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A SIMPLE NONLINEAR COEFFICIENT MEASUREMENT OF HNLF AND ZrEDF BY USING FOUR WAVE MIXING TECHNIQUE

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ABSTRACT

An efficient system for characterization of nonlinear coefficient parameter in a highly nonlinear fiber (HNLF) and Zirconia-Erbium co-doped Fiber (ZrEDF) are demonstrated by using four wave mixing (FWM) technique. Inter laboratory comparison show that the values found with our method are in good agreement with the manufacture. Based on the FWM techniques, the nonlinear coefficient of HNLF is 10.7 $W^{-1}km^{-1}$ with the dispersion slope @ 1550 nm of 0.007 $ps.nm^{-2}km^{-1}$, zero dispersion wavelength (ZDW) of 1531 nm are obtained which is 0.93% error compared to the manufacturer's datasheet values. For a 4 m long ZrEDF, a non-linear coefficient of 7.164 $W^{-1}km^{-1}$ @1565 nm is measured, along with chromatic and slope dispersion values of 1.03 ps/nm.km and 9.34 x 10^{-3} $ps/nm^2.km$, which agree with the theoretical predicted values.

Keywords: four-wave mixing, highly nonlinear fiber, zirconia-erbium co-doped fiber, zero dispersion wavelength.

INTRODUCTION

Nonlinear optical phenomenon in optical fiber has become an important character in the generation of new frequencies which finds many applications in the area of parametric oscillation, multi wavelength fiber lasers (Liu, 2010), (Sun, 2010), and wavelength converters (Zamzuri, *et. al*, 2011), (Hui, 2011). Of interest lately is the ability to develop an all-optical network system whereby the current electrical wavelength converters will be replaced by an all-optical wavelength converter. Therefore, the nonlinear fiber parameters such as zero dispersion wavelength (ZDW), nonlinear coefficient (Agrawal, 1995) and chromatic dispersion (CD) of optical fiber are now becoming significant important.

Several methods have been proposed for characterizing the nonlinear behaviour of fibres. It can be measured by using a number of interferometric or non-interferometric technique based on fiber nonlinear effects. Interferometric methods are based on interferometric detection of the phase shift caused by self-phase modulation SPM) or cross phase modulation (XPM) in fiber under test (FUT) of which non-linear coefficient is to be measured (Fellegara et. al, 1997). These techniques generally need short pulses and a small chromatic dispersion, and only give the Kerr coefficient value. The disadvantage of interferometric detection schemes is related to its susceptibility to the environment perturbation taht lead to a poor stability. The measurement accurancy of these scheme strongly depends on the measurement condition. A more viable approach would be the use of four wave mixing (FWM) (non-interferometric technique) to simultaneously measure the Kerr and dispersion coefficient. As the FWM efficiency curve of an optical fibre as a function of wavelength depends significantly on the CD, the ZDW and the nonlinear coefficient of an optical fibre, the FWM technique has become popular as a tool for measuring these parameters in an optical fibre (Vinegori *et al.* 2003), (Andre *et al.*2003), (Marcuse *et al.* 1991), (Mechels 1997), (Chen, 2003). There are several reports on scanning FWM experiments can be used to measure ZDW, CD, and the nonlinear refractive index both individually (Marcuse, *et al.* 1991), (Mazzali *et al.* 1999), (Kim *et al.* 1998), (Prigent *et al.* 1993) and simultaneously (Vinegori *et al.* 2003), (Chen, 2003).

In this paper, we proposed a simple FWM technique for measuring the nonlinear parameters such as ZDW, CD and nonlinear coefficient of a Highly Nonlinear Fibre (HNLF) and Zirconia-Erbium Co-Doped Fiber (ZrEDF) by varying the signal wavelength and keeping the pump constant. The proposed technique provides an accurate measurement of the nonlinear parameters of the HNLF when compared to the manufacturer specification and theoretical predicted value.

EXPERIMENTAL SETUP

Figure-1 shows a schematic measurement of nonlinear parameter in the HNLF via FWM technique. The main components are a 100 m long HNLF, a polarization controller (PC) and a 3dB coupler. The HNLF is used as the nonlinear medium to generate FWM when two closely spaced signals (pump, P_P and signal, P_S) travel in this fiber. The HNLF used is this experiment is from OFS with specifications of the nominal ZDW, loss coefficient, dispersion slope and nonlinear parameter of the HNLF being 1531 nm, 0.73 dB/km, 0.007 $ps/nm^2.km$ and 10.8 $(W.km)^{-1}$, respectively. In the setup, two Yokogawa (AQ2200) Tunable Laser Sources (designated TLS1 and TLS2); with tuning ranges from 1450 nm to 1620 nm and line widths of 0.015 nm are used as signal, P_s and pump, P_1 sources. Both P_1 and P_s are combined using a 3 dB coupler and a PC to adjust the polarization of the input signals in order to obtain the maximum FWM efficiency. A Yokogawa (aq6370B) Optical Spectrum Analyzer (OSA) with 0.02 nm resolution bandwidth is used to measure the generated FWM spectrum.

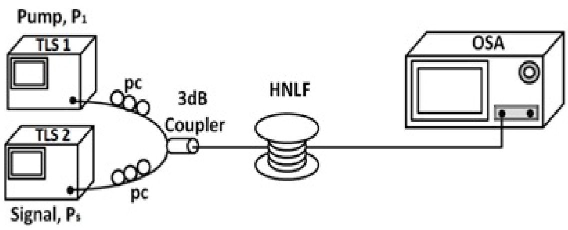


Figure-1. Schematic diagram for generating FWM effect in the HNLF.

For ZrEDF, a diagram of nonlinear coefficient measurement is shown in Figure-2. In the setup, we used two TLS where the first pump, P_1 generated from Tunable laser 1 (TLS 1) is fixed at a wavelength 1560 nm with an average output power is 12.8 dBm and the signal, P_s is generated from another directly TLS 2 by varying wavelength from 1552nm to 1557 nm with average power of 10.8 dBm. This TLSs that manufacture from YOKOGAWA (AQ2200) can be tuned from 1460nm to 1640nm with linewidth of 0.015nm. Two beams where combined by 3 dB coupler via polarization controller (PC). PC is used to adjust the polarization at the input to obtain maximum FWM efficiency. The Two LD pump which at wavelength 1460 nm and 1490 nm are combined by WDM combiner and launched into Zr-EDF by passing through the WDM coupler. These two pumps are used to amplify the erbium inside the zirconium and at the same time, to make the powers of pump and signal exceed the FWM power threshold for generating the new wavelength by using FWM effect. In this system, we have used 3 m of the Zr-EDF with an Erbium concentration of 3000 ppm. The propagation loss of Zr-EDF α = 0.1 dB/m is obtained by using cut back method measurement. The Zr-EDF that we used has the refractive index of the core is 1.466 with the effective area of the fiber is 87 μm^2. The refractive index and the size of core glass are the important parameters to determine the nonlinearity of the fiber. The generation of FWM from the Zr-EDF was measured by an optical spectrum analyzer (OSA) (yokogawa aq6370B) with 0.02nm resolution bandwidth.

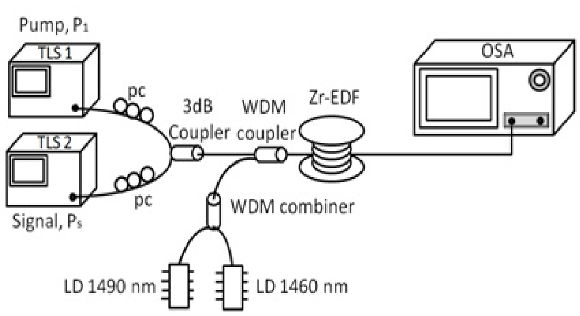
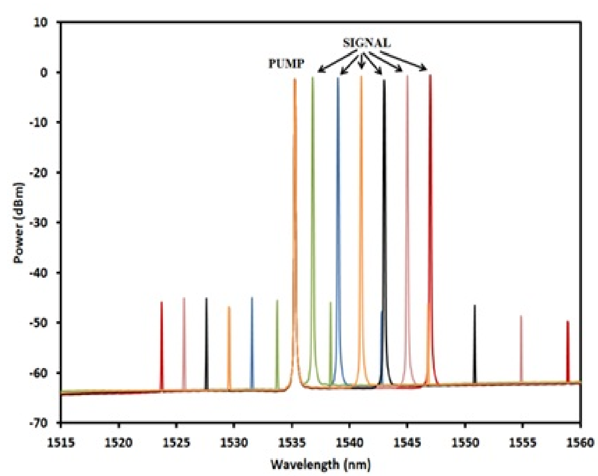


Figure-2. Schematic diagram for generating FWM effect in a Zr-EDF.

RESULTS AND DISCUSSION

Highly nonlinear fiber (HNLF)

In this experiment, the intensity of the FWM converter is measured for every tuned signal wavelength over its entire wavelength range from 1500 nm to 1600 nm with a wavelength detuning range of 125 GHz of between the signal and pump which is shown in Figure-3 (a). The pump and signal powers are set at 5.5 mW and 4.25 mW to measure the highest FWM conversion efficiency. Figure-3 (b) shows the variation of the pump wavelength from 1516 nm, 1518 nm, 1526 nm, 1528 nm, 1533 nm, 1535 nm, 1544 nm and 1545 nm against a varying signal wavelength from 1500 nm to 1600 nm for every pump wavelength. Based on this figure, it can be seen that a full width at half maximum for the FWM generated signals are larger for a smaller wavelength difference between the pump and signal lights due to the phase matched wavelength bandwidth. The phase matched bandwidth within which the FWM light is efficiently generated depends on the wavelength difference between the pump and signal wavelength, and is satisfied at a wavelength spacing region of 1 nm until 15 nm. Above a spacing of 15 nm, the FWM power decreases as illustrated when using the pump wavelength below the ZDW ($\lambda_P < \lambda_0$). However, when the pump wavelength is above the ZDW ($\lambda_P > \lambda_0$) (until 19 nm at the pump wavelength of 1550 nm), an increase in the FWM power can be observed. In this case, a maximum FWM efficiency at 1550 nm can be achieved. However, a narrow phase matching is illustrated when using the pump wavelength of 1550 nm. Consequently, it is difficult to apply this method in other applications such as wavelength converters where it needs a broader phase matched bandwidth. For that reason, the pump wavelength should use at the wavelength nearest to the ZDW. To determine the ZDW, the wavelength spacing is tuned from 10 nm to 15 nm where the clash of spectrum FWM power can be observed as the ZDW of HNLF. Based on this technique, a ZDW of 1531 nm is successfully obtained where it is similar to the manufacturer's specifications.



(a)

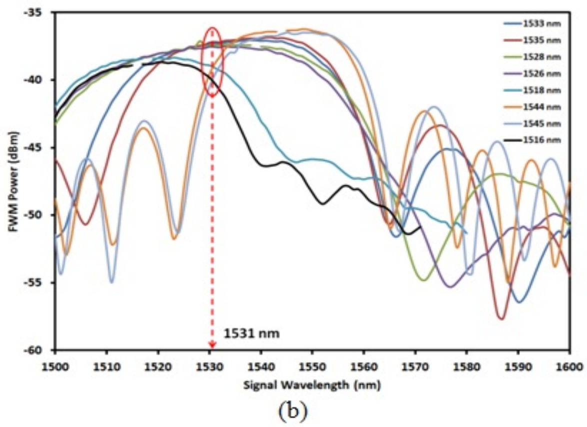


Figure-3. (a) The FWM spectrum by varying the signal and fix the pump wavelength (b) The FWM power of tuning signal wavelength for different pump wavelength.

The generation of FWM in nonlinear fiber can be explained by using the coupled differential equations for the propagating amplitudes, including the contributions to phase mismatch due to XPM and SPM. A well-known formula used for FWM estimation was originally derived by Hill *et al.* 1978 and reformulated later to include the phase mismatch dependent efficiency by Shibata *et al.* 1987. In order to verify ZDW, we compared the measured value with our calculated result obtained from:

$$P_F(L,\Delta\beta) = \eta(\Delta\beta)\gamma^2 L_{eff}^2 P_s P_p^2 e^{-\alpha L}, \tag{1}$$

where P_s and P_p are the two input powers at λ_s and λ_p wavelength, respectively, L is the length of the optical fibre and α is the absorption coefficient and

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

where phase-mismatching, $\Delta\beta$

$$\Delta\beta = -\frac{2\pi c\lambda_0^3}{\lambda_P^3\lambda_S^2}\frac{dD_c}{d\lambda}(\lambda_P-\lambda_0)(\lambda_P-\lambda_S)^2, \tag{3}$$

which requires the FWM power, P_F and FWM efficiency, η, respectively. These values can be obtained by first setting the pump wavelength to a value which is less than the ZDW value ($\lambda_P < \lambda_0$) stated by the manufacturer. Equation (1) requires the HNLF fibre length, L, absorption coefficient, α, as well as the dispersion slope at 1550 nm, $dD_c/d\lambda$, which we obtained from the manufacturer's data sheet with values of L = 100 m, α = 0.000168 m^{-1}, $dD_c/d\lambda$ = 0.007 ps/(nm^2.km), respectively. Before discussing the experimental results, it is worth noting that due to the limitations of the OSA, the measured FWM efficiency and power, η and P, respectively, will never be able to reach the minimum value, i.e. η = 0 and P = -75. In fact, the low sensitivity of the OSA means that we can only measure noise at low values of η and P. From Figure-4, it is clear that the theoretical and experimental values of the FWM efficiency are similar and follow a similar trend when we used the experimental value of the ZDW at 1531 nm obtained via the third technique. However, there is a slight discrepancy when we used the first and second techniques to calculate the FWM efficiency, which implies that the third technique is the most suitable one to employ for FWM efficiency calculations. This technique is much superior to other techniques such as frequency-domain phase shift (Mechels, S. E., *et al.* 1997), modulation instability amplification (Mazzali, C., *et al.* 1999) and the differential phase shift (Mechels, S. E., *et al.* 1997) in determining the ZDW due to the accuracy of the technique as well as simplicity of the setup.

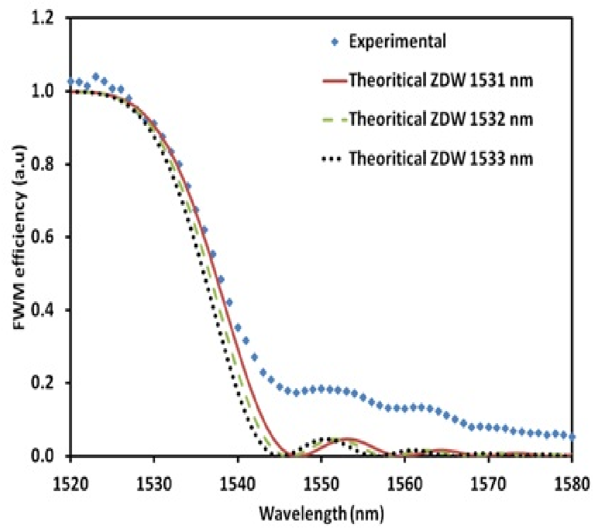


Figure-4. The FWM efficiency as a function of signal wavelength of HNLF.

The FWM efficiency is essentially based on the FWM power that is obtained from the experimental value shown in Figure 5. In this figure, the highest FWM power of -38.5 dBm at 1520 nm is found and observed to be almost constant from 1520 nm to 1532 nm with 1 dB fluctuation power. It then decreases from -39.2 dBm to -46.1 dBm between 1532 nm to 1547 nm, respectively before increasing again to round 0.2 dB at 1552 nm. This spectrum is observed to behave almost like a cosine spectrum due to the changes in dispersion along the whole length at the HNLF. In addition to the experimental results, Figure-3.9 also shows the numerical spectrum of FWM power based on the ZDW at 1531 nm, 1532 nm and 1533 nm, respectively. This spectrum can be obtained by inserting the FWM efficiency value from Figure-5 into equation (2). Therefore, the numerical spectrum of 1531 nm illustrates the same pattern as that of the experimental spectrum due to the fact that the nonlinear parameters in the equation (1) are constant for both cases. For this reason, the other ZDW measurements (at 1532 nm and 1533 nm) gave the different values in the FWM power.

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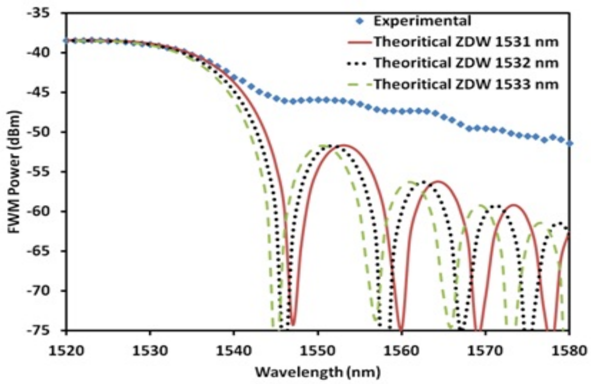

Figure-5. Optical power of FWM as a function of signal wavelength.

In addition to the determination of the ZDW in the HNLF, this technique can also be used in the measurement of the CD in HNLF. In this case, it is referred to as the normalized FWM efficiency, η, as stated in equation (2). To determine the CD, the following equation is employed,

$$\Delta\beta = \frac{2\pi\lambda^2}{c} D.\Delta f^2 \tag{4}$$

with the dispersion parameter, $D = \frac{-2\pi c}{\lambda^2}\beta_2$, and β_2 is the group velocity dispersion parameter. Figure 6 shows the CD coefficient $D(\lambda)$ of a HNLF is obtained from the proposed method. From this figure, the second order dispersion coefficient $dD(\lambda)/d\lambda$ which is related to the dispersion slope of the HNLF is also obtained. The red empty dots show the measurement result by using the third technique for a 100 m length of HNLF where it is in good agreement with those of the manufacturer's datasheet. However, from this figure, the experimental result was obtained only from 1525 nm to 1545 nm due to the limitation of ZDW bandwidth in the FWM technique. This limitation is a drawback of this technique.

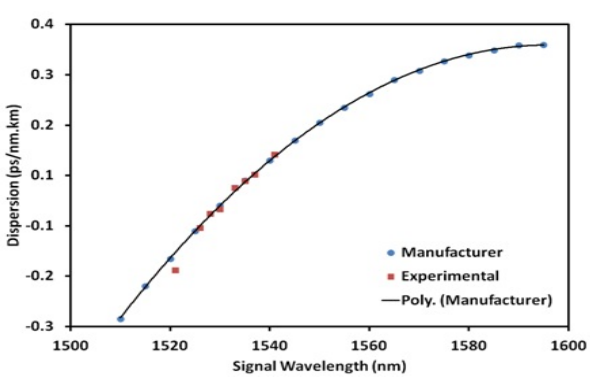

Figure-6. The chromatic dispersion coefficient of HNLF with our proposed technique.

Zirconia-Erbium co-doped fiber (ZrEDF)

For the ZrEDF, we vary the pump and signal wavelength with wavelength detuning of 0.4 nm due to obtain the highest values of FWM power among 1500 nm to 1600 nm which is shown in Figure-7(a). From this figure, the generation of this sideband is depends on the power of the pump and signal wavelengths where a strong pump transfers its energy to create this converted signal. To achieve the highest converted signal output power, the pump power should be higher than the signal power and this can be done by controlling polarization controller. Hence, the highest output power of the converted signal with -45 dBm is obtained when the pump and signal powers are set to +15 dBm and +13dBm respectively. Figure-7(b) show the value of FWM power start to increase from wavelength 1545 nm to 1558 nm and after that, it become flat with 0.5 dB fluctuation powers in the region of 1558 nm to 1565 nm at FWM power of -45 dBm. After this region, the power is decreased rapidly when the signal wavelength increased to L-band region. This spectrum is similar to the gain spectrum of Zr-EDFA where it given the highest gains at wavelength around 1560 nm. It is shown that, the high power is needed to exceed the FWM threshold power in generating the new wavelength (sideband) based on FWM technique. Based on this experiment, the best region to decide the pump wavelength is around the flatness FWM power where in our case, wavelength of 1560 nm is selected as a pump wavelength for measuring the nonlinearity coefficient of Zr-EDF.

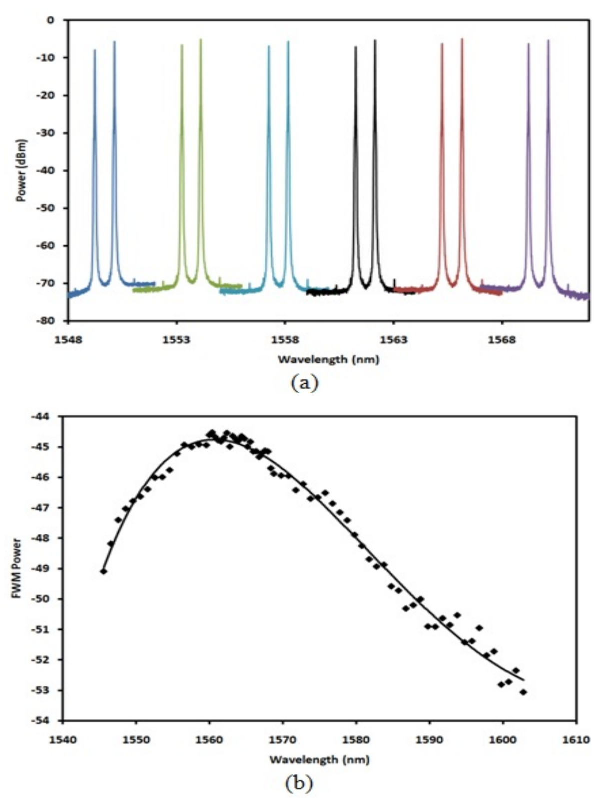

Figure-7. (a) The FWM spectrum by varying the pump and signal wavelength (b) the spectrum of FWM power against converted wavelength.

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In determine of nonlinear coefficient, the pump wavelength is fixed to 1560 nm and the signal wavelength is varied from 1552 nm to 1567 nm with frequency spacing is started from 22.7 GHz (0.2 nm). Figure-8 shows the FWM spectrum that is observed by using 25 dB fix attenuator. From this spectrum, the nonlinear coefficient and dispersion of Zr-EDF could be calculated. The maximum power of the converted wavelength is obtained by adjusting the two PCs as shown in Figure-2 for each measurement.

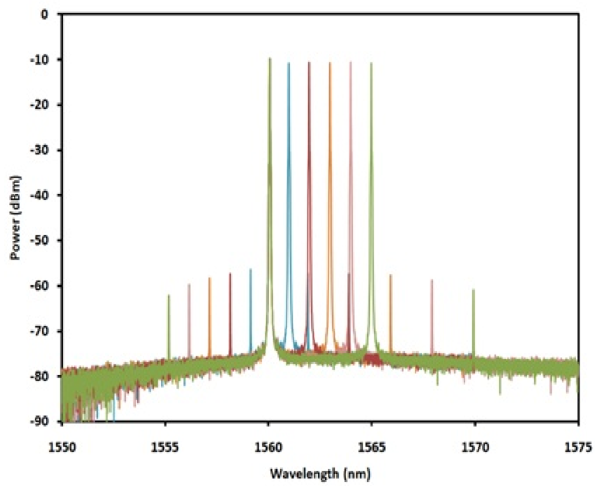

Figure-8. The typical output spectra at P_1 and P_s, as well as their converted signals (sideband fields) C_2 and S_2 when wavelength of P_1 and P_s are 1560nm and varied wavelength from 1552 nm – 1567 nm.

In the FWM process, two chosen wavelengths (λ_{pump} and λ_{signal}) will generate a converted wavelength ($\lambda_{converted\ signal} = 2\lambda_{pump} - \lambda_{signal}$). For analyzing the nonlinearity inside the ZrEDF, the nonlinear coefficient, γ is determine by using equation (5).

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{5}$$

The theoretical value of the nonlinear coefficient for Zr-EDF is measured by using equation (5) where the refractive index of core of 1.46625 and the effective area of 87 μm^2. Therefore, the value of the nonlinear coefficient for the Zr-EDF is 7.164 W^{-1}km^{-1} is obtained. This value is in the range of nonlinear coefficient of experimental value which shown in Figure-9. Whereby, in the experimental, equation (2) is used to calculated the nonlinear coefficient by using the pump power of 15 dBm, signal power of 13 dBm, α of 0.1 dB/m and 3 m length of the fiber. Therefore, the value range of nonlinear coefficient from 6 W^{-1}km^{-1} to 8 W^{-1}km^{-1} is obtained.

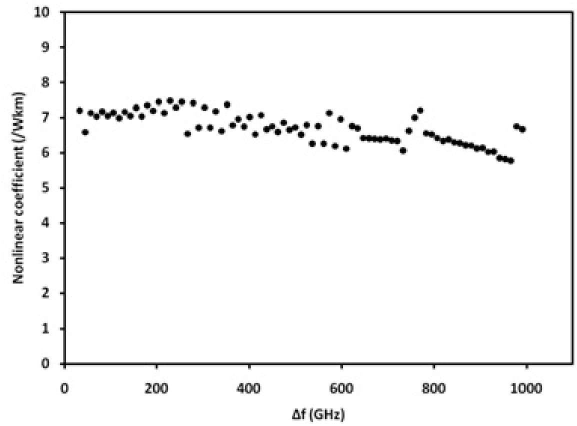

Figure-9. Nonlinear coefficients with varying the frequency spacing.

Figure-10 shows the FWM power is plotted by varying wavelength from 1552 nm to 1567 nm in theoretical and experimental condition. In the experiment case, the FWM that obtain from FWM spectrum which shown in Figure 3 is plotted. From the experimental graph, it is observed that the FWM power is increased from 1552 nm to 1554 nm and the power drop slowly until 1554 nm and then increased back until 1558 nm. After 1558 nm, the FWM power is approximately flat and it will drop again started from 1561 nm to 1562 nm. At around 1562 nm, the FWM power show some increase and after that it drop rapidly until wavelength of 1567 nm. For the theoretical case, the FWM power is calculated by using equation (1), when using the nonlinear coefficient of 7.164 W^{-1}km^{-1} based on the theoretical calculation. Therefore, it lowers than the experimental value due to the nonlinearity coefficient of experimental value. However, the graph pattern is approximately similar to the experimental case.

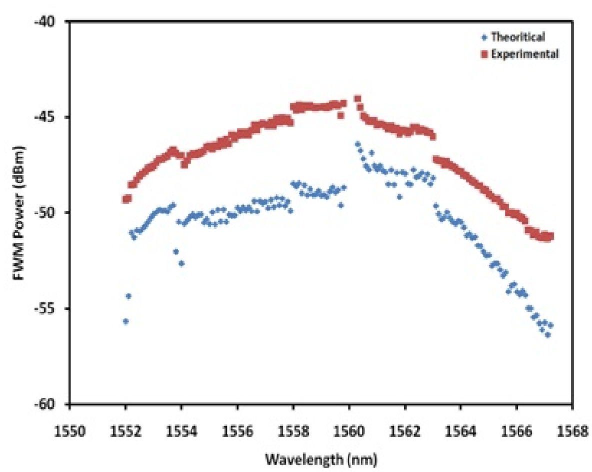

Figure-10. FWM conversion efficiency versus wavelength detuning in Bi-EDF.

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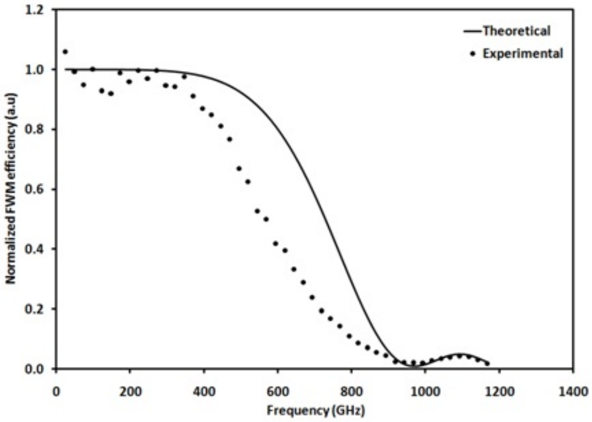

Figure-11. Normalized FWM efficiency against the input signal frequency for the ZrEDF.

The analysis of FWM power in a function of channel spacing can be used to estimate the fiber chromatic dispersion and dispersion slope. Figure-9 shows the normalized FWM efficiency against the input signal frequency. It can be seen that as the channel spacing (frequency) is increased from 30 GHz to 400 GHz, the FWM efficiency remains relatively the same, with fluctuations of about 0.5 a.u. However, above 400GHz, the FWM efficiency begins to drop, reaching with the theoretical predictions for the ZrEDF. According to equation (4), we obtain the chromatic dispersion and slope dispersion of Zr-EDF of 1.03ps/nm.km and 9.34 x 10^{-3} ps/nm^2.km, respectively.

CONCLUSIONS

In the case of HNLF, the manufacturers employed an interferometric technique to characterize the nonlinear parameters of the fiber, which are provided in a datasheet. We used these values as a reference for our FWM non-interferometric characterisation procedure, which is chosen due to its simplicity, high sensitivity and accuracy, as well as suitability in all currently commercially available fibre types and SOAs. By using the proposed technique and employing the FWM effect, the nonlinear parameters of the HNLF were found to be similar to the manufacturer's values as in the datasheet (e.g the dispersion slope @ 1550 nm of 0.007 ps.nm^{-2}km^{-1}, ZDW of 1531 nm and nonlinear coefficient of 10.7 W^{-1}km^{-1}) with 0.93% error. For a ZrEDF, a 4 m long portion with a propagation loss of 0.68 dB/m and an erbium concentration of 3000 ppm is used. FWM power levels of approximately -45 dBm at around 1565 nm are obtained and agree well with the theoretical predicted values. The ZrEDF fiber also shows a non-linear coefficient of 7.164 W^{-1}km^{-1} along with chromatic and dispersion slopes of 1.03ps/nm.km and 9.34 x 10^{-3} ps/nm^2.km that are well in accordance to the theoretical values.

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