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Impairments in Gain-Equalized Distributed Fiber Raman Amplifiers due to Four-Wave Mixing and Parametric Amplification Processes

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Abstract. In this work, by means of numerical simulations, we verify that four-wave mixing (FWM) processes, including depletion and parametric gain, generate a redistribution of pump power in distributed fiber Raman amplifiers (DFRAs). As a consequence of pump-pump FWM, FWM products are generated, as well as a power exchange between pumps, which produces degradation in the performance of the amplifier due to new SRS-FWM interactions. Numerical results show impairments in distributed amplified systems due to these interactions, such as loss of flatness on the spectral gain, reduction on the net Raman gain, and presence of strong FWM products within the transmission band.

Keywords: Distributed fiber Raman amplifiers, four-wave mixing, parametric amplification.

PACS: 42.25.Bs, 42.50.Gy, 42.65.-k, 42.65.Dr, 42.79.Sz.

INTRODUCTION

Distributed fiber Raman amplifiers (DFRAs) have resulted to be one of the most efficient all-optical amplification method due to its ultrawide bandwidth, flexible wavelength operation, low noise and capacity to mitigate fiber nonlinearities. Many works have proposed different techniques to design a DFRA for providing a flat gain in the WDM band [1]-[3]. The objective of all these methods to get this target is to find the optimum spectral position and the optimum input power of each pump in the amplifier. Some of these methods can also be applied to design cascades of DFRAs, in such a way that each amplifier of the cascade provides a flat output power spectrum for all the involved channels. Basically, the optimization problem can be divided into two parts which are carried out sequentially by solving a mathematical model [1], which describes the gain and depletion power due to stimulated Raman scattering (SRS). The first part allows one to find the wavelength of each pump wave, and the second one, to determine the input power of each pump wave. However, the main drawback is that the mathematical model used does not consider the interaction of FWM and SRS. Therefore, if the designed amplifier is then performed with pumps located in a low chromatic dispersion spectral region, pump-pump four-wave mixing (FWM) and parametric amplification of the pumps can be produced. As a consequence, a spectral and longitudinal (along the fiber) redistribution of pump power could occur, producing a gain completely different to the one intended.

In this work we analyze, by using numerical simulations, how the propagation of pumps of a DFRA along the fiber is affected by FWM and parametric amplification processes. The critical situations occur when the pumps are located near the zero dispersion wavelength (λ_{2D}). Analyzing those situations, we also study how the redistribution and exchange of pump power produced by FWM and parametric amplification affects the spectrum of gain for different flat-gain DFRAs.

MATHEMATICAL MODEL

The numerical model used to characterize the interaction of SRS and FWM processes can be derived from the mathematical expressions shown in [1]-[5]. Thus, the propagation equation for the complex envelope of the electric field (A_F) at frequency f_F results to be:

$$\begin{aligned}
\frac{dA_F(z)}{dz} = & -\frac{\alpha_F}{2}A_F(z) + \sum_{f_m > f_F} \frac{g_R(f_F, f_m)}{2A_{eff}K_{eff}(f_F, f_m)} |A_m(z)|^2 A_F(z) - \sum_{f_m < f_F} \frac{f_F}{f_m} \frac{g_R(f_F, f_m)}{2A_{eff}K_{eff}(f_F, f_m)} |A_m(z)|^2 A_F(z) \\
& + j\frac{1}{3}\gamma \sum_{i,j \neq k} \left\{ K_{fwm}(f_i, f_j, f_k) D_{ijk} \times A_i(z) A_j(z) A_k^*(z) \exp(-\Delta\beta_{ijk}z) \right\} \\
& + j\frac{1}{3}\gamma \sum_{p,r \neq q} \left\{ K_{fwm}(f_F, f_q, f_r) D_{pqr} A_p(z) A_q^*(z) A_r(z) \exp(\Delta\beta_{pqr}z) \right\}
\end{aligned} \tag{1}$$

Where $f_F = f_i + f_j - f_k$ represents the condition for new FWM products and parametric gain processes; $f_p = f_f + f_q - f_r$ corresponds to the condition for depletion of the electric field A_F due to FWM; g_R is the Raman gain coefficient, γ is the nonlinear coefficient, $D_{ijk(pqr)}$ is the degeneracy factor, $\Delta\beta_{ijk(pqr)}$ is the linear phase-mismatch, K_{eff} and K_{fwm} are the polarization factors for SRS and FWM, respectively. K_{eff} is 0.5 or 1, depending if the waves at frequency f_F and f_m have identical or random polarization states, respectively [1]. K_{fwm} is 1 when the waves involved on FWM process have parallel linear polarizations, and $(1/2)^{0.5}$ or $(3/8)^{0.5}$ for partially degenerate and nondegenerate FWM with random polarization states, respectively [6].

It is important to emphasize the differences of this model with respect to others previously proposed [7]-[8]. The main advantage is that equation (1) provides a simultaneous description of Raman gain/depletion, parametric gain, depletion due to FWM and generation of new FWM waves. This complete and simultaneous description of both nonlinearities, allows for solving the model by a simple numerical method. Therefore, it is not required to use any iterative method to get convergence in the solution (iterative methods are required when SRS and FWM models are solved separately) [7], while ultimately reducing computing time. It is also a good alternative instead of using closed mathematical expressions based on undepleted conditions for the waves, which can be inappropriate approximations when a strong interaction among SRS and FWM exists.

FWM EFFICIENCY

In order to understand the redistribution of pump power produced by pump-pump FWM processes in DFRAs, we need to analyze the efficiency of each FWM product generated in the amplifier. Equation (2) describes the well-known FWM efficiency [5]:

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

Where α is the attenuation coefficient; L is the fiber length; and $\Delta\beta$ is the linear phase-mismatch factor. Undertaking the frequencies involved in the FWM process (f_i , f_j and f_k), the chromatic dispersion (D_c) and dispersion slope (S_o) of the fiber at a given reference frequency ($f_o = c/\lambda_o$), $\Delta\beta$ can be obtained as follows:

$$\Delta\beta = \frac{2\pi\lambda_o^2}{c} \left\{ (f_i - f_k)(f_j - f_k) \right\} D_c(f_o) - \frac{\pi\lambda_o^4}{c^2} \left\{ (f_i - f_k)(f_j - f_k) \right\} \left\{ f_i + f_j - 2f_o \right\} S_c(f_o) \tag{3}$$

Where c is the light velocity. However, in the case of a spectral region with low chromatic dispersion, equation (3) can be reduced as follows:

$$\Delta\beta = -\frac{\pi\lambda_o^4}{c^2} \left\{ (f_i - f_k)(f_j - f_k) \right\} \left\{ f_i + f_j - 2f_o \right\} S_c(f_o) \tag{4}$$

Where the reference frequency corresponds to the frequency with zero chromatic dispersion ($f_o = c/\lambda_{zD}$). By using the definition of equivalent frequency separation presented in [5], we have:

$$\Delta f_{ijk} = \sqrt{|f_i - f_k| |f_j - f_k|} \tag{5}$$

We can also define the spectral separation of f_0 with respect to the middle frequency between f_i and f_j :

$$\Delta f_{M0} = \frac{f_i + f_j}{2} - f_0 \quad (6)$$

Thus, by applying (5) and (6) into (4) we obtain:

$$\Delta\beta = -\frac{2\pi\lambda_0^4}{c^2} \Delta f_{ijk} \cdot \Delta f_{M0} \cdot S_c(f_0) \quad (7)$$

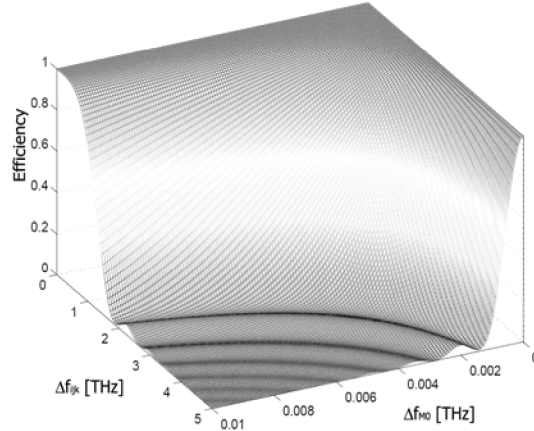


FIGURE 1. FWM efficiency as a function of Δf_{ijk} and Δf_{M0} .

Figure 1 shows the FWM efficiency as a function of Δf_{ijk} and Δf_{M0} . Considering that f_i, f_j and f_k are three Raman pumps of a DFRA, there are two ways to get a strong pump-pump FWM interaction ($\eta = 1$). The first way is when $\Delta f_{ijk} = 0$, however this case needs to satisfy the condition $f_i = f_k$ or $f_j = f_k$, which correspond to SPM and XPM cases. The second way occurs when the condition $\Delta f_{M0} = 0$ is satisfied. In the case of degenerated FWM, it occurs when the degenerated pump coincides with the λ_{ZD} ($f_i = f_j = c/\lambda_{ZD}$). In the case of non-degenerated FWM, that condition occurs when c/λ_{ZD} coincides with the frequency placed in the middle of f_i and f_j ($c/\lambda_{ZD} = (f_i + f_j)/2$).

Taking into account that the intensity of the FWM products depends of the multiplication of the involved pump powers and the efficiency of the process, strong pump-pump FWM products can be obtained even if the FWM efficiency is not equal to 1, because of the high pump power available.

From both conditions presented above, note that the condition $\Delta f_{ijk} \approx 0$ is difficult to satisfy because usually the Raman pumps are spectrally distributed in a broad band. However, $\Delta f_{M0} \approx 0$ easily could occur depending on the number of Raman pumps and the λ_{ZD} (note that it is independent of the spectral spacing of the pumps). Analyzing these two conditions within the pump band of a DFRA, we can deduce that different spectral regions exist in this band, where if λ_{ZD} takes place, at least one high efficient pump-pump FWM product will be generated.

On other hand, analyzing equation (2) we can see that the efficiency has an oscillatory behavior along the fiber because of the factor $\sin^2(\Delta\beta L/2)$ [9]. Thus, if $\Delta\beta \neq 0$ the new FWM product will grow up from noise at the fiber input ($z=0$) until a given distance $z = L_{coh}$, defined as coherence length. In between $z = L_{coh}$ and $z = 2L_{coh}$ the FWM product gives back its energy to the pump of the FWM process. Then, the coherence length is defined as:

$$L_{coh} = \frac{\pi}{\Delta\beta} \quad (8)$$

This parameter is very important for understanding how pump-pump FWM in a DFRA produces an oscillatory redistribution and exchange of pump power between Raman pump and new FWM products [9]. It also allows for explaining the longitudinal oscillation produced on the intensity of Raman pumps due to parametric amplification and FWM (generation/depletion) process.

PUMP-PUMP FOUR-WAVE MIXING IN GAIN-EQUALIZED DFRAS

To evaluate the influence of parametric gain and FWM (generation and depletion) on the propagation of the pumps along a DFRA, 3 different copropagating amplified systems are designed with flat-gain. An optimization method based on genetic algorithm [3] is used to find out the wavelength and power of each forward Raman pump, in order to obtain the flattest net gain in each system. The mathematical model used in the design is the same used in [3], describing just SRS and spontaneous Raman scattering, while neglecting FWM.

The first transmission system is composed by 50 km of TrueWave Single-Mode fiber (TWSMF) and 20 depolarized WDM channels in the band within 1540-1560 nm, and with 0.5 mW/ch input power. By using the optimization method, a ripple of 0.21 dB was obtained with the three Raman pumps shown in Table 1. However, it is expected that strong pump-pump FWM interactions will occur due to the low chromatic dispersion of the used fiber.

TABLE 1. Optimized pumps for 20 nm bandwidth DFRA.

λ [nm]	1420.28	1438.14	1463.52
Power [mW]	160.93	92.24	99.61

From equations (2), (6) and (7), it is possible to see that highly efficient FWM products can be produced when the λ_{ZD} coincides with a pump wavelength (degenerated FWM processes). For example, if the $\lambda_{ZD} = 1463.52$ nm the two FWM products with the longest wavelength will have an efficiency $\eta = 1$. Figure 2 shows a comparison in the propagation of the three Raman pumps when FWM and parametric amplification are undertaken and when they are not considered. It is possible to see the parametric amplification of the pumps at 1420.28 nm and 1438.14 nm along the first kilometers of fiber, as well as the strong depletion of the pump at 1463.52 nm. However, at distances longer than the coherent length, Raman scattering becomes more relevant than FWM. Thus, due to the spectral position and high efficiency of these FWM products, they are strongly amplified by SRS. Therefore, an additional depletion of the pumps with shorter wavelength is produced, mainly due to the Raman amplification of these two FWM products (at 1489.81 nm and 1509.48 nm). Figure 3a depicts the output power spectrum of the amplifier; note that the three Raman pumps have a lower output power than when FWM and parametric amplification are not considered. As a consequence, the depletion of the pumps affects the total net gain as shown Figure 3b. On average, the pump power exchange produces a reduction of ~ 3 dB in the net gain of the DFRA.

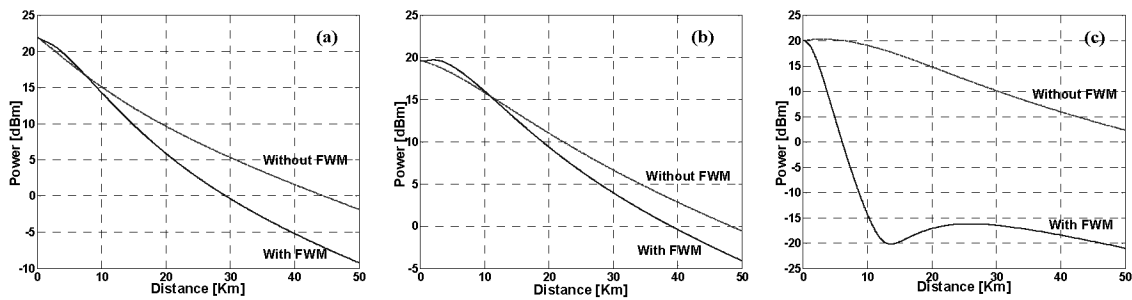


FIGURE 2. Longitudinal propagation of pump power on the first DFRA, when $\lambda_{ZD} = 1463.52$ nm. a) Pump at 1420.28 nm. b) Pump at 1438.14. c) Pump at 1463.52 nm.

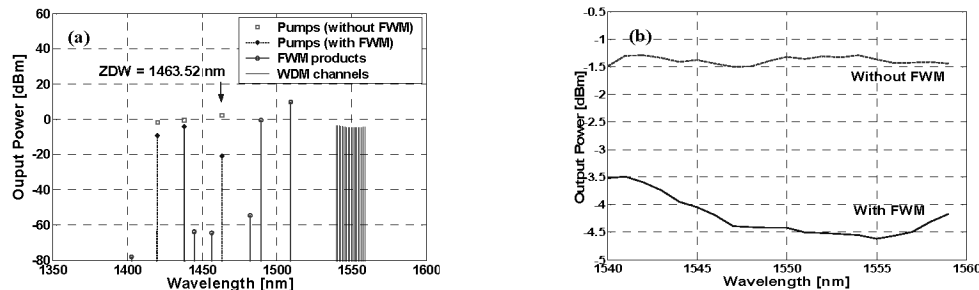


FIGURE 3. Output power of the first DFRA, when $\lambda_{ZD} = 1463.52$ nm. a) Output spectrum, including pumps, FWM products and channels. b) Output power for WDM channels (with and without including FWM and parametric amplification processes).

The second amplified system is composed of 40 channels within the band 1540-1580 nm over 50 km of TWSMF. By using the optimization method a ripple of 0.47 dB is obtained with the four pumps shown in Table 2.

λ [nm]	1420.12	1437.87	1453.41	1474.30
Power [mW]	333.86	120.01	79.04	30.00

Note that an interesting situation occurs when the λ_{ZD} is located in between two Raman pumps. For instance, if $\lambda_{ZD} = 1428.94$ nm two FWM products have unitary efficiency. In this case, the pumps located at 1420.12 nm and 1437.87 nm are depleted due FWM process, while the pumps at 1453.41 nm and 1474.30 nm are amplified by parametric gain along the first kilometers of fiber. Figure 4 shows oscillations of the Raman pumps due to the power exchange produced by parametric amplification and FWM product generation. As we can note, all this power distribution occurs spectrally and spatially along the fiber, affecting the transfer of energy from Raman pumps to the WDM channels. Thus, WDM channels with shorter wavelength are affected by lower Raman gain; however, channels with longer wavelength are strongly amplified by SRS. Figure 5a depicts the output power spectrum of the amplified system. Note that the four pumps show a lower output power than in the cases where FWM is not taken into account. This is because the depletion is caused by the FWM of the two pumps with the lowest wavelengths, and also by the additional depletion due to SRS of the pumps with longer wavelengths. Note that more pump power produces more Raman gain, and also more depletion of the pumps. Figure 5b depicts a comparison between the equalized output power spectrum and the obtained spectrum including parametric gain of the pumps and pump-pump FWM processes. It can be noted that ~ 7.0 dB of ripple is obtained when FWM is undertaken.

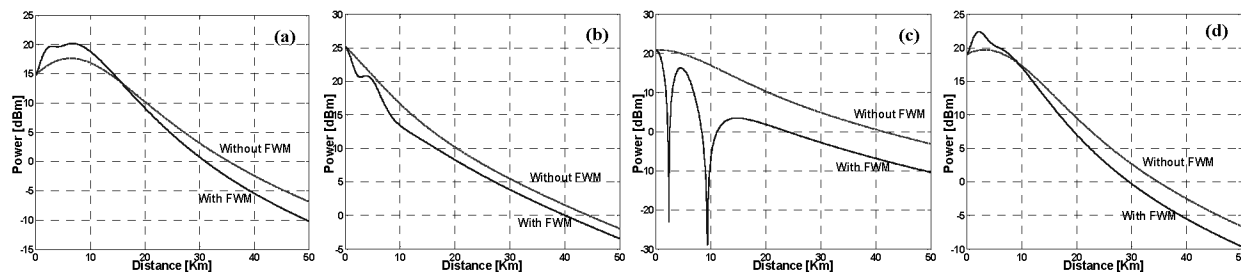


FIGURE 4. Longitudinal propagation of pump power in the second DFRA, when $\lambda_{ZD} = 1428.94$ nm. a) Pump at 1420.12 nm. b) Pump at 1437.87. c) Pump at 1453.41 nm. d) Pump at 1474.30.

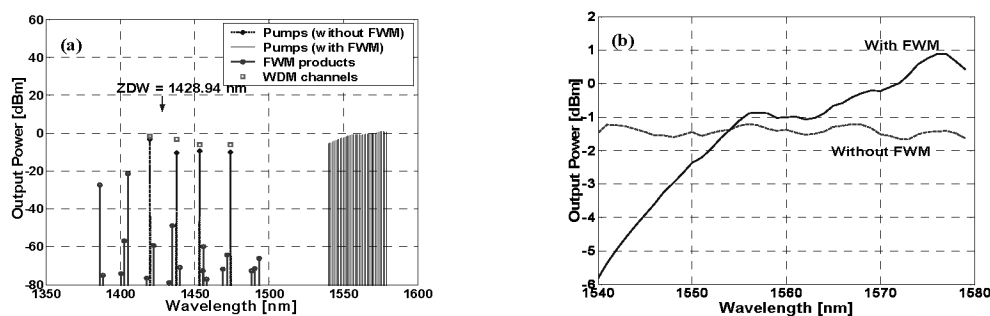


FIGURE 5. Output power of the second DFRA, when $\lambda_{ZD} = 1428.94$ nm. a) Output spectrum, including pumps, FWM products and channels. b) Output power for WDM channels (with and without including FWM and parametric amplification processes).

The third transmission system has a broader bandwidth, and it is composed of 40 WDM channels in the range 1520-1600 nm, and propagating over 50 km of TWSMF. By using the previously mentioned genetic algorithm, six copropagating pumps are obtained (Table 3), producing a ripple of 0.84 dB in the output power.

λ [nm]	1404.80	1420.10	1431.72	1444.41	1466.72	1490.05
Power [mW]	53.43	144.58	113.36	60.93	34.38	16.77

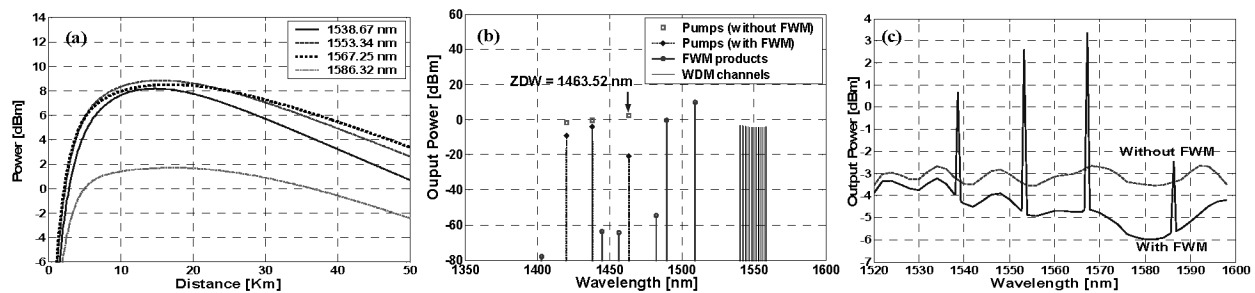


FIGURE 6. Third DFRA, case when $\lambda_{ZD} = 1490.05$ nm. a) Propagation of highly efficient FWM products along the fiber (FWM within WDM band). b) Output spectrum, including pumps, FWM products and channels. c) Output power for WDM channels (with and without including FWM and parametric amplification processes).

Because the pumps of the amplifier are spectrally spread in a band of ~ 85 nm, the FWM products are also generated in a wide bandwidth. When the λ_{ZD} is near the pumps with longer wavelength, strong Raman gain will be achieved by the most efficient FWM products. For instance, when $\lambda_{ZD} = 1490.05$ nm, strong FWM products are generated in longer wavelengths. Those FWM products grow from noise at $z = 0$ km achieving a maximum intensity at a distance equal to the coherence length. Then, they are amplified by SRS with a gain depending of the wavelength of each of them, as shown Figs. 6a-b. The main drawback is that the FWM products with the highest intensities are generated within the WDM band, as shown Figs. 6b-c. Note that real FWM products have a linewidth depending of the linewidth of the pumps; so many channels could be affected. Moreover, because the pump at 1490.05 nm exchanges power with the most efficient FWM products, it has a strong depletion due to these processes. Nevertheless, the pumps with shorter wavelength are affected just by a small depletion. As consequence, the net gain of the DFRA achieves a maximum penalty of 2.5 dB for the longest wavelength.

CONCLUSIONS

In this work, we have analyzed the interplay between SRS and FWM in DFRA. Numerical results show that FWM process in a DFRA produces new FWM-to-SRS interactions, generating new pumps in the amplifier. Because of the generation of new FWM products, depletion due to FWM and parametric gain, spectral and longitudinal exchange of pump power in different DFRA configurations are shown. The power exchange between pumps and new FWM products has an oscillatory behavior along the fiber, depending on the position of the λ_{ZD} , producing a performance degradation of a DFRA. Thus, it could cause loss of gain-equalization, net gain lower than the designed one (because of pump depletions produced by new SRS-FWM interactions) and the existence of interference due to strong FWM products within the transmission band. It is possible to conclude that FWM processes (including depletion and parametric amplification) must be taken into account when DFRA are designed, in order to ensure an expected performance.

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