Polarization pulling and signal amplification using Raman scattering for a Polarization Division Multiplexing transmission system

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Abstract—The numerical modeling of Raman polarization attraction and amplification process in the telecommunication band around 1550nm are presented. The possibility of achieving both polarization pulling and amplification in a Polarization Division Multiplexing transmission system by exploiting the polarization dependence of stimulated Raman scattering is investigated. The acceptable crosstalk and Raman gain for Polarization Division Multiplexing transmission systems were achieved for some attraction/amplification block parameters.

The interest in multifunction optical phenomena or multifunction optical devices should be stimulated in the near future. For example, the stimulated Raman scattering effect can be used for a combination of polarization controlling and optical amplification. The stimulated Raman scattering is an optical phenomenon that recently has had commercial interest because of its potential technologies in engineering. Stimulated Raman scattering has become important in the application of optical amplification for several important reasons as compared to other amplifications [1]. Additionally, stimulated Raman scattering can be used to achieve the polarization attraction effect [2, 3].

In real fibers the input states of polarization (SOPs) are not preserved because of the random birefringence (polarization mode dispersion). The uncontrolled SOPs variable can dramatically affect the performance of telecommunication systems. This phenomenon is very important, especially for a Polarization Division Multiplexing (PDM) transmission system. In this system two independently modulated data channels with the same wavelength but orthogonal SOPs are simultaneously transmitted in a single optical fiber. Two orthogonally polarized signals are transmitted to double the data throughput. At the receiver end, two polarization channels are separated by a polarization beam splitter and detected independently. The SOP for an output optical signal should be linear +45° [4]. For this SOP value, the demultiplexing process is correct and crosstalk between polarization channels is neglected. However, separating the two polarization channels with an acceptable crosstalk

(less than −20dB) at the receiving end is not trivial, because the polarization states of the two channels change rapidly with time [5]. This problem can be solved by means of the polarization attraction effect. Polarization pulling, which is based on the stimulated Raman scattering effect, can be implemented for the polarization stabilization in a PDM transmission system.

In the present paper the possibility of achieving both polarization pulling and amplification in a PDM transmission system is investigated by exploiting the polarization dependence of stimulated Raman scattering.

The conceptual diagram of a polarization attraction/amplification block scheme for a PDM transmission system is shown in Fig. 1. Optical data streams TX1 and TX2 with orthogonal SOPs (LH – linear horizontal, LV – linear vertical) are generated at the same wavelength and then multiplexed through a polarization beam combiner (PBC). During signal transmission over an optical fiber transmission link (FOL), the signal SOP evolves into an arbitrary polarization at point A in Fig. 1. The attraction/amplification block (AAB) followed by a polarization beam splitter (PBS) is used for polarization pulling and output signal amplification. The output signal SOP should be linear +45° at point B. Next, the two polarization channels are separated by PBS.
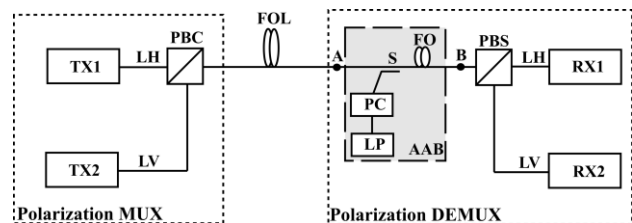

Fig. 1. Diagram of proposed polarization DEMUX using stimulated Raman scattering effect. TX1, TX2 – transmitters, LH – linear horizontal polarization, LV – linear vertical polarization, PBC – polarization beam combiner, FOL – optical fiber transmission link, AAB - attraction/amplification block, LP – Raman laser pump, PC – polarization controller, FO – optical fiber link for Raman amplification, S – splitter, PBS – polarization beam splitter, RX1, RX2 – receivers.

The polarization attraction/amplification block (AAB) consists of: a laser pump (LP), polarization controller (PC) and single mode optical fiber link (FO). The values of attraction/amplification block parameters (i.e. pump power, pump SOP and optical fiber link length) should be accurately selected depending on expected polarization pulling and Raman gain. The Raman gain is defined as the ratio of the power of the signal with and without Raman amplification. The polarization pulling quality is assessed by the crosstalk value between polarization channels. The crosstalk (CX) is the difference between a proper signal and a crosstalk signal from the adjacent polarization channel. The power evolution of the pump (**P**) and signal (**S**) for co-pumped configuration along the optical fiber link FO can be modeled by means of coupled equations, respectively [8]:

$$\frac{d\mathbf{P}}{dz} = -\alpha_p \mathbf{P} - \frac{\omega_p}{2\omega_s} g_R (P_0 \mathbf{S} + S_0 \mathbf{P}) + (\omega_p \mathbf{b} + \mathbf{W_p^{NL}}) \times \mathbf{P}, \quad (1)$$

$$\frac{d\mathbf{S}}{dz} = -\alpha_s \mathbf{S} + \frac{1}{2} g_R (S_0 \mathbf{P} + P_0 \mathbf{S}) + (\omega_s \mathbf{b} + \mathbf{W_s^{NL}}) \times \mathbf{S}, \quad (2)$$

where ω_p and ω_s are the pump and signal carrier angular frequencies, α_p and α_s are the optical fiber FO attenuation coefficients for the pump and signal wavelengths, respectively. The g_R component is the Raman gain coefficient. The vector lengths $P_0=|\mathbf{P}|$ and $S_0=|\mathbf{S}|$ represent the pump and signal powers, respectively. Vector **b** is a local linear birefringence for the optical fiber FO. The linear birefringence vector used in the numerical solutions was derived from the Random Modulus Model [3]. In turn, the vectors $\mathbf{W_p^{NL}}$ and $\mathbf{W_s^{NL}}$ are given by [2]:

$$\mathbf{W_p^{NL}} = \frac{2}{3} \gamma_p (-2S_{S,1}, -2S_{S,2}, S_{P,3}), \quad (3)$$

$$\mathbf{W_s^{NL}} = \frac{2}{3} \gamma_s (-2S_{P,1}, -2S_{P,2}, S_{S,3}), \quad (4)$$

where γ_p and γ_s are the nonlinear Kerr coefficients, $S_{P,1}$, $S_{P,2}, S_{P,3}, S_{S,1}, S_{S,2}, S_{S,3}$ are the Stokes parameters for the pump and signal, respectively.

Equations (1) and (2) were numerically solved by a Runge-Kutta method of 4th order. The following simulation conditions were assumed. Optical signals parameters: 1) the pump and signal angular frequencies are $\omega_p=2\pi c/\lambda_p$ ($\lambda_p=1450nm$) and $\omega_s=2\pi c/\lambda_s$ ($\lambda_s=1550nm$); where c is the vacuum speed of light. 2) the signal power at point A is set to $10\mu W$ (–20dBm). Optical fiber link FO parameters: 1) the attenuation coefficients for the pump and signal wavelengths are $\alpha_p=0.273dB/km$ and $\alpha_s=0.2dB/km$, respectively; 2) the Raman gain coefficient $g_R=0.6W^{-1}km^{-1}$; 3) The nonlinear Kerr coefficients

$\gamma_p=1.24W^{-1}km^{-1}$ and $\gamma_s=1.06W^{-1}km^{-1}$; 4) the beat length is equal to 44m, the correlation length is 340m and the polarization mode dispersion coefficient is 0.1 $ps/\sqrt{km}$. We assumed that the environmental conditions for the polarization attraction/amplification block are stationary. Therefore the same birefringence realization for an optical fiber link FO was taken into account. In the beginning, for a single arbitrarily polarized signal at point A (Fig. 1) the input pump SOP was searched for signal polarization pulling towards linear +45° polarization at point B (Fig. 1). The proper value of an input pump SOP was searched by an algorithm which describes the distributing of SOPs uniformly over the Poincare sphere [9]. The input pump SOP can be changed by means of a polarization controller (PC). Numerical simulations were performed for an input pump power $P_0(0)$ equal to 1 W, 2 W, 5 W and an optical fiber link FO length of 5 km. Table 1 shows input pump Stokes parameters (S_1, S_2, S_3) for achieving of linear +45° signal polarization at point B. Next, the quality of polarization pulling was assessed by calculating the polarization crosstalk. The crosstalk values [eq. (1)] were calculated for 100 arbitrary signal SOPs at point A.

Table 1. The input pump SOP for the signal polarization converging to linear +45° polarization; $L_{FO}=5km$

$P_0(0) = 1W$	$P_0(0) = 2W$	$P_0(0) = 5W$
$S_1 = 0.8343$	$S_1 = 0.2239$	$S_1 = 0.9992$
$S_2 = -0.0384$	$S_2 = 0.4745$	$S_2 = -0.0143$
$S_3 = -0.5499$	$S_3 = -0.8513$	$S_3 = 0.0372$

The crosstalk values were calculated for the above mentioned input pump power, input pump Stokes parameters and optical fiber link length. Figure 2a shows the histogram of crosstalk values for a PDM system without an attraction/amplification block.
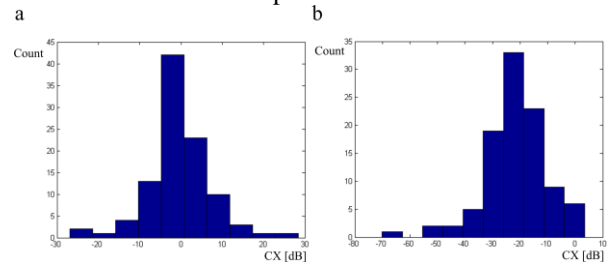

Fig. 2. Histogram of a crosstalk for a PDM system without (a) and with (b) attraction/amplification block; $L_{FO}=5km$, $P_0(0)=$ W, input pump SOP (0.8343, -0.0384, -0.5499).

In turn, Fig. 2b and 3 show polarization crosstalk distributions for a PDM system with an attraction/amplification block.
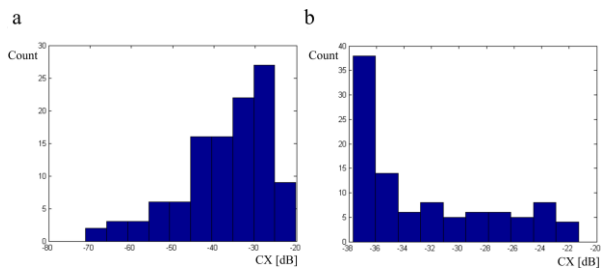
Fig. 3. Histogram of a crosstalk for a PDM system with an attraction/amplification block; L_{FO}=5km, a): $P_0(0)$=2W, input pump SOP (0.2239, 0.4745, -0.8513),b): $P_0(0)$=5W, input pump SOP (0.9992, -0.0143, 0.0372).

Figures 4 and 5 show simulated examples of the polarization pulling effect for L_{FO}=5km and $P_0(0)$=1W, 2W and 5W. When the pump power increases the output signal SOPs collapse to a particular, preferred state. The output signal SOPs converge to linear +45° polarization. The acceptable crosstalk for a PDM system (CX < −20dB) was obtained for L_{FO}=5km and $P_0(0)$=2W or $P_0(0)$=5W. We can find a commercially available Raman laser pump with an optical power up 2W. This value is still safe for optical fiber links, especially for optical components (e.g. connectors). The pump with a 5W power should be treated as a theoretical approach. Therefore we can assume that optimal conditions of the AAB block for the polarization pulling function are: a pump power of 2W, input pump SOP (0.2239, 0.4745, −0.8513) and the length of the optical fiber link FO equal to 5 km.
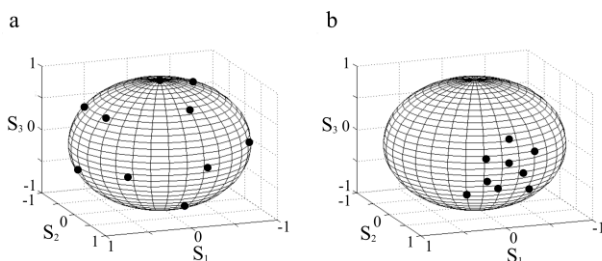

Fig. 4. Simulated examples of polarization pulling; a - distribution of arbitrarily polarized signals at point A (a), b - distribution of output signal SOPs at point B for L_{FO}=5km, $P_0(0)$=1W and input pump SOP (0.8343, -0.0384, -0.5499)
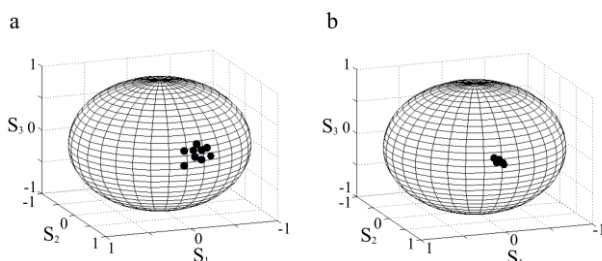

Fig. 5. Simulated examples of polarization pulling; a - distribution of output signal SOPs at point B for L_{FO}=5km, $P_0(0)$=2W and input pump SOP (0.2239, 0.4745, -0.8513), b - distribution of output signal SOPs at

point B for L_{FO}=5km, $P_0(0)$=5W and input pump SOP (0.9992, -0.0143, 0.0372)

Next, the power and Raman gain evolution for the above mentioned conditions were calculated. The power evolution of the signal along optical fiber link FO is shown in Fig. 6a. In turn, Fig. 6b shows the evolution of the distributed Raman gain along optical fiber link FO. As can be seen in Fig. 6, the values of the optical signal power and Raman gain which were obtained by means of an attraction/amplification block are appropriate for telecommunication applications.
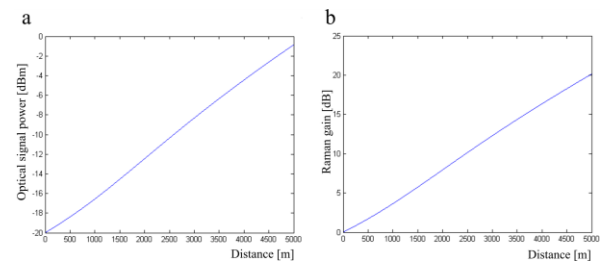

Fig. 6. Signal power evolution (a) and Raman gain evolution (b) along optical fiber link FO; L_{FO}=5km, $P_0(0)$=2W, input pump SOP (0.2239, 0.4745, -0.8513), arbitrary signal SOP at point A.

In conclusion, proper Raman polarization pulling and amplification for PDM systems can be simultaneously achieved. An acceptable crosstalk for the PDM systems was achieved. The best polarization pulling phenomenon was observed for L_{FO}=5km and $P_0(0)$=2W or $P_0(0)$=5W. Nevertheless, I would like to emphasize that a critical challenge in the present system here is the high pump power required. Very highly nonlinear fibers could be used so that the required powers for the Raman polarization attraction process may be compatible with usual telecommunication parameters.

References

[1] G.P. Agrawal, *Fiber-Optic Communications Systems* (New York, Wiley 2002).
[2] M. Martinelli *et. al.*, Opt. Exp. **2**, 947 (2009).
[3] A. Galtarossa *et. al.*, J. Lightwave Technol. **11**, 4055 (2006).
[4] X. S. Yao *et. al.*, Opt. Exp. **15**, 7407 (2007).
[5] D. van den Borne *et. al.*, J. Lightwave Technol. **12**, 4004 (2005).
[6] E. Rochat *et. al.*, Opt. Exp. **10**, 2280 (2004).
[7] E. Collet, *Polarized light in fiber optics* (Lincroft, NJ, The PolaWave Group 2003).
[8] Q. Lin *et. al.*, Opt. Lett. **4**, 227 (2003).
[9] E. B. Saff *et. al.*, Math. Intell. **1**, 5 (1997).