpha L})^2}\sin^2(\Delta\beta \times \frac{L}{2})\right] \quad (2)$$

The term $\Delta\beta$ in the above equation represents the phase mismatch of the propagation constant and may be written as [7]

$$\Delta\beta = \beta_{signal} + \beta_{converted} - 2\beta_{pump} = \frac{2\pi\lambda_s^2}{c}\Delta f^2\left[D(\lambda_s) + \Delta f\frac{\lambda_s^2}{c}\frac{\partial D}{\partial \lambda}\right] \quad (3)$$

where $D(\lambda_s)$ is the chromatic dispersion of the signal, $\frac{\partial D}{\partial \lambda}$ is the chromatic dispersion slope, Δf is the frequency separation between the pump (f_p) and the input signal (f_s) ($\Delta f = f_p - f_s$), c is the speed of light in vacuum and λ_s is the input signal wavelength.

3. Experimental Setup

The highly nonlinear photonic crystal fibre (NL 2. 3 1555 of CRYSTAL FIBRE) used in this experiment is 9.4 m long and has a core diameter of 2.3 µm [8]. The cladding diameter is 125 µm. An effective area of 5 µm^2 and attenuation coefficient of 60 dB/km at 1550 nm are specified. The average pitch to hole size ratio is d/Λ = 0.5 and the pitch period of the hole structure is Λ=1.6 µm. According to [9] this fibre is in single-mode operation at the third window of optical communication. The fibre has a non-linear coefficient γ of 18 $W^{-1}km^{-1}$ and a chromatic dispersion slope of -0.25 $ps/nm^2/km$. The zero dispersion wavelength is 1560 nm (see Fig. 2). The experimental setup is shown in Figure 2.

As light sources, two 10 mW lasers were used. One laser was operating as the pump at the zero dispersion wavelength of the PCF fibre and the other laser as the signal itself. The signal laser wavelength range is 1530 nm - 1570 nm. After each laser, a polarization controller was placed in order to align the pump and signal polarizations, so that the process efficiency could be improved.

The signals were then power coupled and amplified in a 500 mW Erbium Doped Fibre Amplifier (EDFA). From this stage, the signals were launched into the 9 m PCF where the FWM effect was produced. A low loss splice (< 0.4 dB) between SMF 28 and PCF was obtained using a conventional fusion splicer (*Fujikura* FSM-40S). At the other end, wavelength generation as a result of the FWM was monitored using an Optical Spectrum Analyzer (OSA). The result is shown in Fig. 3 (a).

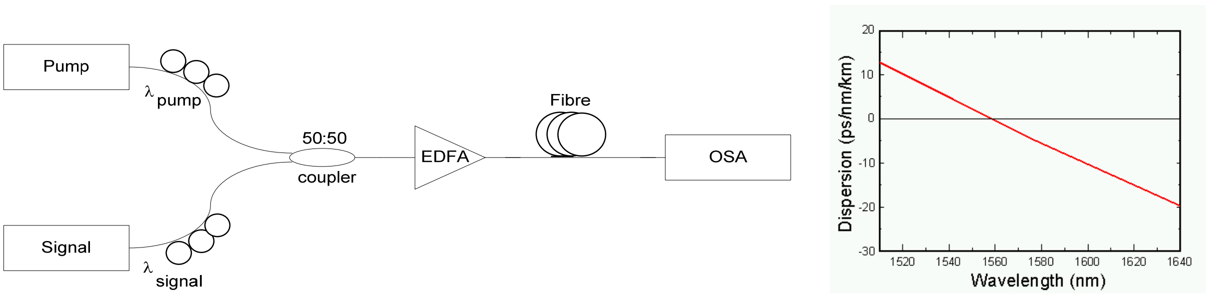

Figure 2: Experimental setup and chromatic dispersion characteristic of the PCF

The experimental procedure is now described. First, the pump wavelength was set to the fibre zero-dispersion wavelength in order that the phase-matching condition can be satisfied. The input signal was moved away from the pump wavelength in steps of 0.2 nm, according to the ITU WDM grid. In each step, the conversion efficiency was calculated from the OSA spectrum data. The measured input and pump signals powers at the input of the PCF, were 21.3 dBm and 20.7 dBm respectively.

4. Results and Discussion

Figure 3 (a) shows the measured spectra of the pump, satellite and converted signals, the arrows indicating the evolution of the signals with the progression of the input signal through the ITU WDM grid. Figure 3 (b) shows the measured conversion efficiency. Measurements were taken over the range of 16 nm centred on 1560 nm.

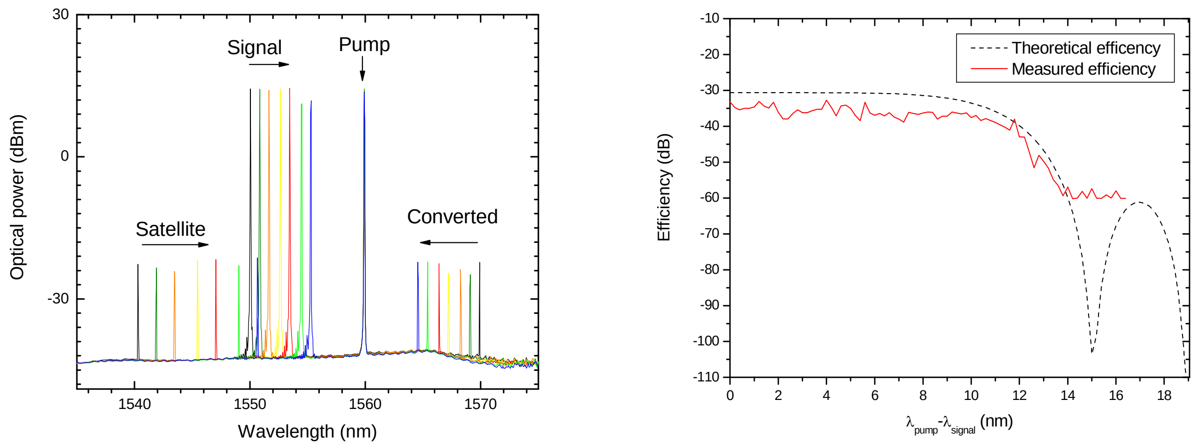

Figure 3: (a) Measured spectra for different input signals (b) Four-Wave Mixing conversion efficiency

A conversion efficiency of approximately -35 dB was obtained, over a bandwidth of 10 nm (20 nm two-sided bandwidth). The dashed line in figure 3 (b) shows the corresponding theoretical results. These are in good agreement with the experimental results. When compared with previously published results, our experiment demonstrates broader bandwidth, albeit a lower efficiency. Despite having higher dispersion slope, the fact that the PCF length is small is the reason for the relatively large bandwidth obtained. The high value for the attenuation, α, originates an effective length, L_{eff} of 8.8 m, which limits the maximum available conversion efficiency.

As the technology of PCF fabrication evolves new fibres are being developed with significant improvements in attenuation losses, making the use of PFC fibres more attractive from the application point of view.

5. Conclusions

Wavelength conversion through the FWM effect has been achieved using a PCF with a high non-linear coefficient. A theoretical and experimental study of the conversion efficiency and operation bandwidth has been presented. A conversion efficiency of -35 dB over a bandwidth of 20 nm has been obtained in good agreement with the theoretical results. A great advantage of the PCF is the small length of fibre required to achieve wavelength conversion due to its high non-linear coefficient. One other main advantage of this kind of fibres is its broader bandwidth in comparison to other fibres where FWM can be obtained, such as DSF. In conclusion, PCF is more suitable for applications requiring broader bandwidths, such as dense WDM. Moreover, wavelength converters using PCF can be made much smaller, which can be a very important reason to develop PCF-based wavelength converters or routers. Work is also under way to develop optical switches/cross-connects based on non-linear effects in photonic crystal fibres.

Acknowledgments

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