Optical Frequency Comb based on Multiple Four-Wave Mixing and Erbium-Doped Fiber

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***Abstract*—This paper presents a scheme to enhance the nonlinear phenomenon of Multiple Four-Wave Mixing (MFWM) by making use of Erbium-doped fiber combined with highly nonlinear fibers. Experimental results were obtained and prove the efficiency of the proposed approach.**

***Index Terms*—Four-wave mixing, Optical Comb Generator, erbium-doped fiber, high-speed communications.**

I. INTRODUCTION

Four-Wave Mixing is a third order parametric nonlinear process based on the interaction among two or more waves creating new photons at different wavelengths [1]. Particularly, FWM processes may occur involving the waves generated previously, creating photons at further new frequencies. This phenomenon is referred to as multiple four-wave mixing (MFWM) [2] and can be efficiently applied for the development of Optical Frequency Comb (OFC) Generators, which can enable the transmission of multiple orthogonally separated subcarriers, increasing this way the system spectral efficiency.

OFCs have an important role in optical communications. It produces a spectrum of frequency modes, which are discrete and uniformly spaced from each other. This comb enables measurements over a large range of terahertz (tHz), and its applications covers arbitrary waveform generation [3], low noise microwave sources [4], high resolution and broadband spectroscopy [5], astronomic spectrograph calibration [6], etc.

There are many different ways to produce an OFC. Lately, the most common technique rely on the use of mode-locked lasers (MLL) [7] that has led to combs with low noise and wideband of spectral lines. Some problems regarding this technique can be numbered. Firstly, it requires great complexity of design and operation when working at high repetition rates. Then, as the MLL is based on a cavity configuration, it is not possible to reconfigure and stabilize the MLL cavity at the same time, so the comb pitch cannot be effectively changed [8]. Another approach to produce combs with flat optical spectra and good OSNR is based on the use of electro-optic modulators with resonant cavities [9, 10]. However, most combs seen in literature do not provide wideband spectral lines. Also we can find combs produced with index doped silica waveguide [11]; using techniques based on pulsed picosecond source [12, 13]; and using a monolithic ultra-high-Q microresonator [14] which provides combs with great efficiency, but the requirement for a resonator does not allow a free running tuning because of its physical size which fixes the line spacing.

MFWM based on highly nonlinear fiber has been an alternatively way to produce OFCs which has been investigated extensively lately [2] [15]. In order to meet this target, highly nonlinear and dispersion-flattened fibers have been used to enhance the nonlinear efficiency [2]. This work proposes to simultaneously generate and amplify an optical frequency by using highly nonlinear and Erbium-doped fibers. It is organized as follows. The second session describes the theoretical treatment of the four-wave mixing. Third session shows the proposed scheme and the experimental setup. The experimental results and analysis are reported in fourth session. Fifth session presents discussion and conclusions.

II. THEORETICAL ANALYSIS OF FOUR-WAVE MIXING

There are three main processes that play an important role in optical fibers: attenuation, dispersion and nonlinear processes. The attenuation is known to be very small, 0.2 dB/km in the telecommunications window of 1550 nm for monomode fibers. Consequently, it can be easily managed using optical amplifiers after many kilometers of signal propagation. The second parameter which influences and causes signal degradation is the dispersion. There are some different types of dispersion: as chromatic dispersion, which is caused by speed difference in the colors or frequencies present in the pulse; polarization mode dispersion, which results from the velocity difference in the two orthogonal modes present in the fiber due to random imperfections and asymmetries in the fiber fabrication; and modal dispersion, most common in multimode fibers where the different propagation modes have different speed in the optical waveguide. All three types of dispersion cause spreading of the transmitted signal, and can lead to system degradation due to intersymbol interference. Even being a very severe phenomena, there are many techniques to counteract this, such the use of Dispersion Compensating Fibers (DCF) or Fiber Bragg Gratings (FBG).

Nonlinear processes in optical fibers, such as self-phase modulation, cross-phase modulation and four-wave mixing do occur directly depending mainly of three parameters: power injected, length of the link and nonlinear coefficient of the fiber employed. For WDM system these processes are undesired and causes degradation in the carriers transmitted. Unlike the linear processes as attenuation and dispersion, nonlinear effects are difficult to manage and there are no trivial techniques to combat these effects in a real-time propagation in optical fibers.

Within nonlinear processes, we have the third order parametric process which involve the interaction among four optical waves and are responsible for the creation of some phenomena as third-harmonic generation, FWM and parametric amplification [1]. FWM in optical fibers is a nonlinear interaction between four different waves, under the conservation conditions of wave-vector and energy [16]. This requirement is referred as phase matching and it is strongly dependent on fiber chromatic dispersion and nonlinearities.

There are two different types of interaction in the FWM process. The first one is the case in which three photons transfer energy to a single photon at frequency $\omega_4 = \omega_1 + \omega_2 - \omega_3$. The second case occurs when two photons at frequencies ω_1 and ω_2 are annihilated and two other photons are created simultaneously with the relation $\omega_3 + \omega_4 = \omega_1 + \omega_2$ [1]. These new frequencies generated can be used to create further new frequencies, while the photons created at frequencies that belong to the incident field provide parametric gain.

To satisfy the phase matching condition the phase mismatching $\Delta\beta$ must be equals to zero [1].

$$\Delta\beta = \beta(f_i) + \beta(f_j) - \beta(f_k) - \beta(f_F)$$

Where, $\Delta\beta$ is the phase mismatching, and β the propagation constant. For the partially degenerated case, where $\omega_1 = \omega_2$, it is relatively easy to satisfy $\Delta\beta = 0$.

According to [16], $\Delta\beta$ can be expanded around the zero dispersion wavelength, and for the partially degenerated case, the expression turns to be the following:

$$\Delta\beta = -\frac{\lambda^4\pi}{c^2}.\ \frac{dD_c}{d\lambda}.\ 2.\ (f_i - f_k)^2(f_i - f_0)$$

where λ is the wavelength, c is light velocity in vacuum and D_c is the fiber chromatic dispersion. The efficiency of the FWM process depends strongly on the phase mismatching, which is written as [16]

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

Where α is the fiber loss coefficient and L is the fiber length. By means of plotting the graph of efficiency as a function of the relative pump frequency between f_i and f_0,, Fig. 1, we can observe that the efficiency is maximum when f_i coincides with the zero dispersion wavelength, i.e., $f_i = f_0$ [16].

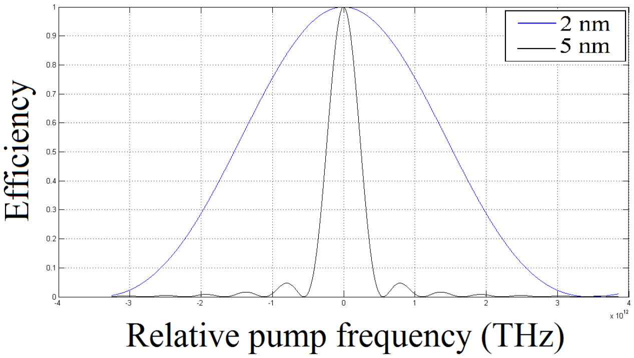

Fig. 1. Efficiency of FWM for the partially degenerate case plotted as a function of the relative frequency between f_i and f_0.

The used parameters are λ = 1560 nm, $dD_c/d\lambda$ = 0.07 ps/km.nm.nm, L = 1000 m and α = 0.674 dB/km. In the figure above, the black curve is for a wavelength detuning between pump and probe light (f_i and f_k) of 5 nm, and the blue one for a wavelength difference of 2 nm.

We can also observe that for an increasing detuning between the pump and the zero dispersion wavelengths, the curve rapidly decreases. This phenomenon happens because the phase matching condition is not satisfied anymore and the efficiency becomes smaller until it reaches almost zero. Also the phase matched frequency bandwidth turns narrower when the wavelength difference between pump and probe lights become larger.

Undesirable variation on the zero dispersion wavelength can reduce the efficiency of FWM due to inherent fabrication process of the fiber. For this cause, very short nonlinear fibers used in our experiments can improve FWM efficiency since the phase matching condition is determined at each local segment.

When phase-matching condition is satisfied another important concept is applied. Under the conservation of energy and momentum there is phase coherence among the comb spectral lines. This also can be assured when operating in the normal regime dispersion of the HNLF, which was demonstrated in [17] Also, the short length of the HNLF can avoid linewidth broadening and stimulated Brillouin scattering [18].

III. NEW APPROACH

The traditional and new approaches are shown in Fig. 2. Fig. 2 (a) is the traditional approach, based in a comb generator already created by another technique, two cascaded optical amplifiers and a highly nonlinear fiber (HNLF). On the other hand, Fig. 2 (b) presents the technique with the erbium-doped fiber (EDF), in which the output of the EDF is launched into the HNLF. By using this scheme is expected to increase the number of products and their optical signal-to-noise ratio (OSNR).

The HNLF has the following parameters: reference wavelength at 1560 nm, attenuation of 0.674 dB/km, 9um^2 effective area and nonlinear coefficient 10 W^{-1}km^{-1}. The power after the second erbium-doped fiber amplifier (EDFA) is 33 dBm and the HNLF length is 90 meters. In the second approach, the parameters are the same before the EDF. The EDF has 23 meters with a 1480 nm pump. The HNLF has the same length as the previous experiment. An optical isolator after the second EDFA was included to avoid pump-back reflection of the pump applied to the EDF. A 3 dB coupler is used to combine the 20 lines coming from the original frequency comb and the co-propagating pump of the EDF at 1480 nm. Then the signal is propagated through the EDF followed by the HNLF. The final spectrum is analyzed using an Optical Spectrum Analyzer (OSA) with 0.1 nm resolution.

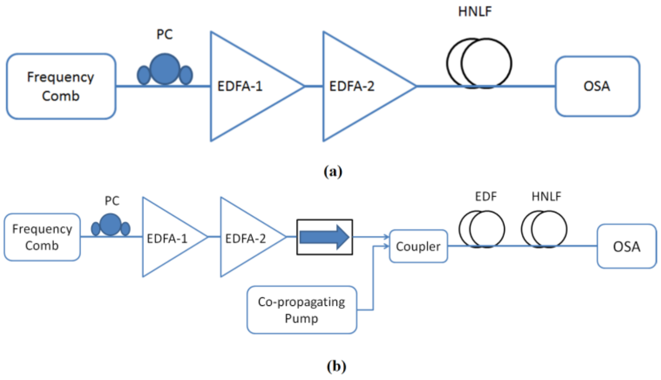

Fig. 2. Block diagrams of the experiments: (a) Traditional approach; (b) Use of erbium-doped fiber.

The original comb is shown in Fig. 3. The method used to produce this comb is Recirculating Shifting Frequency (RFS) [19], which is based by the modulation single side band suppressed carrier (SSB-SC). The advantage of this method is the great number of produced lines, but in other hand, requires a great complexity. Our purpose is to expand the original comb to obtain wideband spectral lines in order to transmit real data in the carriers of the expanded comb. The total optical input power has been kept around 1 dBm for both cases. In the original comb we already have 20 subcarriers and they go from 1550.22 nm to 1552.13 nm, with 12.5 GHz of spacing.

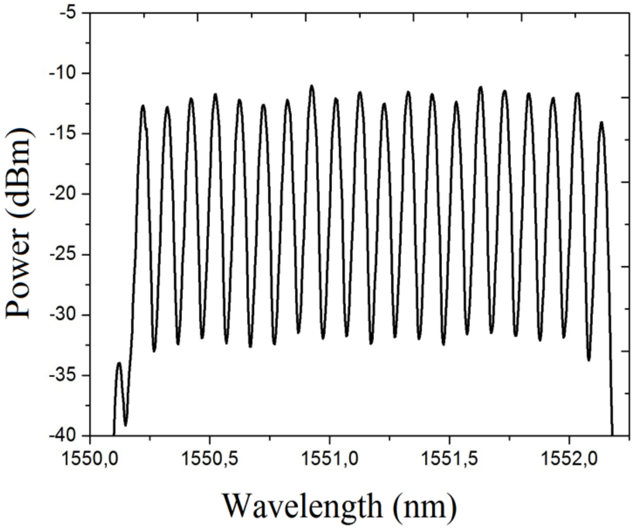

Fig. 3. Original comb.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

In order to analyze the behavior of the FWM products a characterization of the setup and some previous analysis were performed. For this reason, to obtain a reliable set of measurements, meticulous investigations of the parameters such as length of both fibers, power of the co-propagation pump and of the EDFAs and position of the polarization controller were realized. Therefore, some parameters were varied. When a parameter is varied, the other ones are kept fixed. The first analyzed parameter was the HNLF length, without the erbium-doped fiber. Fig. 4 displays the experimental obtained curves for 60, 70 and 90 m.

One can note that for the left products, the 60 meters fiber has presented a slightly better performance if compared to 90 m fiber. On the other hand, for the right side the best performance has been obtained for 90 m fiber length. However, considering that there is a deviation of the peak power and the OSNR of the generated components, we can conclude that the results are closely enough. Because of a little small difference we have chosen the 90 meters fiber for the next experiment with EDF.

Another parameter investigated was the EDF length. The pump signal of the EDF is 1480 nm and the EDF length is 23 meters. This length was chosen after analyzing the graph shown in Fig. 5.

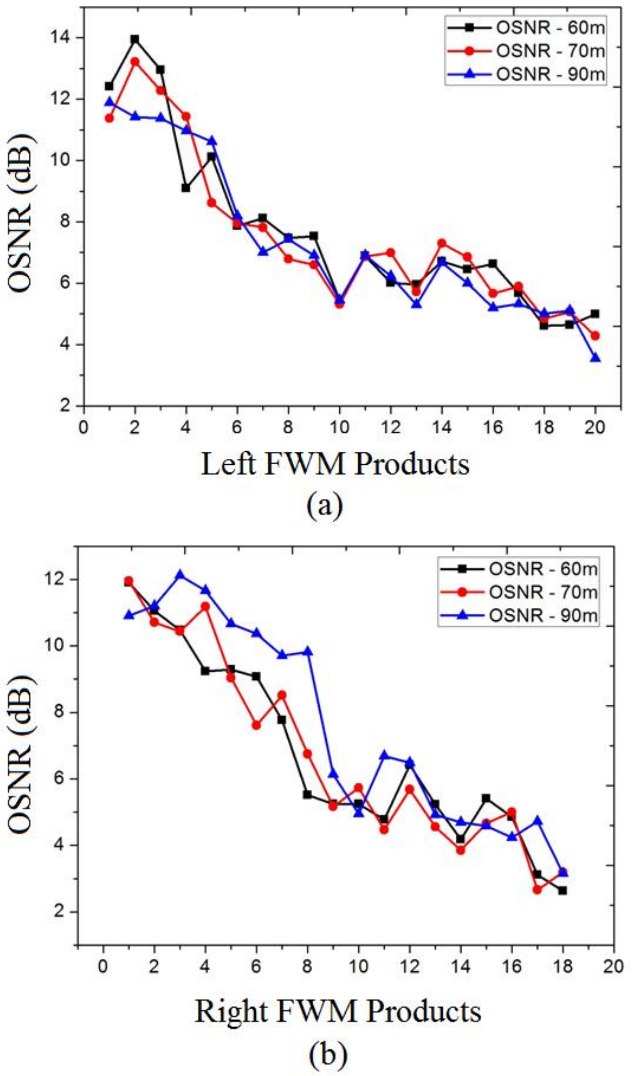

Fig. 4. Measured OSNR of the new created FWM products: (a) left side products of the comb; (b) right side products of the comb.

The black curve with the square points is the EDF characterization for a laser (L1) at 1550 nm. The red curve with circle points represents the gain variation of a second laser (L2) at 1560 nm. The choice of these two wavelengths was due to the zero dispersion wavelength of the HNLF that is at 1560 nm, whereas comb central wavelength is at 1551 nm. We can see that for 1550 nm the gain is higher for shorter EDF lengths. The opposite happens at 1560 nm: better gain profile is achieved with EDF longer. After careful analyzing, it has been chosen an EDF length of 23 meters, which was the length that best suit both wavelengths analyzed.

The outputs of both schemes are reported in Fig. 6: Fig. 6 (a) and (b) represents the output of the approach and new approach (with the EDF), respectively. The images demonstrate the new approach allows increasing the number of generated FWM products and their OSNR is higher.

The pump of the EDF has been varied in order to optimize the FWM efficiency. The values used in the experiments were: 27 dBm, 28 dBm, 30 dBm, 31 dBm, 32 dBm and 33 dBm. The best result was obtained for 33 dBm and Fig. 6 (b) corresponds to this value.

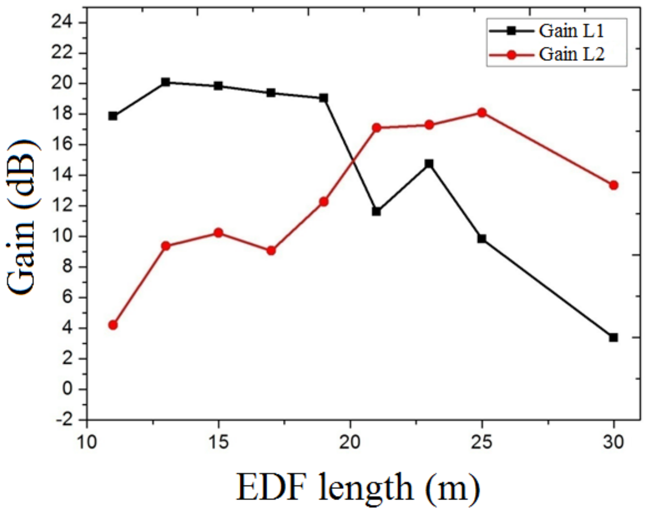

Fig. 5. Characterization of the EDF. Graph that shows the behavior of the gain as a function of the length.

The products generated were only taken into account if its OSNR was above 10 dB. So, in the traditional approach, we have 9 new products created by MFWM with good optical signal-to-noise ratio. For the technique using erbium-doped fiber instead, we have 30 new products with the same OSNR, totalizing 50 sub-carries for the comb.

Experimental results of OSNR higher than 10 dB demonstrate that as we increase the EDF pump power, the number of new products generated is raised. For 27 dBm EDF pump power, the number of new FWM products is 28 and the average OSNR in this case is 15.8 dB. Moreover, for 33 dBm of EDF pump power, we have 30 new FWM products and the average OSNR is around 16.4 dB, showing a slightly better performance in the last case.

V. CONCLUSIONS

A new all-fiber scheme to enhance MFWM efficiency was proposed, analyzed and reported. It consists of injecting an initial frequency comb into short pieces of highly nonlinear and Erbium-doped fibers. The most important fiber parameters were investigated to optimize the nonlinear effect: length of the highly nonlinear fiber, length of the erbium-doped fiber and pump power of the EDF. We have experimentally obtained an optical frequency comb generated by four-wave mixing with 30 new products with 16.4 dB of average OSNR. The bandwidth achieved was three times the bandwidth of the original comb. This result can be considered an important move to reach ultra-fast data transmission in the way of optical communications.

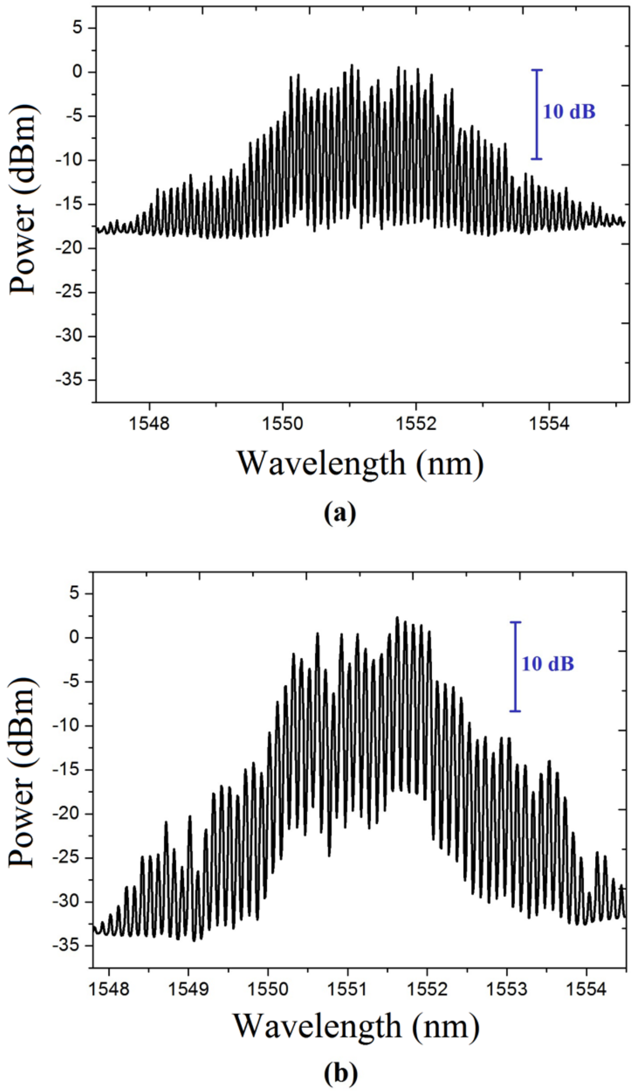

Fig. 6. (a) Output spectra for the traditional approach (b) output spectra for the setup with the erbium-doped fiber.

VI. ACKNOWLEDGEMENTS

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