Four Wave Mixing in Distributed Raman Amplified Optical Transmission Systems

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***Abstract*—We report a simple analytical approximation and experimental validation describing four wave mixing efficiency in distributed Raman transmission system with different pumping schemes. The experimental results match the theoretical predictions with error margin <0.7dB.**

***Keywords*— Nonlinear wave mixing; Distributed Raman amplifiecation; Optical trasnmission system.**

I. Introduction

The performance of optical communication systems is limited by the accumulated noise generated within the system; this noise can be categorized into two types: the linear amplified spontaneous emission (ASE) noise added by inline amplifiers, and nonlinear noise which is signal power dependent noise produced within the fiber spans in the system. Four wave mixing (FWM) is considered to be the dominant nonlinear effect (over self-phase modulation SPM and cross phase modulation XPM) in transmission systems that deploy densely spaced coherent-orthogonal frequency division multiplexing (CO-OFDM) [1] or Nyquist super channels. Several studies have been conducted to characterize the efficiency of FWM in lumped amplified optical links [2]; these studies have introduced a closed form analytical description of FWM efficiency as a function of fiber and optical signal properties. The closed form FWM equation for lumped amplified optical link has been the base of many studies that address performance limits in terms of signal to noise ratio estimations for multichannel CO-OFDM [1] and wavelength division multiplexing (WDM) systems [3]. Similar calculations may be performed for ideal lossless Raman amplification, which is known to offer the optimum trade-off between ASE noise and accumulated nonlinearity [4]. However, in practice approaching ideal lossless Raman amplified spans requires either higher order Raman amplification, including dual order [5], third order [6] or ultra-long Raman lasers [7] which may suffer from additional noise processes such as double Rayleigh scattering [8], and more complex signal power profiles are often encountered in order to minimize excess noise, maximize power symmetry, or simplify the pump configuration. In this paper, we present an analytical approximation, and experimental validation, of FWM efficiency based on piecewise power profile approximation in optical links deploying distributed Raman amplified (DRA) that are dominantly forward or backward pumped. The analytical predictions of the piecewise power profile approximation match the analytical predictions of integral form [9] and within 0.7dB margin of error compared to the experimental results.

II. Analytical Approximation

FWM efficiency and the phase matching condition is largely dependent on the power profile along the link because of the distance integral needed to solve the nonlinear Schrödinger equation (NLSE) [9]. The power profile of signals along first order distributed Raman amplifier (DRA) span have been described in compact closed form [10] which depends on the forward pumping ratio (r_f) of the total Raman pumping power, Raman gain factor, fiber attenuation constant, and the total pumping power. Fig. 1 shows the typical configuration of first order DRA system and the power profile along each span considering different pumping schemes ($r_f \rightarrow 0$ and $r_f \rightarrow 1$). As in Fig. 1, we can see that the power profile of DRA can be approximated as two sections with constant gain/loss coefficients: the first section has constant attenuation $-\delta_1$ and the second section constant gain δ_2 if the power profile is dominated by backwards pumping, or the first section has gain δ_1 and the second section attenuation $-\delta_2$ if forward pumping dominates.

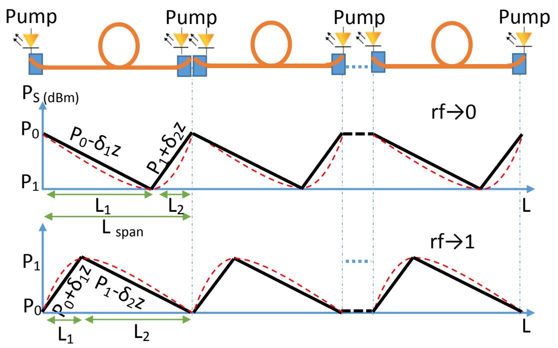


Fig. 1 Two section approximation for power profile: The upper part is the schematic of multi span DRA, the middle graph is power profile in the case of dominating backward pumped DRA ($r_f \rightarrow 0$), and the last graph is the case of dominating forward pumped DRA($r_f \rightarrow 1$).

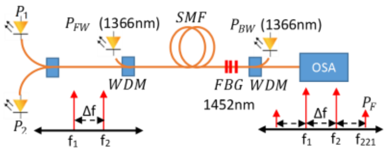
The previous two section piecewise approximation of signal power profile along DRA spans simplifies solving the distance integration of the NLSE through the system to result the FWM power efficiency ($\eta = P_{FWM}/[P_i P_j P_k]$) described in Eqn.1, where D is the degeneracy factor, γ is the nonlinear parameter of the fiber, N_s is the number of spans in the system, $\Delta\beta$ is phase mismatch between signals (i, j, k, and FWM product), L_s is span length, $\psi = exp(\mp\delta_1 L_1)$ is the loss/gain (respectively) at the point of transition between the two section in the DRA span, and the $\pm$ in the third term refers to the cases of $r_f \rightarrow 0$ and $r_f \rightarrow 1$ respectively. In essence, Eqn. 1 contains a term for each segment

$$\eta = \left(\frac{D\gamma}{3}\right)^2 \frac{\sin\left(N_s \Delta\beta L_s/2\right)^2}{\sin\left(\Delta\beta L_s/2\right)^2}\left[\frac{(1-\psi)^2 + 4\psi\sin\left(\Delta\beta L_1/2\right)^2}{\delta_1^{\,2}+\Delta\beta^2} + \frac{(1-\psi)^2 + 4\psi\sin\left(\Delta\beta L_2/2\right)^2}{\delta_2^{\,2}+\Delta\beta^2} - 2\mathbb{R}\left\{\frac{\left(\psi - e^{i\Delta\beta L_1}\right)\left(\psi - e^{i\Delta\beta L_2}\right)}{-\delta_1\delta_2 \pm i\left(|\delta_1|+|\delta_2|\right)\Delta\beta + \Delta\beta^2}\right\}\right] \qquad (1)$$

(δ_1 and δ_2) of the DRA span scaled with an effective length of the first segment $(1-\psi)/\delta_1$ instead of the effective length of the full span $(1-exp(-\alpha L_s))/\alpha$ as in lumped system [2], plus an additional term representing the coherent addition of the four wave mixing powers generated by each section.

III. Expiremental Setup and results

Fig. 2 shows the experimental setup for the measurements of FWM efficiency in Raman fiber laser (RFL) based DRA with fiber Bragg grating (FBG) and second order pump at 1366nm [11]. The power profile of this effective second order DRA shows a significantly smaller signal power variation along its length compared to the power variation along first order DRA span [11]. The table in Fig. 2 shows the pump powers used and input tuneable lasers powers used at the input (tuneable laser powers were adjusted from one profile to another to have matching FWM power at low frequency separation). A 62km G.652 single mode fiber was used in this experiment, two tuneable lasers (P_1 and P_2), and a high resolution optical spectrum analyzer (OSA). The OSA was used in the "MaxHold" mode to record the FWM efficiency spectrum, continuously as the frequency of one laser was swept away from the other laser (fixed frequency) to give frequency separation (*Δf*) in the range 2GHz to 30GHz. Fig. 3 (left) shows the experimental results of FWM power as a function of frequency separation (left graph) for different power profiles specified in Fig. 2, and the signal power evolution along the second order DRA span measured by OTDR (optical time domain reflectometer) setup or approximated using two sections reported in Fig. 3 (right).



Profile Number	P_{FW} , P_{BW}	r_f	P_1 , P_2
1	0 , 1.1W	0	0.5 , 0.5dBm
2	0.25 , 0.98W	0.2	0.1 , 0.1dBm
3	1.25 , 0.36W	0.78	-0.3 , -0.3dBm
4	1.5 , 0W	1	-0.6 , -0.6dBm

Fig. 2 Experimental setup of second order DRA and the table of different pumping schemes to realize different power profiles, forward/backward pump powers, and the input laser powers.

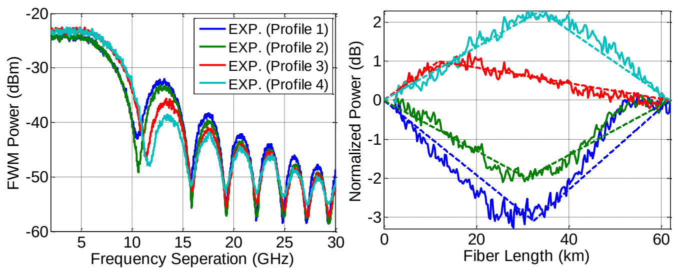


Fig. 3 (left) FWM power as a function of frequency separation. (right) Power profile along the second order DRA. (Solid lines) OTDR measurement for power profile of different profiles 1-4, (dashed lines) assumed power profile for the two section approximation. The color code of the right graph matches the color code in the left graph.

Considering a matched FWM power at low frequency separation, we can notice that the FWM power drops gradually as frequency separation increases for $r_f \rightarrow 1$ pumping scheme and the first null shifts to wider frequency spacing; the opposite FWM power behavior appeared for $r_f \rightarrow 0$ pumping scheme. To compare the FWM power resulted from DRA setup with the theory of Eq. 1, we have chosen the values of L_1, L_2, δ_1, and δ_2 to fit OTDR reading (instead of using power profile equation for first order Raman [10]). We also compare the experimental results with the theory in its integral form [9] by numerically integrating the OTDR power profile with 2km sections and then calculating the FWM efficiency. Fig. 4 shows a comparison between the experimental results, the integral calculated FWM power, and the two section approximation from Eq. 1. In general, we can see good agreement between the experimental results and theoretical predictions with error margin of 0.7dB if we consider only the FWM power higher than -50dBm (excluding nulls). We believe that this difference between theory and experimental results in the region of nulls is related to the laser linewidth and the resolution of OSA.

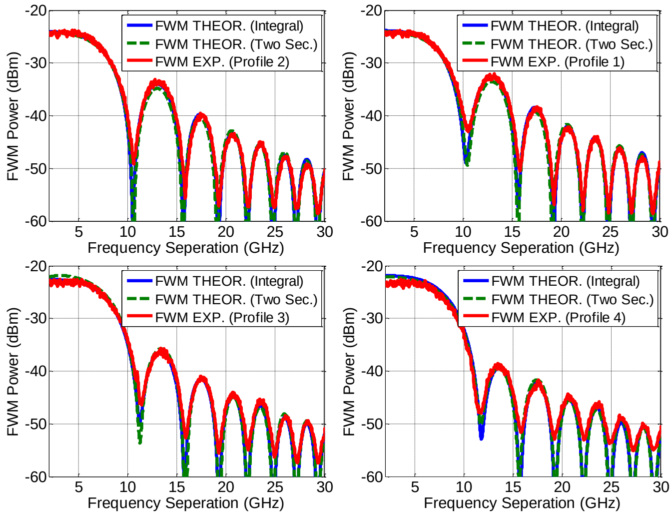


Fig. 4 Comparison of FWM power results from experiment, integral theory [9], and the proposed two section approximation (Eqn. 1).

Conclusion

We propose and experimentally validate, for the first time to the best of our knowledge, a closed form approximation of FWM efficiency in distributed Raman systems that are dominantly forward pumped or dominantly backward pumped by dividing the Raman amplifier spans into two section (one with gain properties and the other with lossy properties). The experimental results reported show an agreement of 0.7dB with our approximation, and match with the integral form of calculating FWM efficiency reported in literature.

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