Highly efficient generation of broadband cascaded four-wave mixing products

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Abstract: We report and investigate on a highly efficient technique to generate broadband cascaded four-wave mixing (FWM) products. It consists of launching two strong pump waves near the zero-dispersion wavelength of very short (of order of few meters) optical fibers. Simulations based on split step fourier method (SSFM) and experimental data demonstrate the efficiency of this approach. Multiple FWM products have been investigated by using conventional fibers and ultra-flattened dispersion photonic crystal fibers. Measured results present bandwidths of 300 nm with up to 118 FWM products. We have also demonstrated a flat bandwidth of 110 nm covering the C and L bands, with a small variation of only 1.2 dB between the powers of FWM products, achieved by using highly nonlinear fibers (HNLFs). The use of dispersion tailored photonic crystal fibers has been shown interesting for improving the multiple FWM efficiency and reducing the separation between the pump wavelengths.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2280) Fiber design and fabrication; (190.0190) Nonlinear optics; (190.4380) Four-wave mixing.

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1. Introduction

Four-wave mixing (FWM) in optical fibers refers to a nonlinear interaction among four different waves, in which the energy and wave-vector must be conserved [1]. This requirement is often referred to as phase matching and depends strongly on the chromatic dispersion.

In a quantum-mechanical picture FWM takes place when photons from one or more waves are annihilated and new photons are created. In one scenario, three incident waves (at, say, ω_1, ω_2 and ω_3) interact in the fiber in such a way that two photons (at ω_1 and ω_2) are annihilated and two new photons (at ω_3 and $\omega_4 = \omega_1 + \omega_2 - \omega_3$) are created. The creation of photons at frequencies not present in the incident field can be used to generate light at new frequencies (ω_4), whereas photons created at frequencies that are present (ω_3) in the incident field provide parametric gain.

The particular case $\omega_1 = \omega_2$ is referred to as degenerate FWM and will be further explored in this paper. FWM processes are generally described in terms of a nonlinear optical polarization that is cubic in the field:

$$P(\omega_4) \propto E_1 E_2 E_3^* e^{-i[\beta(\omega_1)+\beta(\omega_2)-\beta(\omega_3)]z}, \tag{1}$$

where $\beta(\omega)$ is the waveguide propagation constant at frequency ω, z is the position along the fiber, and E_j is the field amplitude at ω_j. For efficient generation, the phase of this nonlinear polarization must match the phase of the field wave at ω_4 as it propagates through the fiber. This phase-matching requirement occurs when the net wave-vector mismatch $\kappa = 0$, where κ is given by [2]:

$$\kappa = \Delta\kappa_M + \Delta\kappa_W + \Delta\kappa_{NL} = 0, \tag{2}$$

where $\Delta\kappa_{M}$, $\Delta\kappa_W$ and $\Delta\kappa_{NL}$ represent the mismatch occurring as a result of material dispersion, waveguide dispersion and nonlinear effects, respectively. This equation shows the tradeoff between nonlinearity and dispersion. In the degenerate FWM, the three contributions are [2]:

$$\Delta\kappa_M = [n_3\omega_3 + n_4\omega_4 - 2n_1\omega_1]/c, \tag{3.1}$$
$$\Delta\kappa_W = [\Delta n_3\omega_3 + \Delta n_4\omega_4 - (\Delta n_1 + \Delta n_2)\,\omega_1]/c, \tag{3.2}$$

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$$\Delta\,\kappa_{NL} = \gamma\,(P_1 + P_2), \tag{3.3}$$

where γ is the fiber nonlinear coefficient, P_1 and P_2 are the incident power of ω_1 and ω_2, respectively. To obtain phase matching, at least one of them should be negative. In order to obtain high efficiency, the product $\Delta\beta L$ must be small, where L is the fiber length, and

$$\Delta\beta = \beta(\omega_4) + \beta(\omega_3) - \beta(\omega_1) - \beta(\omega_2) \tag{4}$$

As the waves propagate through the fiber, FWM processes may occur involving the waves generated previously, creating in this way photons at further new frequencies. This is referred to as cascaded or multiple FWM. This frequency cascading is formed by signals with well-defined frequency and phase differences. Mckinstrie et al have obtained exact formulas to predict the amplitude of light waves involved in four-wave mixing cascades for the case of dispersion-less fibers [3] [4].

Another way of describing cascaded FWM processes, which is particularly useful in the degenerate FWM case considered here, is based on a different interpretation [5]: the two incident laser fields at ω_1 and ω_2 produce a refractive index moving grating (with spatial period $2\pi/\Delta\beta$, where $\Delta\beta = |\beta(\omega_2) - \beta(\omega_1)|$) which is temporally modulated at the beat frequency $\Delta\omega = |\omega_2 - \omega_1|$; then any wave at a frequency ω that propagates in the fiber will be inelastically diffracted by the grating at frequencies $\omega \pm \Delta\omega$ and, as these propagate, will be further diffracted generating waves at $\omega + n\Delta\omega$ ($n = \pm1, \pm2,...$). In particular, the incident lasers will be self-diffracted and, if no other wave is present in the input field, the output spectrum will exhibit a number of sidebands at $\pm n\Delta\omega$ on each side of the laser lines. The importance of phase matching in this grating picture can be perceived by noting that, for efficient sideband build-up, the wave-vector of the diffracted wave, $\beta(\omega) + n\Delta\beta$, must nearly match the corresponding wave-vector of the fiber modes at $\omega + n\Delta\omega$, i.e., the quantity $|\,\beta(\omega) + n\Delta\beta - \beta(\omega + n\Delta\omega)|L$ must be small.

Chromatic dispersion plays a fundamental role in phase matching. The efficiency of cascaded FWM can be optimized by using two pump lasers with frequencies near the zero-dispersion frequency, ω_0, of the fiber ($\omega_0 = 2\pi c/\lambda_0$, where λ_0 is the zero dispersion wavelength). Therefore, the use of fibers that provide efficient dispersion management, such as Photonic Crystal Fibers, can be useful to enhance the efficiency of multiple FWM process.

Cascaded four-wave mixing products have been studied both theoretically and experimentally regarding several applications. Since this frequency cascading is formed by signals with well-defined frequency and phase differences a well studied application is related to waveform generation. For example, Fatome et al have proposed the use of kilometer lengths of optical fiber for the generation of high repetition rate pulse sources [6]. For this goal, they reported a multiple four-wave mixing bandwidth of 90 nm. In the same vein, trains of ultra-short RZ pulses were generated by using FWM in a few kilometers of highly nonlinear optical fiber [7] or 20 m of highly nonlinear photonic crystal fiber [8]. Cascaded FWM may be used as a multiwavelength source for DWDM systems or as a frequency comb generator for metrology applications [9] (with the advantage of using cw lasers instead of femtosecond lasers). In the context of phase-sensitive parametric amplification, McKinstrie et al. have found that the number of products increases with the distance [4].

We have recently reported [10] highly efficient generation of broadband cascaded FWM products spanning over 110 nm, obtained by using hybrid photonic crystal fibers [11]. In the current work we numerically and experimentally investigate cascaded FWM products in various types of optical fibers, including conventional optical fibers and photonic crystal fibers (PCFs). Simulations were based on a split step fourier method (SSFM) code, which exactly treats the nonlinear ellipse rotation terms [12].

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By performing these simulations and carrying out nonlinear experiments, the physical phenomenon behind efficient generation of multiple FWM products has been analyzed as a function of the fiber dispersion and nonlinear properties. Furthermore, we demonstrate that shortening the fiber length to a few meters and by employing a multi-section arrangement we can generate cascaded four-wave mixing products spanning over 300 nm.

2. Method

It is well known that a large refractive index difference between the core and cladding indices leads to tight optical confinement into the fiber core and higher nonlinear coefficients. In addition to enhancing the nonlinear coefficient, long fiber lengths, of order of hundreds of meters or even a few kilometers, are usually used to increase the efficiency of the nonlinear processes [13]. In this work we suggest shortening the fiber length to a few meters with the purpose of generating broadband four-wave mixing products. The advantages of using very short optical fibers rely on three features: fiber random birefringence; group velocity dispersion fluctuation and phase mismatch $\Delta\beta L$.

FWM efficiency is substantially degraded by state of polarization (SOP) mismatching of the pump waves. The birefringence of fiber increases the SOP mismatch as the light propagates along the fiber. The relative phase difference $\Delta\Phi$ is proportional to the fiber length L, therefore the use of very short lengths can be used as a strategy for reducing $\Delta\Phi$ of non-polarization maintaining fibers.

The fiber fabrication process inevitably results in undesirable variation of the zero-dispersion wavelength [14]. The phase-matching condition is determined at each local segment, thus large λ_0 variations imply a reduction of the FWM efficiency. Consequently very short fibers can improve FWM efficiency as well.

Perhaps the most important benefit of the current approach is to keep the phase mismatch $\Delta\beta L$ small. One can increase the efficiency of the FWM process by increasing the fiber length. However, for long fiber lengths the amplification of the broadband noise severely limits the efficiency of generation of multiple FWM products. On the other hand, by using short propagation lengths, optical fibers provide an essentially lossless system that can display periodic and/or chaotic transfer between multiple frequencies. Furthermore, very short lengths of fiber allow a moderate phase mismatch, by keeping the product $\Delta\beta L$ small. To better explain this idea we performed simulation using the SSFM [12] with realistic fiber parameters. We have not taken into account Raman and Brillouin scatterings, because for the lengths used in the simulations (some meters) the thresholds of these nonlinear effects are larger than 200 W, which was the maximum peak power used in the simulations. Therefore the only nonlinear effect taken into account was the nonlinear refraction originated from third-order susceptibility. Typical parameters of a HNLF have been used, namely, $\gamma = 10\ W^{-1}\ km^{-1}$, and $\lambda_0 = 1550$ nm. The input spectrum was given by two 100 W pumps at 1555 and 1563 nm and a white-gaussian noise with optical signal-to-noise ratio (OSNR) of 80 dB @ 12.5 GHz. We have used a spectral window of 164 THz, 2^17 sample points and a constant longitudinal step of 0.5 cm in all the simulations. Furthermore, we have always checked the convergence of our simulations, guarantying that the numerical error at each sample point was always below 0.2 dB.

The number of FWM products with OSNR above 30 dB as a function of the fiber length is shown in Fig. 1(a). Clearly, after a maximum is reached, the number of FWM products with an acceptable OSNR drops with the length increase. This makes clear that the use of very short fiber lengths enables highly efficient generation of multiple FWM products. For this fiber the optimal length is around L = 2.0 m. We also propose the use of fibers with low dispersion slope (S_0) to further improve the multiple FWM efficiency, as shown in Fig. 1(b). For this case, we have fixed the fiber length to L = 3.0 m and simulated how the number of FWM products with acceptable OSNR depends on S_0. All the other parameters where kept as in the simulations in Fig.1 (a). The improvement of the number of FWM for low S_0 values is

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obvious. These simulation results qualitatively illustrate how the FWM efficiency depends on fiber length and dispersion slope.

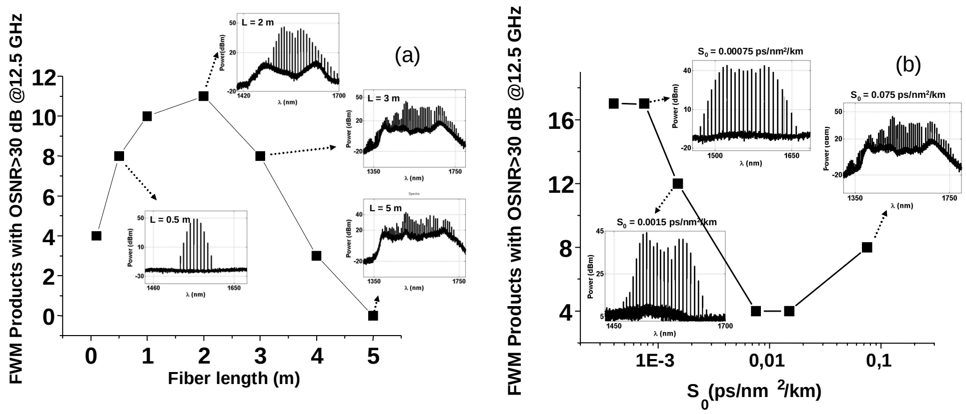

Fig. 1. Length and dispersion slope analyses. (a) Number of FWM products with OSNR > 30 dB as a function of the fiber length for S_0 = 0.075 ps/nm^2/km and typical HNLF parameters. (b) The same as in (a), but now fixing the fiber L = 3.0 m and varying S_0.

3. Experimental setup

The experimental setup is shown in Fig. 2. Two external cavity lasers were combined with a 3-dB coupler and amplified by two cascaded erbium doped fiber amplifiers (EDFAs). In order to obtain high power (around 10 W) the lasers were amplitude modulated in the form of 40 ns pulses with a low duty-cycle.

The first EDFA was used as a pre-amplifier (average output power of 12 mW) while the second EDFA was a booster (average output power of 250 mW). Polarization controllers were used to optimize the efficiency of FWM in the fibers under test. The measured peak power at the fiber input was about 10 W for each laser. Output spectra were measured using an optical spectrum analyzer (OSA) with 0.01 nm resolution, and the peak powers using a photodiode and an oscilloscope with combined rise-time response < 1 ns. We stress that a background noise level due to stray light inside the OSA limited the OSNR in the experiments.

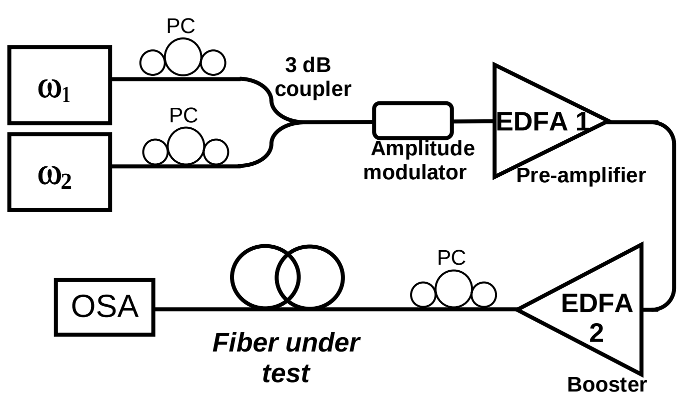

Fig.2. Experimental setup.

Photonic crystal fiber technology has opened new perspectives in optical fiber design. In particular, they have been shown to be extremely useful for dispersion management due to the great flexibility provided by the photonic crystal cladding. Ultra-flattened dispersion photonic

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crystal fibers have been investigated numerically by Ferrando *et al* [15] and were first fabricated by Reeves *et al* [16]. PCF with ultra-low and flat dispersion requires precise control of hole shape, size, pitch and core diameter, since it is based on sub-micron air holes. We used ultra-flattened and near zero dispersion fibers like those in ref [16], but with zero-dispersion wavelengths λ_{01} = 1400 nm for the PCF 1 nm and λ_{02} = 1330 nm for the PCF 2. They are formed by 13 rings of air holes with roughly hole size d = 0.58 μm, interhole spacing Λ = 2.45 μm and nonlinear coefficient $\gamma = 2.5\ W^{-1}km^{-1}$.

4. Results

In order to investigate the physical mechanism behind the efficient generation of cascaded FWM, we have used conventional fibers and photonic crystal fibers with different optical properties, such as effective area, nonlinear coefficient, zero-dispersion wavelength, and dispersion slope. This section is divided in two parts. The first subsection is focused on the results obtained by using only conventional optical fibers. The second presents the generation of FWM products achieved by using ultra-flattened photonic crystal fibers and, in some cases, by employing together PCFs and conventional fibers.

4.1 FWM products obtained by using conventional fibers

This subsection is focused on the generation of cascaded FWM products obtained by using only conventional optical fibers. As shown in Fig. 3(a), we have observed that the first few FWM peaks are already produced inside the EDFA booster. This is important for the overall generation of multiple FWM products, since more than two waves will be launched into the fiber. The ASE level after the booster can be easily improved by using optical filters. Figure 3(b) shows the output spectrum after a standard (STD) telecom fiber which is only 2 m long. It was an SMF28 fiber (Corning), with nominal effective area A_{eff} = 80 μm^2, λ_0 = 1310 nm, dispersion slope S_0 = 0.06 ps/nm^2km and nonlinear coefficient $\gamma = 1.5\ W^{-1}km^{-1}$. As in the previous case, the two initial pumps can be easily identified by the two strongest signals. The bandwidth spanned by the FWM products is now larger than that of the previous case, but the efficiency of the generation of cascaded FWM products is low because the pump waves were launched far from the zero-dispersion wavelength of the fiber under test. With the purpose of finding a solution to this problem, we decided to use a dispersion shifted fiber (DSF) with the following features: λ_{ZD} = 1559 nm, nonlinear coefficient $\gamma = 2.1\ W^{-1}km^{-1}$ and dispersion slope S_0 = 0.075 ps/nm^2km. As seen in Fig. 3(c), by using this fiber one obtains more efficient generation of FWM products that extends from 1500 to 1630 nm.

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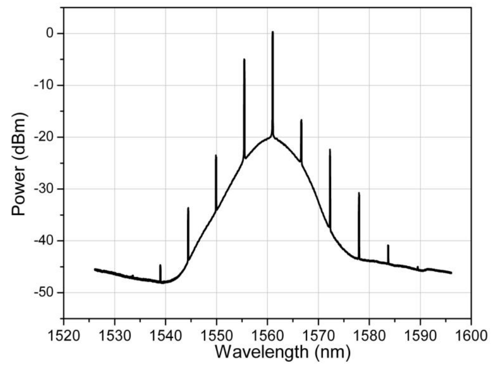
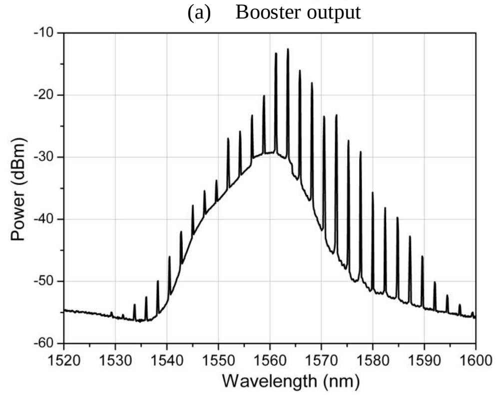
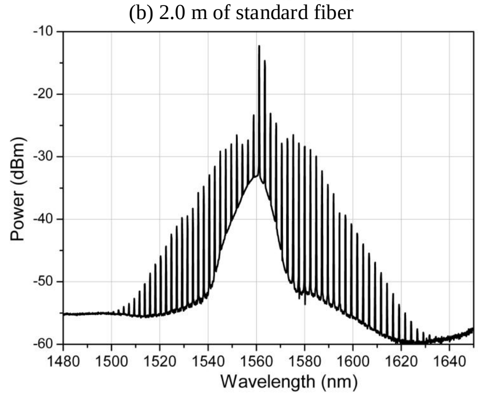


(a) Booster output



(b) 2.0 m of standard fiber



(c) 2.0 m of DSF

Fig.3. FWM products obtained at the booster output and by using STD and DSF.

Afterwards, we launched the two pump lasers into 2.0 meters of different highly nonlinear fibers. The fiber that gave the best results has the following parameters: λ_{ZD} = 1560 nm, A_{eff} = 9 μm^2, γ = 15 $W^{-1}km^{-1}$ and S_0 = 0.02 ps/nm^2km. By using this fiber, we could launch two pump waves near to the fiber zero-dispersion wavelength in a fiber with a high nonlinear coefficient. To obtain the best configuration for broadband generation of cascaded FWM products, the two lasers were tuned between 1535 and 1565 nm and their separation was kept around 6.3 nm. The most efficient generation of those products, Fig. 4(b), has been obtained when the lasers were tuned to λ_1 = 1555.5 nm and λ_2 = 1561.8 nm. Note that intense FWM products covering a measured bandwidth of 300 nm, from 1400 to 1700 nm, have been generated. We highlight that the highest measured FWM product at 1700 nm is still strong, so we believe that because of limitations of our Optical Spectrum Analyzer it was not possible to

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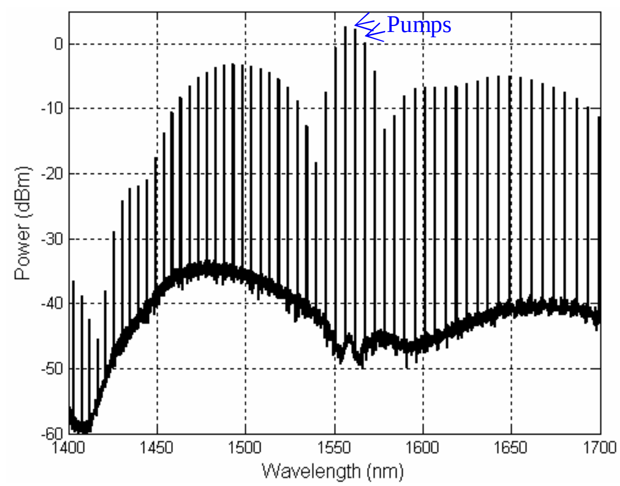
measure the real generated bandwidth of this configuration. This result is in good qualitative agreement with the SSFM simulation shown in Fig. 4(a). The discrepancy between the simulated and measured OSNR is due to the high stray light of our OSA. The noise bump around 1550-1570 nm comes from amplified spontaneous emission (ASE) noise of EDFAs.

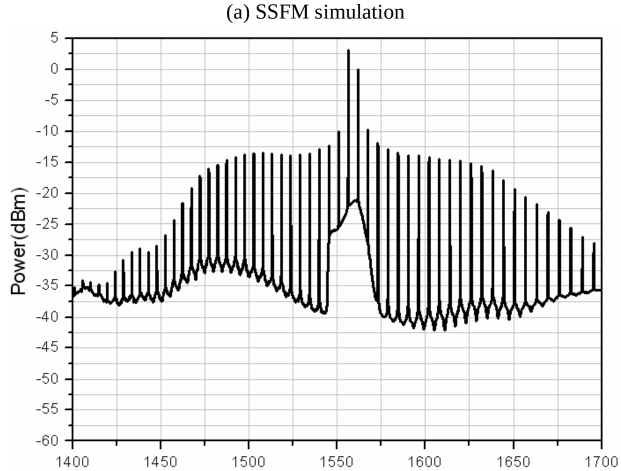
This large bandwidth of generated cascaded FWM products implies good phase matching. In order to ensure this phase matching we must preserve $\Delta\beta L < \pi$, where $\Delta\beta$ is the propagation constant mismatch and L is the fiber length. For the studied FWM process we have

$$\Delta\beta \approx \beta_2(\omega_l)\Delta\omega^2, \tag{5}$$

where $\Delta\omega$ is the frequency separation between the lasers and β_2 is the second order dispersion evaluated at the laser frequency. As the lasers propagate along the fiber, first the two initial frequencies at ω_1 and ω_2 interact and create new waves at frequencies $\omega_1 - \Delta\omega$ and $\omega_2 + \Delta\omega$, where $\Delta\omega = \omega_1 - \omega_2$. Then, due to multiple four-wave mixing processes, many harmonic bands are generated, leading to a strong spectral broadening. Essentially, $\Delta\beta$ for the new FWM products has an identical $\Delta\omega$ but $\beta_2$changes. This short segment of fiber would allow a moderate phase mismatch and therefore a highly efficient generation from 1400 to 1700 nm. Note also that this spectrum as well as being broader, is also quite flat compared to the previous ones, constituting about 160 nm of flat band.



(a) SSFM simulation



(b) Experimental result

Fig.4. Efficient generation of FWM products obtaining by using 2.0 m of HNLF.

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One of the potential applications of cascaded FWM products is the development of multiwavelength sources for Wavelength Division Multiplexing systems. Figure 5 illustrates this idea and presents an 80 nm long spectrum, covering all C and L bands, in which the maximum power variation between the generated FWM products is only 1.2 dB.

The generation of cascaded FWM products can also be maximized by applying a comb-like dispersion profiled fiber (CDPF). This technique was proposed in 1994 by Inoue for obtaining wide wavelength conversion range in fiber four-wave mixing [17]. Subsequently, Marhic et al [18] and Provino [19] et al have also applied this technique to maximize optical parametric amplifier performance. It comprises a nonlinear medium consisting of N segments of cascaded dispersion shifted fibers (DSF) and highly nonlinear fibers. The main idea of this technique is to enhance the FWM efficiency by properly designing the dispersion profile (map) along the nonlinear fiber and the nonlinear phase shifts by selecting appropriate lengths of fiber segments. Since we want to extend the multiple FWM spectrum to shorter wavelengths, these fiber segments (FS) are cascaded in such a way that they form a discrete dispersion increasing fiber (the zero dispersion of the fibers shifts to shorter wavelengths from the pump end to the output end). The zero dispersion wavelength of the first segment coincides with the peak (or center) of the pump source spectrum. As a result, the output light spectrum of the FS1 is efficiently broadened by multiple FWM in the fiber. In order to maximize the broadening caused by multiple FWM, in the second fiber segment, the zero dispersion of the FS2 should be placed near the blue edge of the multiple FWM spectrum obtained by FS1. For the same reason, the zero dispersion wavelength of the nth segment FS(n) should be placed at the blue edge of the spectrum output from the FS(n-1). CDPF technique is demonstrated by using the following example: L = 2.0 m of the same HNLF of the previous experiment (Fig. 4b) and L = 1.0 m of LEAF fiber with λ_{ZD} = 1520 nm and γ = 1.7 $W^{-1}km^{-1}$. The measured spectrum is shown in Fig. 6. By applying a CDPF with a fiber that provides a lower zero-dispersion wavelength, the efficiency of the FWM products generated between 1450 and 1500 nm has been improved, resulting in a larger equalized band of 200 nm compared to the 160 nm of the previous case. The efficiency of multiple FWM process would be further improved by using a CDPF with more fibers with carefully chosen dispersion properties.

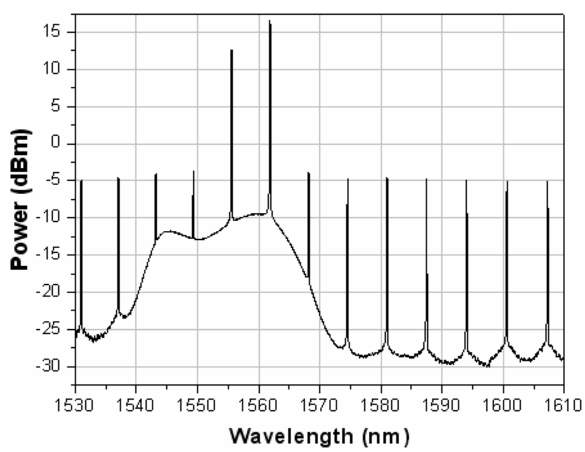

Fig.5 . FWM products over 80 nm with maximum power variation between the generated FWM products of only 1.2 dB.

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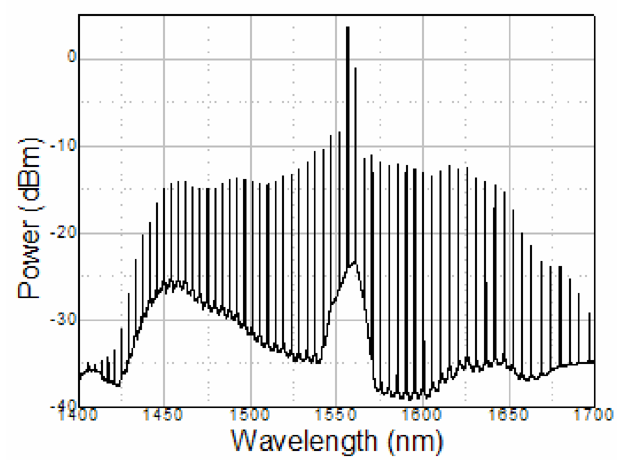

Fig.6. FWM products obtained by using a comb-like dispersion profiled fiber.

4.2 FWM products obtained by photonic crystal fibers

The results of the last subsection have demonstrated that the use of fibers with low dispersion slope can enable efficient generation of multiple FWM products. Based on this reasoning, we have decided to investigate ultra-flattened dispersion photonic crystal fibers. This subsection presents results concerning the use of PCFs described in Section 2. Both fibers used provide ultra-flattened and near zero dispersion. The main difference between them is their zero-dispersion wavelengths and dispersion slopes at 1550 nm, which are λ_{01} = 1400 nm and S_{01} = 0.003 ps/nm^{2}km for the PCF 1 and λ_{02} = 1330 nm and S_{02} = 0.004 ps/nm^{2}km for PCF 2.

Figure 7 displays the generation of cascaded FWM products obtained by using the PCF 1. The measured dispersion of this fiber at the pump wavelengths is D = 0.3 ps/nm.km. The FWM products span over 300 nm as in the previous cases.

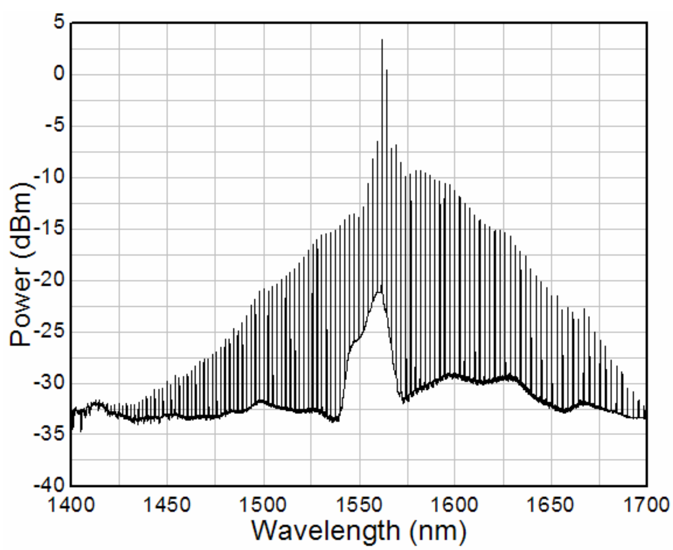

Fig. 7. 118 FWM products spaced by 2.5 m obtained by applying the PCF 1.

However, note that the separation between the pump waves, and consequently the spacing between the FWM products, could be reduced to 2.5 nm by using this fiber. The lower fiber

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dispersion slope allows reduced spacing between the FWM products. In this case 118 cascaded FWM products have been generated.

The comb-like dispersion profiled fiber technique was again applied for taking advantage of the properties of both PCFs and HNLFs. By using a section constituted by 10 meters of the PCF 2 and another one formed by 2 meters of HNLF with λ_0 = 1560 nm, it was possible to work with a small spacing between the FWM products and, at the same time, launching the lasers near the HNLF zero-dispersion wavelength. The measured dispersion of PCF 2 at the pump wavelengths is D = 1.2 ps/nm.km. Figure 8 illustrates efficient generation of multiple FWM products in the C Band. It is clear that beyond allowing launching the pump waves with reduced spectral spacing, the use of ultra-flattened dispersion fibers results in an improvement of FWM efficiency, since the power of the generated FWM products are now close to those of the pump waves in contrast to the cases in which only conventional fibers have been used. The power difference between the pump wave at 1552.3 nm and the FWM product at 1558.5 nm is only 1.0 dB.

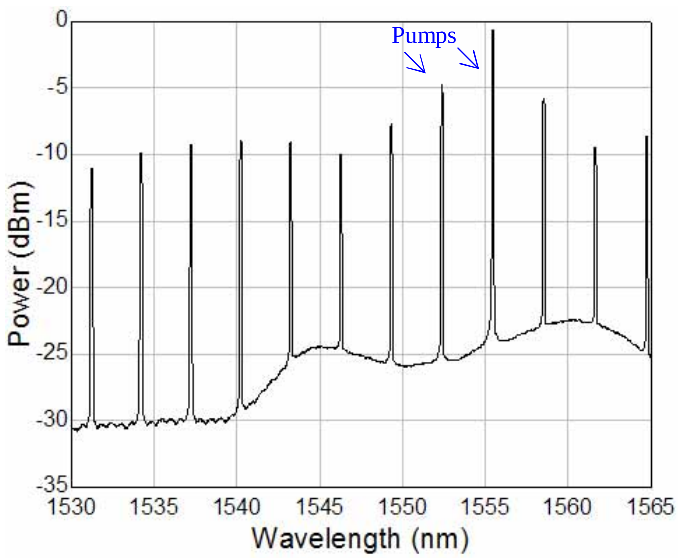

Fig. 8. Result obtained by using a CDPF formed by 10 m of PCF 2 and 2 m of HNLF.

Figure 9 also demonstrates the improvement in the FWM efficiency obtained by the use of ultra-flattened dispersion PCFs. It presents efficient generation of cascaded FWM products, covering all of the C band and most of the L band, in which the average conversion efficiency is - 5.0 dB. This result has been obtained by using 8 meters of PCF 1. We have also obtained agreement between SSFM simulations, using the measured dispersion data of the ultra-flattened dispersion PCFs, and the last 3 experimental results.

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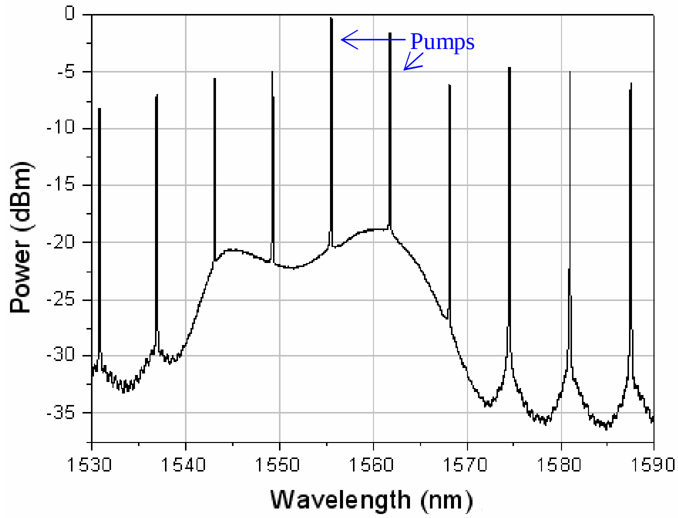

Fig. 9. FWM products obtained by using a 8.0 m of PCF 1.

5. Conclusions

A highly efficient technique to generate broadband cascaded four-wave mixing products has been reported and analyzed. It consists of injecting two strong pump waves into very short optical fibers with zero-dispersion wavelength close to the pump. This method has been numerically and experimentally investigated as a function of the fiber dispersion and nonlinear properties. It has been applied to conventional fibers, ultra-flattened dispersion photonic crystal fibers and comb-like dispersion profiled fibers composed by either conventional fibers or PCFs.

The advantages of using very short optical fibers result from 3 effects: reducing the relative phase difference $\Delta\Phi$ of non-polarization maintaining fibers; avoiding undesirable variation of the zero-dispersion wavelength and preserving the phase matching condition. In order to guarantee this phase matching, $\Delta\beta L$ must be kept small. Essentially, $\Delta\beta$ for the new FWM products has an identical $\Delta\omega$ but β_2 changes. The very short segment of fiber would allow a moderate phase mismatch and therefore a highly efficient generation and large bandwidth of FWM products. Simulations based on the Split-Step-Fourier Method demonstrated how the multiple FWM efficiency can be improved by using very short optical fibers with low dispersion slope. Furthermore, the SSFM code was used to verify and optimize the experimental results presented in this work.

We have demonstrated that the generation of FWM products starts in the second cascaded EDFA. Moreover, by investigating different fibers and CDPFs, we have demonstrated that the efficiency of generation of cascaded FWM products depends strongly on the following parameters: zero-dispersion wavelength, dispersion slope and nonlinear coefficient. Depending on the desired application, these parameters must be properly chosen in order to obtain the required bandwidth, uniformity and separation between the FWM products. Comb-like dispersion profiled fibers can in addition be used to optimize the efficiency of the generation of FWM products

Highly nonlinear fibers with λ_0 near the pump wavelength, high nonlinear coefficient and low dispersion slope have been shown to be very efficient for the generation of cascaded FWM products. In the best case, we have reported broadband generation of cascaded FWM products spanning over 300 nm. To the best of our knowledge this is the largest bandwidth obtained up to now. Furthermore, it has been proved that an equalized bandwidth of 110 nm covering C and L bands, with a small variation of only 1.2 dB between the powers of FWM products, can also be achieved by using HNLFs.

The use of ultra-flattened dispersion photonic crystal fibers enabled us to improve the efficiency of the generation of cascaded FWM products and to reduce the separation of the pump waves. By using these fibers, we have reported efficient generation of cascaded FWM products covering the entire C band and most of the L band, in which the average power of FWM products was just 5.0 dB below that of the pump waves. Additionally, we have demonstrated a case in which the difference of power between one of the pump wave and a FWM product was only 1.0 dB.

The efficient generation of broadband cascaded FWM products could be extremely useful for many applications, such as multiwavelength generation, multiple-channel optical communications, ultra-short pulse generation, generation of frequency combs and optical metrology. One remarkable advantage is that it uses low cost diode lasers.

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