

Comparison of Different FWM Realization Methods in Optical Fibre

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Introduction

Four-wave mixing (FWM) is referred to as a parametric process. Parametric processes are a separate class of optical nonlinear phenomena where optical fibre (OF) play a passive role except for mediating interaction among optical waves. These processes only involve modulation of a medium parameter such as the fibre refractive index [1].

The origin of parametric processes lies in the nonlinear response of bound electrons of a material to an applied optical field. More specifically, the polarization induced in the medium is not linear in the applied field but contains nonlinear terms, whose magnitude is governed by the nonlinear susceptibilities of different order. The main reason of nonlinear effects in OF is due to ultrafast third-order susceptibility $\chi^{(3)}$ of the medium [2]. In general FWM involve nonlinear interaction among four optical waves and is referred to as third order parametric process because it is caused by the third order nonlinear susceptibility [1].

FWM in OF has been studied extensively because it can be quite efficient for the generation of new optical waves at varied frequencies [1]. Other FWM applications include different OF parameter measurements such as dispersion and nonlinear coefficient and various optical signal processing possibilities.

In OF notable FWM occurs only if the phase mismatch almost disappears. This means the necessity for matching the wave vectors and corresponding frequencies. Such a requirement is referred to as phase matching. The quantum-mechanical explanation of FWM is, it occurs when photons from one or more waves are annihilated and new photons are created at different frequencies such that the net energy and momentum are conserved during the parametric interaction [1]. For parametric processes to occur the phase-matching condition requires a specific choice of the frequencies and the refractive indices [2]. If compared to stimulated scatterings in OF, the phase-matching condition is automatically satisfied as a result of the active participation of the nonlinear medium.

There are different types of FWM depending on the involved optical waves. In the case of three distinct optical wave frequencies three photons transfer their energy to a

single photon at the frequency $\omega_4 = \omega_1 + \omega_2 + \omega_3$. This is so called non-degenerate FWM. For this process it is difficult to satisfy phase matching in OF with high efficiency [1].

Another case is when there are two optical wavelength at distinct frequencies ω_1 and ω_2 . Then photons from frequencies ω_1 and ω_2 are annihilated with simultaneous creation of two photons at frequencies ω_3 and ω_4 such that

$$\omega_3 + \omega_4 = \omega_1 + \omega_2. \quad (1)$$

It is so called partially degenerate case [1]. The phase-matching requirement for this process to occur is

$$\Delta k = k_3 + k_4 - k_1 - k_2 = 0. \quad (2)$$

Specific FWM realisation case is when $\omega_1 = \omega_2$. This is used in parametric amplifiers. Parametric amplification occurs when in OF simultaneously with pump wave at ω_1 are coupled signal wave at ω_3 . Signal wave gets amplified by parametric amplification and at the same time idler wave at frequency ω_4 is generated so that frequency shift is

$$\Omega_s = \omega_1 - \omega_3 = \omega_4 - \omega_1, \quad (3)$$

where $\omega_3 < \omega_4$ [2]. The low-frequency sideband at ω_3 and the high-frequency sideband at ω_4 are referred to as the Stokes and anti-Stokes bands [1].

If the pump wavelength lies in the anomalous-GVD (group velocity dispersion) range ($\lambda > \lambda_0$, where λ_0 is zero dispersion wavelength of fibre), it is possible to determine the phase matching condition for FWM in OF by calculating the frequency shift Ω_s between source pump wavelength ω_1 and ω_2 as

$$\Omega_s = \sqrt{\frac{2\gamma P_o}{|\beta_2|}}, \quad (4)$$

where Ω_s is the frequency shift between pump wavelengths, P_o is the input pump power, β_2 is second order dispersion, γ is nonlinear coefficient [2].

From the equation (4) it is possible to express input pump power as the function of frequency shift Ω_s between pump wavelength at which phase matching condition for FWM is satisfied

$$P_o = \frac{\Omega_s^2 * |\beta_2|}{2\gamma} \quad (5)$$

For comparison to simulation data presented further we have calculated this power dependence for wavelength separation in a range of 2 nm between two pump waves for partially degenerate FWM (Fig. 1).

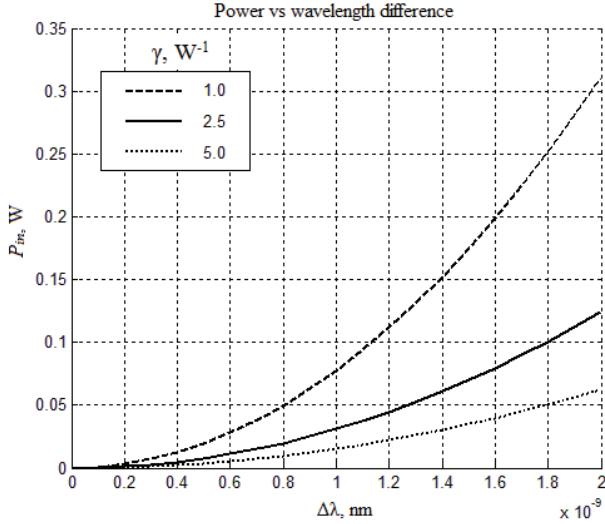


Fig. 1. Input power dependence on source pump wavelength separation at three different OF nonlinear coefficients n_2/A_{eff}

Three lines correspond to three different nonlinear coefficients. From calculation results we can conclude that input power is not linearly related to incident optical beam wavelength separation. At small $\Delta\lambda$ values input power increment is much lower than for larger $\Delta\lambda$ values. This means that in wavelength division multiplexing (WDM) systems FWM is most undesirable for even spaced neighbour channels. But if we want to realize FWM effect, than this graph can be useful for input power level evaluation. Predictably for higher nonlinear coefficient, lower optical power is necessary to gain FWM. For further investigation we will use fibre nonlinear coefficient value $\gamma=2.5 \text{ W}^{-1}$ as it is most common for OF [2].

Simulation schemes and parameters

This paper is based on simulations that was performed by OptSim 5.0 Simulation Platform. We have considered two different FWM realisation schemes and have compared them by achievable nonlinear interaction for different optical power and wavelength separation.

First off all lets view to FWM realization scheme with optical signal polarization rotator (Fig. 2).

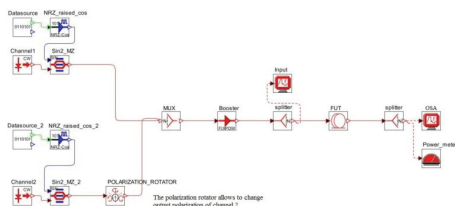


Fig. 2. FWM realization scheme with two optical input sources and polarization rotator

This is classical FWM realisation scheme which employs two optical channels and polarization rotator, that enables possibility to set the 2nd channel output signal polarization state, to match it with other channel signal polarization state [4]. Transmitter part consists of two identical parts that include: laser source with external Mach-Zehnder modulator, electrical signal datasource that act like a pulse pattern generator and is connected to code shaper that forms a NRZ code pulses for modulator electrical high frequency input. Both channels are multiplexed together with optical combiner and amplified by EDFA optical amplifier. After amplifier follows fiber under test (FUT) where nonlinear interaction takes place. The FUT length is 1 km to minimise dispersion produced signal phase mismatch that causes FWM interaction weakening. To estimate FWM effect we use optical spectrum analyzer and optical power meter at the fiber far end. Simulation results uncertainty is in the 5% range.

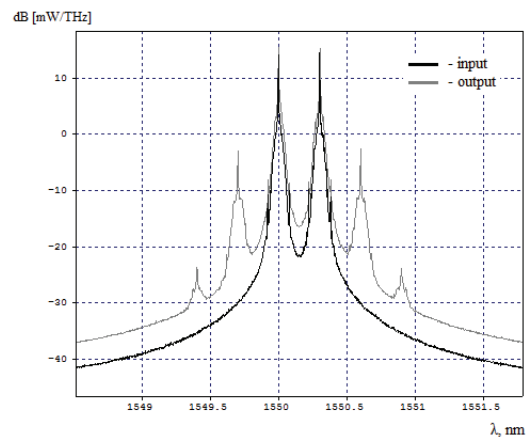


Fig. 3. Input/output signal spectra at $\Delta\lambda=0.3\text{nm}$

Fig. 3 shows superimposed input and output signal spectra from OF. FWM at the fibre output signal spectra appears as a symmetrically located spectral sidebands. The more power is induced in spectral sidebands, the more intense is FWM process [3]. To determine FWM interaction intensity we will use nonlinear coefficient, that describes relation between incident wave and spectral sidebands maximum power.

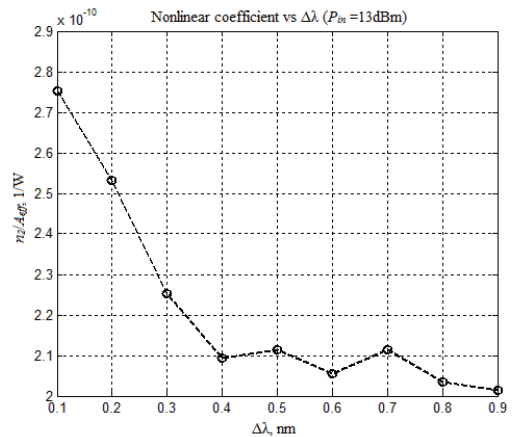


Fig. 4. Nonlinear coefficient dependence on wavelength difference by FWM scheme with two optical channels and a polarization rotator.

Scheme with Amplitude modulated RF signal

Interesting FWM realization scheme is described in publication by Bostjan Batagelj „A simple non-linear coefficient measurement scheme based on Four-Wave Mixing” [5]. Idea is to use one optical source and external modulator that is driven by amplitude modulated RF signal. At the modulator output there are two optical waves with twice the modulation frequency separation due to AM signal characteristics. Main benefit from such a scheme is that output signals are with the same polarisation. So no polarization rotators are necessary [5, 6].

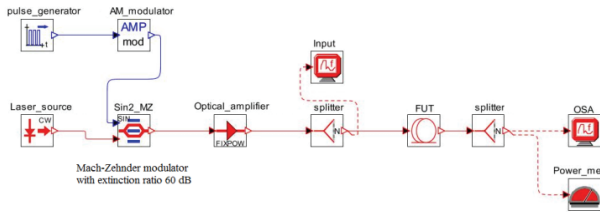


Fig. 5. FWM realization scheme with AM signal

Simulated scheme employs one optical source with wavelength $\lambda=1550.1$ nm and external Mach-Zehnder modulator with extinction ratio set to 60 dB to suppress carrier frequency at the modulator output. Electrical signal source is square pulse generator and its frequency is 10MHz. Electrical amplitude generator forms an AM signal. When changes the AM signal's carrier frequency output optical signal spectral components frequency difference also changes. In our simulations we have set five different modulation frequencies in a range from 5 to 100 GHz to determine achieved nonlinear coefficients dependence on the wavelength difference between initial signals at four different input power levels. FUT parameters are exactly the same as in previous simulation scheme.

In the next four Figs (Figs. 6 till 9) are simulation results for four different input power levels: 13, 16, 19 and 22dBm. As we can see, these results confirm our previous theoretical calculations about FWM interaction in relation to necessary input power at different frequency separations.

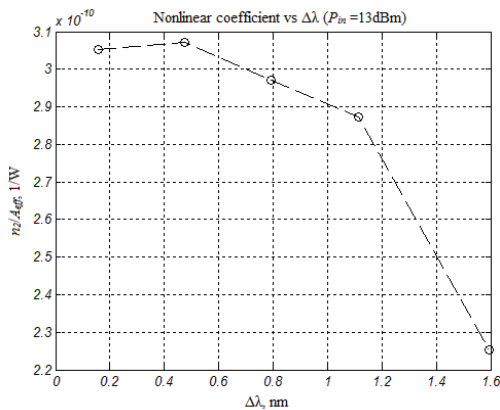


Fig. 6. Nonlinear coefficient dependence on wavelength difference by FWM scheme with AM signal

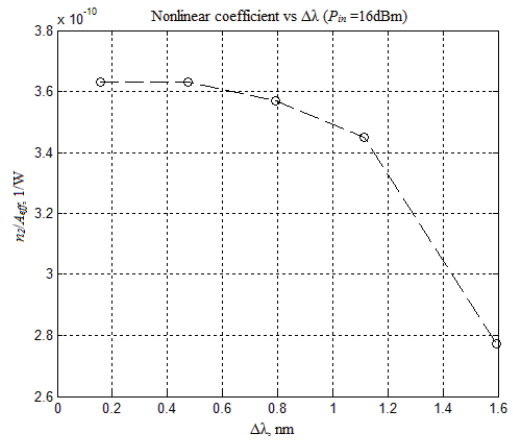


Fig. 7. Nonlinear coefficient dependence on wavelength difference by FWM scheme with AM signal

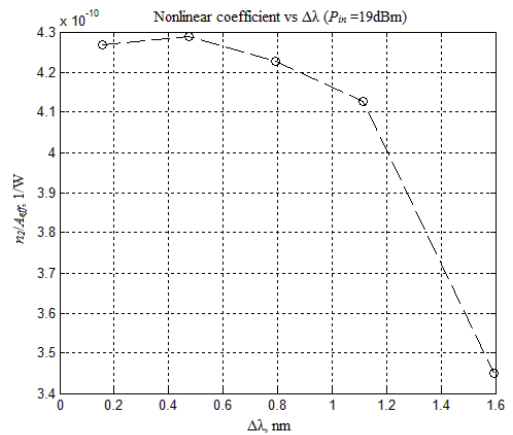


Fig. 8. Nonlinear coefficient dependence on wavelength difference by FWM scheme with AM signal

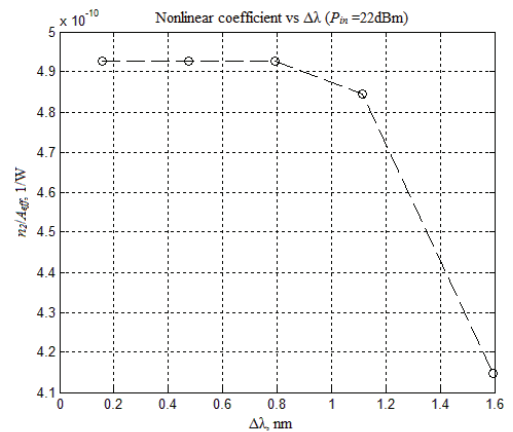


Fig. 9. Nonlinear coefficient dependence on wavelength difference by FWM scheme with AM signal

We can determine that FWM efficiency in the term of nonlinear coefficient is practically constant for a wavelength separations till 0.8 nm. But for larger differences FWM efficiency drops rapidly. This effect is noticeable for different input power levels. At higher input power the FWM intensity is higher, but as it is noticeable from simulation results the dependency on wavelength separation remains almost the same. Achieved graphs

show that this dependence is similar to diminishing exponential connection.

Conclusions

For comparison two different FWM interaction schemes were studied. These schemes are: two optical channel model with polarization rotator and FWM generation by AM modulated RF signal. FWM interaction intensity (that is stated by nonlinear coefficient) relation to the incident pulse wavelength separation is determined by simulation and calculation results.

Achieved results by two different FWM realisation schemes are not quite equivalent. In the case of two channel scheme with polarisation rotator FWM intensity (Fig. 4.) mainly drop till wavelength difference 0.4nm but further decrease is flat. Different results are gained with scheme with AM modulated RF signal. In this case (Figs. 6. till 9.) FWM intensity is changing slowly for wavelength separation till $\Delta\lambda=0.8\text{nm}$ and mostly drop for larger separations. This is as well observed in theoretically calculated results (Fig. 1.).

One of reasons for difference in results could be slightly different input optical signals wavelength as follows a slightly different dispersion coefficients. These small differences in wavelength utilization is related with simulation characteristics in each simulation scheme case. But one of the main reasons from our opinion is that AM modulated signal scheme provides better phase matching between generated optical waves as for FWM process it is an important condition. So scheme with AM modulated RF signal is more suitable to generate FWM nonlinear interaction in OF.

Results show as well that FWM process is dependent on input optical signal power, but at the same time conserves almost unchanged dependence on a pump wavelength separation (Fig. 6–Fig. 9).

Achieved results can be used to avoid or to realize FWM nonlinear interaction in OF. We are planning to perform the same measurements experimentally for different optical fibres.

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This paper describes detailed study in optical fibre nonlinear phenomenon – four wave mixing (FWM). It includes explanation of physical reason and realisation methods in optical fibres. Comparison of two generation schemes in terms of realizing FWM process in optical fibres has given. Results between theoretical calculations and simulation results by OptSim 5.0 software show that FWM interaction intensity is almost invariable for wavelength separation between incident waves till $\Delta\lambda=0.8\text{ nm}$. But for larger wavelength separation it sharply decrease. Ill. 9, bibl. 6 (in English; abstracts in English and Lithuanian).

A. Supe, J. Porins. Keturbangiu postūmiu optiniuose kabeliuose pritaikymo metodų palyginimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 5(111). – P. 37–40.

Aprašomi optiniuose kabeliuose vykstantys netiesiniai reiškiniai, kuriuos sukelia keturbangiai postūmiai. Teoriniai ir praktiniai eksperimentai įrodo, kad postūmiai neturi reikšmės, kai žadinimo bangų ilgio skirtumai neviršija $\Delta\lambda=0,8\text{ nm}$, tačiau gerokai išauga minėtam skirtumui didėjant. Il. 9, bibl. 6 (anglų kalba; santraukos anglų ir lietuvių k.).