Optical Fiber Nonlinear Coefficient Measurements Using FWM

A. Supe, J. Porins, and G. Ivanovs
Institute of Telecommunications, Riga Technical University, Azenes st. 12, Riga LV-1010, Latvia

Abstract— In this article is given research results about nonlinear phenomena four-wave mixing (FWM) potential use in the optical fiber (OF) nonlinear coefficient γ and polarization mode dispersion (PMD) evaluation. First of all we give theoretical review about FWM causes in the OF. Afterwards the γ parameter measurement technique based on FWM is proposed. Fiber used in the experimental measurements is highly non-linear fiber (HNLF) wich γ parameter is unknown and therefore is suitable for this research work.

1. INTRODUCTION

Continuously increasing amount of data in telecommunication networks requires higher and higher data rates. Nonlinear fiber optics plays an important role in the design of high capacity lightwave systems. Mostly due to the huge advantage over other technologies by achievable data rates and promising future development. One of the research areas is related with optical fiber non-linear characteristics. From one side non-linearity is not desirable because it causes distortions to the transmitted optical signals. It is very essential in the case of wavelength division multiplexed transmission systems for long transmission distances with several amplification regions. But nonlinear optical effects (NOE) also can be utilized in optical signal processing. In this case it is desirable to use the medium with increased non-linearity to achieve better NOE manifestation. For this reason very suitable are HNLFs [1].

Several approaches are used to determine optical fiber's γ parameter. Both interferometer based measurements or realization of some specific NOE in the OF [2, 3]. From wide range of NOEs that can be observed in OF, very promising is FWM. It is simple to induce and provide not only γ parameter characterization possibility, but also optical fiber PMD characteristics [5].

This paper consists of four parts. In Section 2 FWM process is described in details. The background of FWM is described in relation to OF and optical radiation parameters. FWM dependency on the two optical component — pump and signal — polarization state reciprocal matching is explained. Section 3 is devoted to describe the measurement scheme that was used to estimate γ and PMD parameters for the HNLF fiber. In Section 4 the main results and conclusions are given.

2. FOUR-WAVE MIXING IN OPTICAL FIBER

Four-wave mixing (FWM) is referred to as a parametric process. These processes only involve modulation of an OF refractive index or so called nonlinear refractive index [2, 3]. It is caused by ultrafast third-order nonlinear susceptibility $\chi^{(3)}$ of the SiO_2 [2]. FWM is a very harmful for a multichannel fiber optics transmission systems such as wavelength division multiplexing (WDM). It is because FWM can significantly reduce WDM performance by increasing crosstalk between all the system channels. This is due to optical signal generation at new frequencies that are defined by intermediate frequencies between any two initial optical signal frequencies.

In general FWM involve nonlinear interaction among four and more optical waves. But for simplicity let's consider case with two waves with different frequencies usually called pump and signal that generate third optical wave called as idler. According with the publication by S. Jung et al. [6] the idler component can be expressed as

$$P_3\left(L\right)=\left(\gamma P_1\left(0\right)L_{\mathit{eff}}\right)^2P_2(0)\exp(-\alpha L)\eta \tag{1}$$

where L is the fiber length, L_{eff} — effective length, α — fiber losses, $P_1(0)$ — pump power, $P_2(0)$ — signal power and η is the efficiency of the FWM that can be expressed as

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

where $\Delta\beta$ is the phase-matching condition.

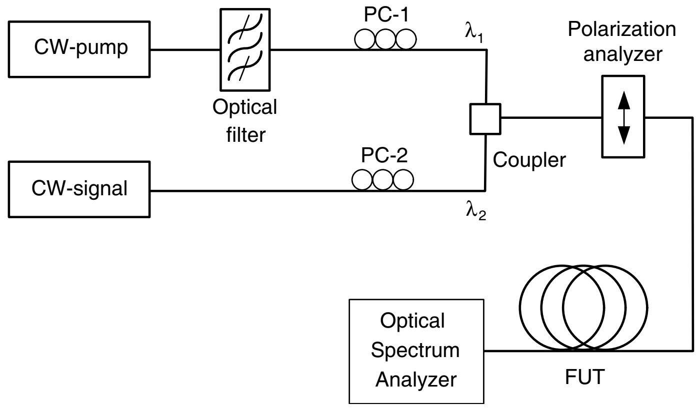

Figure 1: Experimental OF nonlinear coefficient measurement scheme based on FWM.

The efficiency of the FWM process is also dependent of the relative polarization of pump and signal fields. The best efficiency is obtained when pump and signal are co-polarized, whereas the orthogonal scheme leads to the worst efficiency [2]. When pump and signal are orthogonal the optical power of the idler component is approximately 8/9 times smaller than in the co-polarized state [2]. This polarization state influence to the FWM origins from the $\chi^{(3)}$ dependence of polarization state.

3. MEASUREMENTS USING FWM

To determine HNLF fiber nonlinear parameter the FWM based measurements were performed. The actual experimental measurement layot is shown in the Figure 1.

In this scheme two laser sources are used to generate pump and signal optical components with wavelength λ_1 and λ_2. Both lasers are DFB and are working in the continuous radiation mode. Since the pump laser is working with higher optical output power there is an optical filter to reduce the laser radiation sideband noisiness at the output signal. To achieve co-polarized state between pump and signal there are two polarization controllers (PC-1 and PC-2). Afterwards both optical waves are coupled together and goes through the polarization analyzer. That allows us to control that both components has the same state of polarization. After polarization analyzer the fiber under test is connected. In our experiment it is 860 meters long HNLF. To see the FWM induced idler component at the wavelength:

$$\lambda_{\text{idler}} = 2\lambda_{\text{pump}} - \lambda_{\text{signal}} \tag{3}$$

From the HNLF output spectrums we can define what is the idler component's power level. Since the FWM process is dependent of OF γ it can be used to determine this parameter for the specific fiber. The relation between parameter γ and the FWM generated idler wave can be seen in the Equation (1). To estimate HNLF γ parameter the pump and signal wavelength separation was set to 1 nm. Larger wavelength separations could be used, but then we have to take into account polarization induced FWM efficiency reduction. From HNLF fiber output spectrum measurements it was estimated that γ parameter for this specific OF is $10.7\,\text{W}^{-1}\,\text{km}^{-1}$. It is approximately 4 times higher than standard single mode fiber γ. It means this fiber is much more effective for NOE generation and it does not require so high optical power to achieve the same nonlinear manifestation as standard OFs.

To find out OF PMD characteristics the FWM measurements were performed for different pump and signal wavelength separations. Pump wavelength is kept constant while the signal wavelength is gradually increased. In the Figure 2, all the measured spectrums are represented in the same graph (legend shows the difference between the pump and signal wavelengths). It allows to better observe the evolution of the idler component. From measured output spectrums it can be seen that at certain threshold the idler components start to decrease. Nearer image to the FWM generated idler components is given in the Figure 3. Calculated results were achieved using Equation (1). Up to 3 nm separation between pump and signal wavelengths the idler remains almost constant, but afterwards start to decrease. It can be explained by the theory of the principal states of polarization. Exist a small frequency region over which the PMD vector is reasonably constant [7]

$$\Delta\omega \approx \frac{\pi}{4\langle \text{DGD} \rangle} \tag{4}$$

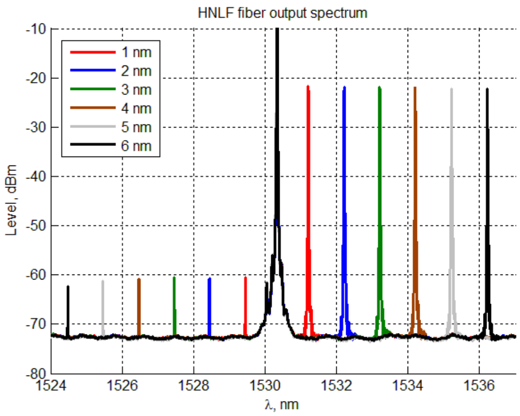

Figure 2: Measured HNLF output spectrums. Six different signal wavelength are shown in the graph.

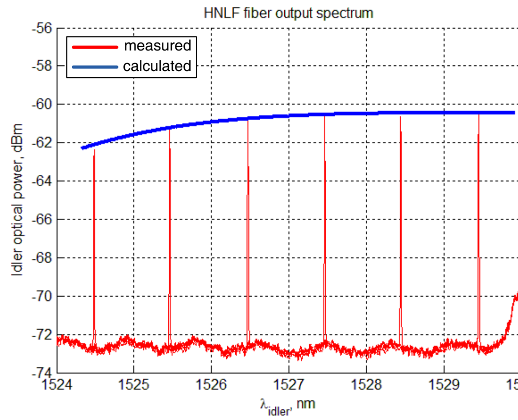

Figure 3: Calculated and measured idler components for six different signal wavelengths.

where ⟨DGD⟩ is the mean differential group delay or fiber PMD. From here it is possible to express the PMD depending on the frequency region over which the two signals propagating in the OF remain co-polarized. In this case the indication of co-polarized state existence in the OF is the FWM generated idler signals. From Figure 3, it can be seen, that region over which the PMD vector is almost constant is ~ 3 nm. Using Equation (4) the estimated HNLF fiber PMD value is 2.19 ps.

4. CONCLUSIONS

FWM use in fiber parameter measurements is very topical and promising. This NOE is easy to initiate and therefore does not require very complicated techniques. In this research we have shown the relation between FWM nonlinear effect and OF γ and PMD parameters. Afterwards it is used to determine both parameters for the HNLF fiber. Nonlinear parameter γ is $10.7\,\mathrm{W}^{-1}\mathrm{km}^{-1}$ and PMD is estimated to be 2.19 ps.

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