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

Suzanne A. S. Melo
Instituto Nacional de Telecomunicações - Inatel
CEP: 37540-000
Santa Rita do Sapucaí - MG - Brazil
suzanne@gee.inatel.br

Arismar Cerqueira S. Jr.
Instituto Nacional de Telecomunicações - Inatel
CEP: 37540-000
Santa Rita do Sapucaí - MG - Brazil
arismar@inatel.br

A. R. do Nascimento Jr.
Universidade Estadual de Campinas - Unicamp
CEP: 13484-332
Limeira - SP - Brazil
adrianocpu@gmail.com

L. H. H. Carvalho
Centro de Pesquisa e Desenvolvimento em Telecomunicações - CPqD
CEP: 13086-902
Campinas - SP - Brazil
lhecker@cpqd.com.br

R. Silva
Centro de Pesquisa e Desenvolvimento em Telecomunicações - CPqD
CEP: 13086-902
Campinas - SP - Brazil
rdsilva@cpqd.com.br

J. C. R. F. Oliveira
Centro de Pesquisa e Desenvolvimento em Telecomunicações - CPqD
CEP: 13086-902
Campinas - SP - Brazil
julioc@cpqd.com.br

***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.

MFWM based on highly nonlinear fiber has been investigated extensively lately [2] [7] as a means to produce OFC. 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

FWM in optical fibers is a nonlinear interaction between four different waves, under the conservation conditions of wave-vector and energy [8]. 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 two photons at frequencies ω_1 and ω_2 are annihilated and two new photons are created at frequencies ω_3 and ω_4 with the relation: $\omega_4 = \omega_1 + \omega_2 - \omega_3$. To satisfy the phase matching condition the phase mismatching $\Delta\beta$ must be equals to zero [1].

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

Δβ 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 [8], Δβ 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 [8]

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

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., $f_i = f_0$ [8].

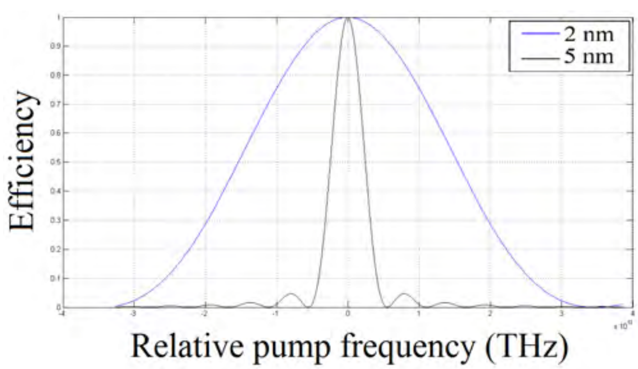

Fig. 1. Efficiency of FWM for the partially degenerate case plotted as a function of the relative frequency between f_i and f_0.

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.

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.

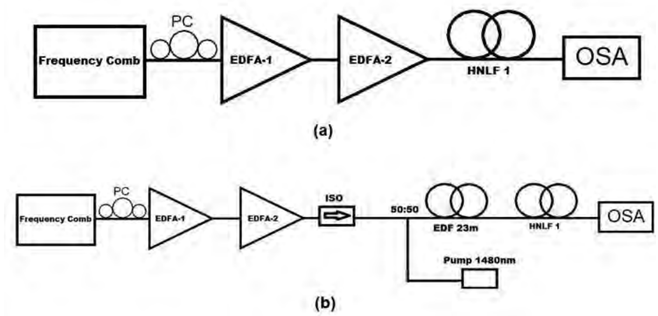

Fig. 2. Block diagrams of the experiments: (a) Traditional approach; (b) Use of erbium-doped fiber.

The original comb is shown in Fig. 3. The 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.

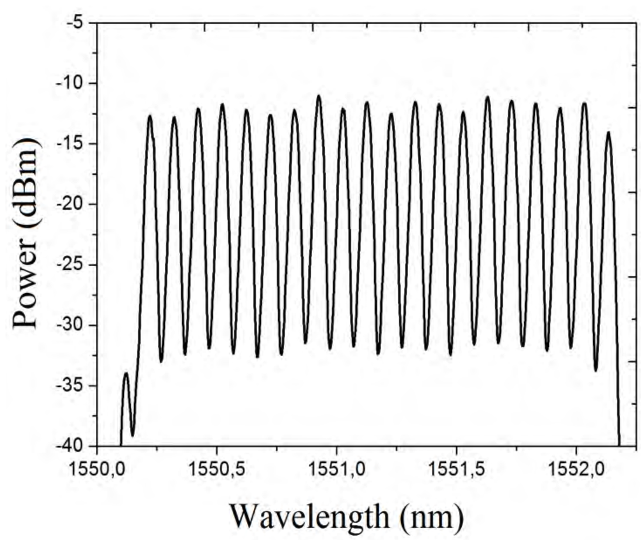

Fig. 3. Original comb.

IV. Experimental Results and Analysis

In order to analyze the behavior of the FWM products 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.

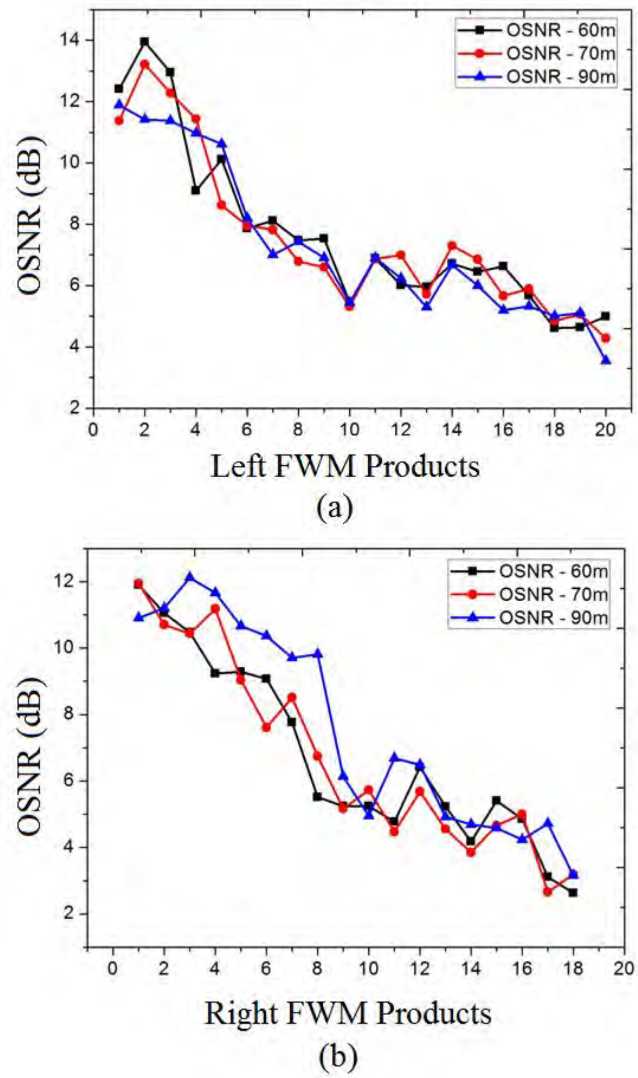

Fig. 4. Measured OSNR of the new created FWM products: (a) left side products of the comb; (b) right side products of the comb.

The black curve with the square points is the EDF characterization at 1550 nm. The red curve with circle points represents the gain variation 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.

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.

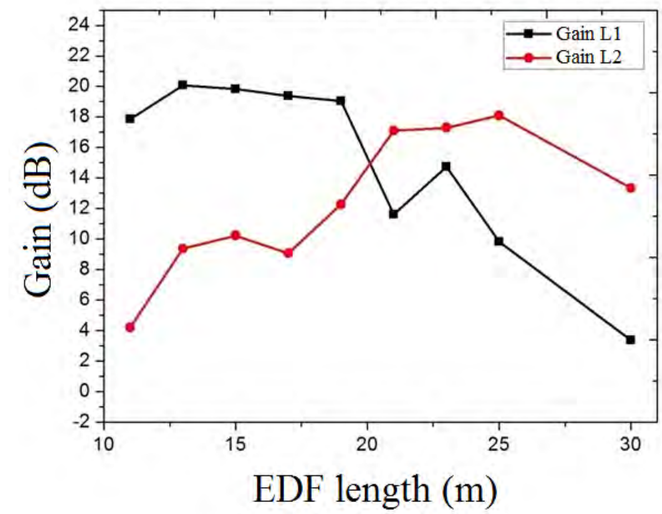

Fig. 5. Characterization of the EDF. Graph that shows the behavior of the gain as a function of the length.

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.

VI. ACKNOWLEDGEMENTS

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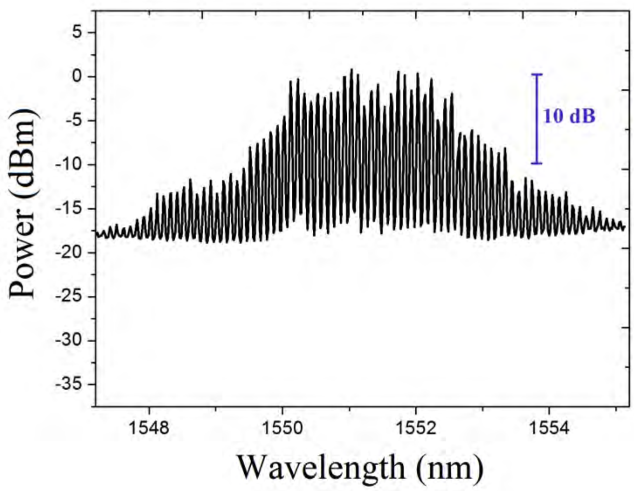
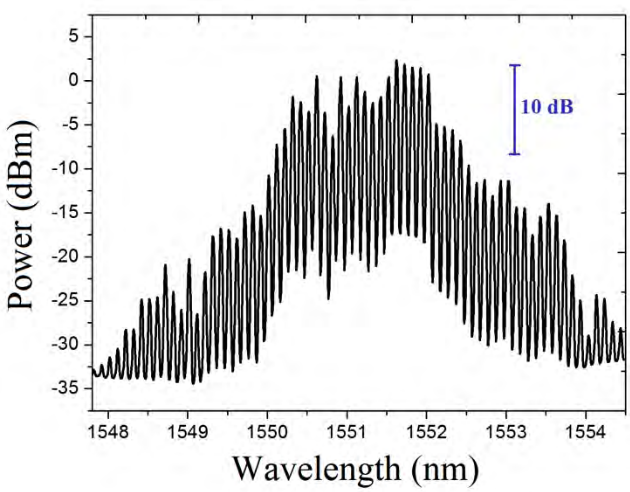


(a)



(b)

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

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