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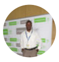

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Effects of Polarization Mode Dispersion (PMD) on Raman Gain and PMD Measurement using an Optical Fibre Raman Amplifier

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***Abstract*—We experimentally investigate the effects of increase of the differential group delay (DGD) on Raman gain and gain value. It was found that the increase of DGD values lead to the formation and the increase in the number of ripples at the expense of gain. A Raman amplifier with gain of 6.65 dB has been experimentally designed using a 24 km-SMF fibre spool with a gain fluctuation of ±0.2dB. Measurement of PMD using an optical fibre Raman amplifier has also been investigated and validated. This work recommends low values of DGD to reduce signal and gain distortion.**

Keywords— Stimulated Raman Scattering, Optical Fibre Raman Amplifier, DGD, PMD

I. INTRODUCTION

Optical Fibre Raman Amplifiers (OFRAs), based on the nonlinear effect of stimulated Raman scattering (SRS) have found application in light wave systems for compensating signal power losses in fibre. A Raman amplifier amplifies a signal based on Stimulated Raman Scattering (SRS) where a high power pump transfers energy to a weak signal of any wavelength as far as the right pump wavelength is chosen to provide a frequency shift of 13.2THz (100 nm).The increasing bandwidth demand in dense-wavelength-division multiplexing (DWDM) systems has also enhanced the use of OFRAs in broadband amplification [1, 2]. OFRAs have unique characteristics which include; a wide amplification bandwidth, low noise and high optical saturation power. The gain is tunable to any wavelength and signal amplification occurs during transmission in the fibre thus allowing distributed Raman amplification. Also, fibre nonlinearities are relatively weak compared with other materials. As a result, most fibre-based nonlinear photonic devices often require long fibre length and high power levels.

We present experimental validation of the introduction of gain ripples on Raman gain profile, the reduction of gain due to the presence and the subsequent increase in DGD values and the measurement of PMD using Raman amplifier.

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This paper is organized as follows: A brief introduction to PMD is provided in section II, Raman amplification, Methodology, experimental results and discussions.

II. POLARIZATION MODE DISPERSION

In practice, fibre birefringence generally varies both in magnitude and orientation randomly along the length on a length scale of 10 metres (birefringence correlation length l_c) [3] because of imperfections in both the manufacturing process and handling conditions. Moreover, it also changes randomly with time on a timescale associated with external environmental perturbations (such as temperature and stress variations).

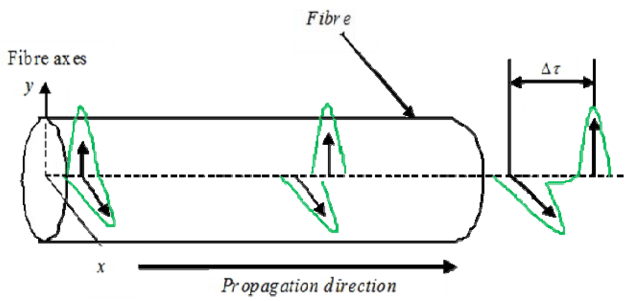

Fig.1. Shows the effect of PMD in a fibre, where a pulse launched with equal power on the two birefringent axes, x and y, becomes two pulses at the output, separated by the DGD, $\Delta\tau$

Owing to its frequency-dependent nature, fibre birefringence not only introduces random differential group delay (DGD) between the two polarization modes of one pulse, but also depolarizes relative SOPs among optical waves of different frequencies. This phenomenon is known as polarization-mode dispersion(PMD) and causes time Delays as shown in fig. 1 and has been extensively studied in recent years in the context of optical communications [4, 5] and turns out to be an ultimate limiting factor for high-bit rate communication systems.

III. RAMAN AMPLIFICATION

During Raman amplification, the signal and pump power

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evolution over fibre length is guided by the following coupled equations [6]:

$$\frac{d\vec{S}}{dz} = -\alpha_s \vec{S} + \frac{1}{2}\frac{g_R}{A_{eff}}\left(s_o\vec{P} + p_o\vec{S}\right) + \omega_s \beta \times \vec{S} \qquad (1)$$

$$\pm \frac{d\vec{P}}{dz} = -\alpha_p \vec{P} - \frac{\omega_p}{\omega_s}\frac{g_R}{2A_{eff}}\left(p_o\vec{S} + s_o\vec{P}\right) + \omega_p \beta \times \vec{P} \qquad (2)$$

where p_o, s_o represents the input signal and pump powers, g_R is the Raman gain coefficient, $\alpha_{s,p}$ represents signal and pump loses/ attenuation and $\omega_{s,p}$ are signal and pump frequencies, respectively. $\vec{P}$ and $\vec{S}$ are pump and signal polarization vectors, respectively, β is the linear birefringence vector and ω_s and ω_p account for the SPM and XPM induced nonlinear polarization rotation respectively. A_{eff} is the effective core area and z is the propagation distance. The presence of DGD causes the rapid rotation of SOPs of the birefringence signal which in turn limits the signal-pump interaction and the eventual power exchange. This limitation of power transferred to the signal reduces the Raman gain.

PMD is given by a factor of DGD, $(DGD/\sqrt{L})$.

Fixed analyzer technique of PMD measurement involves extrema counting and mean-level crossing methods [7]. In the counting of extrema, DGD ($\Delta\tau$), is given by

$$\Delta\tau = k\pi\langle N_e\rangle / \Delta\omega \qquad (3)$$

where $k = 0.824$ is the mode coupling factor, $\langle N_e\rangle$ is the number of extrema and $\Delta\omega$ is the angular frequency [7,8].

With the presence of PMD, Raman gain, defined as the ratio of the power of the signal with and without Raman amplification, is given by,

$$G_{AV} = \exp\left[\frac{1}{2}(1+3\mu)\frac{g_R P_0 L_{eff}}{A_{eff}} - \alpha_s L\right] \qquad (4)$$

where L_{eff} is the effective length in which nonlinear effects accumulate.

It thus implies that PMD reduces Raman gain (g_R) by $\frac{1}{2}(1+3\mu)$ which is the g_R coefficient in the co-polarized and orthogonally polarized cases; where μ is the ratio of Raman gain for co-polarized and orthogonally polarized of pumps (μ have the range values of 0 - 1). But in Silicon, which forms the basis of the optical fibres, $\mu = 0.012$ imply that $\mu <<< 1$ and therefore g_R reduces by a factor of 2. [6, 9]

IV. METHODOLOGY

Fig. 2 shows the experimental setup that was used. Two Raman pumps operating at frequency of 1450 nm (λ_P) with a maximum power supply of 25 dBm, a tunable laser source and a broadband source (λ_S) operating at C+L bands were used. Attenuators were used to reduce the power so as to attain the optimum signal power. Isolators were used to ensure unidirectional propagation and thus protect the laser sources from the counter-propagating pump laser as well as back reflections. The states of polarization (SOPs) of the signal and the pump were varied using polarization controllers (PCs).

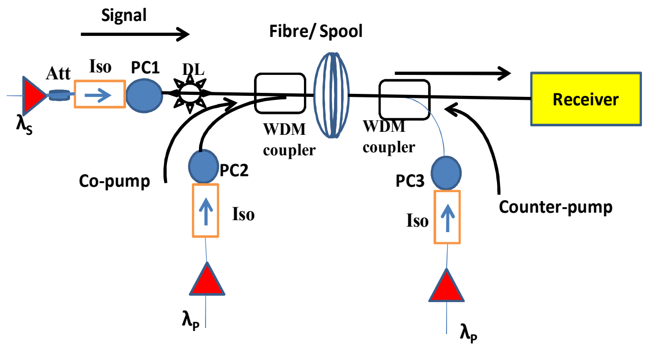

Fig.2. shows the experimental design of a Raman amplifier

A delay line (DL) was introduced on the signal before being coupled with the pump onto the fibre so as to vary the DGD of the signal. Both the signal and pump were coupled together using WDM couplers. A 24 km SMF, True-Wave REACH Low Water Peak G.655spool was used. A WDM filter type coupler was used to separate the signal and the pump. The output was measured using an optical spectrum analyzer (OSA).

V. RESULTS AND DISCUSSION

A 24-km fibre spool was used in the experiment.

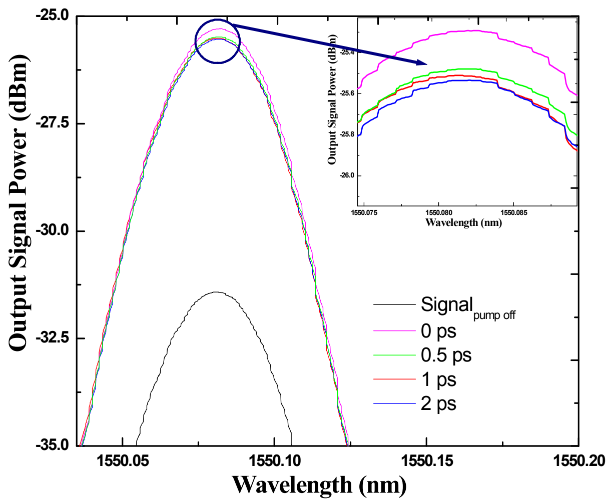

Fig.3.Illustrates both pumped and un-pumped output signal at 1550 nm. The inset is the zoomed output signals for different DGD values. A 24-km fibre spool was used.

A -10 dBm optimized broadband signal was biredirectionally pumped using two 25 dBm Raman pumps. A tunable laser source at a wavelength 1550 nm was also used. The single source signal spectrum at 1550 nm showed reducing output powers for increasing DGD (0-2 ps) as shown in Fig. 3. A -10 dBm signal was pumped using a 25 dBm laser. The presence of DGD in the signal causes the rotation of SOPs hence polarization change. The increase in DGDs for a single wavelength only reduces the output power while shifting the wavelength ripples. This limits the interaction between the signal and pump vectors.

The un-pumped output signal power was -31.5 dBm with the pumped power averaging -25.2 dBm.

The output signal spectrum for a broadband source is shown in fig. 4.

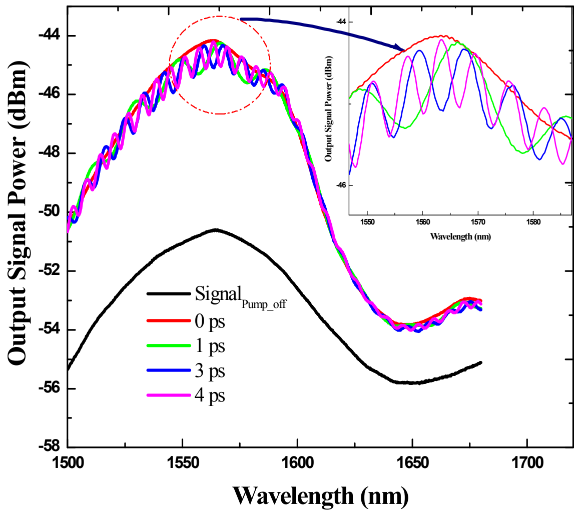

Fig.4. Illustrates both pumped and un-pumped output signal for a broadband. The inset is the zoomed output signals for different DGD values. A 24-km fibre spool was used.

The reduction in the output signal power due to increase in DGD for the broadband source is depicted by fig. 4. Like the single source, the interaction between the signal and pump ensures energy transfer from the pump to the signal and hence gain. However, with the introduction of DGD to the signal, this interaction is impaired. DGD causes rotation of propagation axis leading to mismatch in the polarization axis leading to less power transfer to the signal.

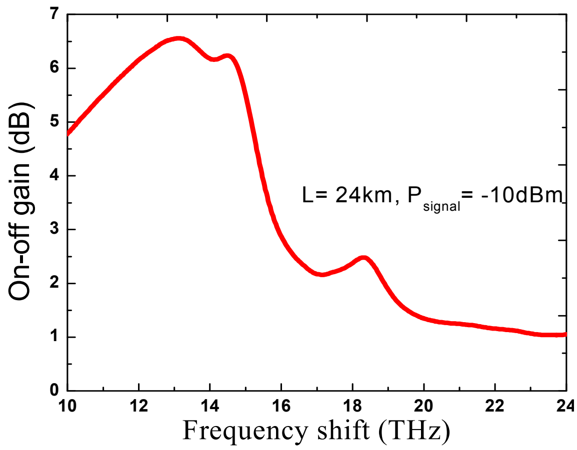

Fig. 5.Shows the on-off Raman gain profile.

Higher values of DGD rotate the SOPs rapidly as shown by the increase in the number of ripples in the spectra of fig. 4. DGD of 4 ps had the highest number of ripples compared with DGD = 0 ps. Consequently, high DGD produced the lowest output power.

The on-off Raman gain was taken as the difference between the output active (pumped) and the passive (Pump-off) signal powers. The profile is shown in fig. 5.

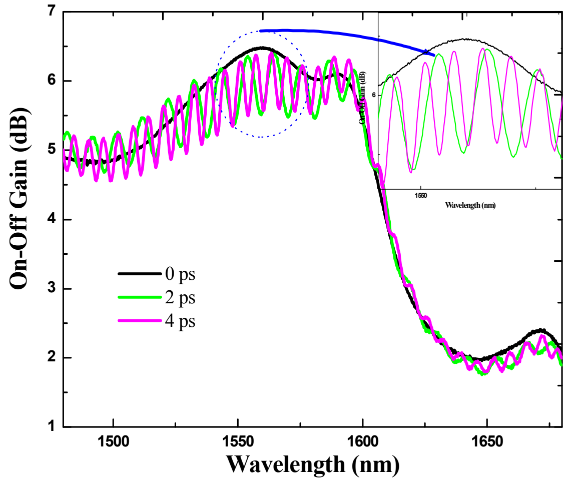

Fig.6. Illustration of Raman gain profile when group delays are introduced onto the signal. The inset is the zoomed profile for different DGDs.

Fig. 5 shows the spectrum for gain with the peak Raman gain of 6.65 dB at a frequency shift of 13.2THz which is an equivalent of 100 nm (ω_p-ω_s) between the signal and the pump frequency. The signal DGD was set to 0 ps using DL to imply a co-polarized setup and as a result no gain ripples were observed. The 13.2 THz frequency shift is attributed to the non-crystalline nature of Silica glass (has inconsistent physical and chemical structure) which allows molecular vibrational frequencies produced as a result of SRS to spread out into overlapping bands and creates a continuum. This means that all the frequencies within the bandwidth are distributed with energy. When DGD is introduced on the signal, gain ripples are formed as shown in fig.6.

Fig. 6 indicates that the gain fluctuations occur due to the ripples caused by the introduction of delays. The delay is due to the difference in propagation constants between the slow and fast axis. The number of ripples increases with DGD but gain fluctuates as shown in fig. 6. Raman gain varies at different wavelengths because of the mismatch between the signal wavelength and the Stokes wavelength that is due to PMD which affects SRS. Different frequency shifts thus occur between pump frequency and the Stokes frequencies. As such, the gain fluctuates and causes ripples. For DGD of 0 ps, fig.6 (inset) shows a single gain peak at 1550 nm which shows that there's a match between the pump and the signal and therefore a 100 nm bandwidth. But when DGD =2 ps, 5 gain peaks occur within a wavelength difference of 10 nm. This is due to a time delay on the Stokes and signal wavelengths thus imply that the Stokes will be amplified at different wavelengths. The number of ripples is even higher for higher DGDs but the value of gain for these DGDs reduce. This is because higher values of DGD rapidly and randomly rotate the SOPs of the signal causing the increase in the number of ripples. The rapid rotation of SOPs also allows the signal and the pump to have a shorter interaction span, transfer of energy to the signal and hence lower gain values. The gain variation with increasing DGD is shown in fig.7.

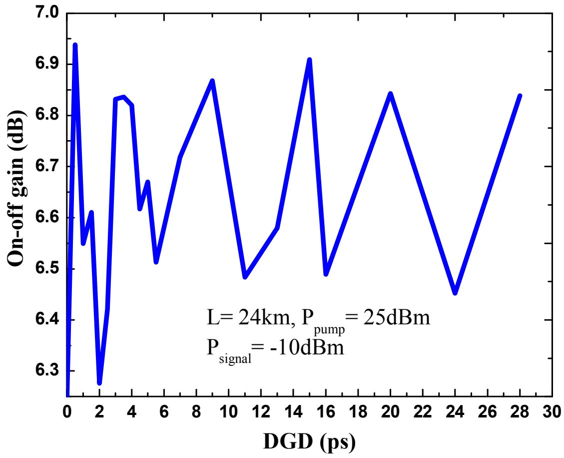

Fig.7.Shows gain fluctuation with increasing DGD values

Fig. 7 illustrates a gain fluctuating with DGD for a 24 km fibre spool with a signal of -10 dBm and pump of 25 dBm. The gain values for different DGDs were obtained by determining the gain peak at wavelength1550 nm for all the DGDs. These gain peak values for the on-off gain were plotted against the increasing DGD. The gain fluctuates with increase in DGD and forms ripples which average to 6.65 dB. DGD changes the orientation of the signal vector from its state of polarization with the pump vector. The introduction of DGD causes the pump to amplify the signal wavelengths differently with different pump powers when the two interact. The maximum gain peak occurs when the pump and Stokes polarization match while the minimum occurs when there's a mismatch in the polarization and thus the reduction in gain. Also, the increase in DGD induces a rapid rotation of SOPs and lowers the signal-pump interaction and thus the gain fluctuates.

PMD MEASUREMENT USING RAMAN AMPLIFIER

The inset of fig. 4 can be used to measure the PMD of a fibre by determining the DGD. The number of extrema as shown by fig. 8 which are within a certain frequency difference were used to approximate the DGD values by employing equation 3.

The points have been effectively utilized to approximate the DGD values within the fibre under test (FUT). The summarized DGDs measured are represented in table 1.

DGDs 3ps and 4ps are close to the values used in the set-up while 1ps are far different from the DGD values used in the DL. This error is due to the wide resolution in the 1ps spectrum which is a plot-error that affects its accuracy [8]. As such, higher DGDs are best for PMD measurement

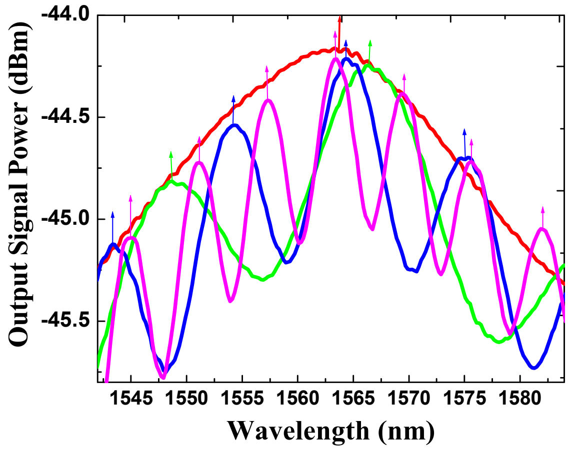

Fig.8 shows the extrema points for PMD measurements using Raman amplifier

Table 1.Shows PMD measurement using number of extrema in the Raman amplifier

Spectrum	$\Delta\omega$ (THz)	N_e	DGD (ps)	Exact DGD (ps)
Red	0	1	0	0
Green	2.665	2	≈ 1.9	1
Cyan	4.249	5	≈ 3.046	3
Magenta	3.8175	6	≈ 4.07	4

VI. CONCLUSION

In this study, we experimentally depict that the Raman gain profile is greatly affected by the presence of PMD due to the introduction of ripples on the signal gain profile. The increase in DGD values reduces the value of the gain. These gain fluctuations eventually reduce signal integrity during transmission. An experimental validation of PMD measurement employing the Raman amplifier technique has also been achieved with higher values of DGDs being found to give a conjunction between the induced and experimentally measured PMD. An average gain of 6.65 dB has been obtained for a co-polarized transmission meaning that OFRAs are recommended for long distance data transmissions.

A Raman amplifier can therefore be used to determine the presence and the value PMD of a signal in an optical fibre.

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