ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
Fakulta elektrotechnická

BAKALÁŘSKÁ PRÁCE

2014 **Dmytro Suslov**

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
Fakulta elektrotechnická
Katedra telekomunikační techniky

Aplikace čtyřvlnného směšování v celooptických sítích

květen 2012

Bakalant: Dmytro Suslov
Vedoucí: doc. Ing. Stanislav Zvánovec, Ph.D.
Školitel: Ing. Matěj Komanec, Ph.D.

Čestné prohlášení

Prohlašuji, že jsem zadanou bakalářskou práci zpracoval sám s přispěním vedoucího práce a konzultanta a používal jsem pouze literaturu v práci uvedenou. Dále prohlašuji, že nemám námitek proti půjčování nebo zveřejňování mé bakalářské práce nebo její části se souhlasem katedry.

Datum: 25. 5. 2014

……………….……………………

podpis bakalanta

zadání

Anotace

V této bakalářské práci analyzuji účinky čtyřvlnného směšování a jeho využití v celooptických sítích. V teoretické části diskutuji vlastnosti čtyřvlnného směšování a souvisejících jevů, jako je Brillouinův rozptyl a Kerrův efekt. Také se zabývám praktickým využitím čtyřvlnného směšování pro multicast a v parametrickém zesilovači. V praktické části pak testuji čtyřvlnné směšování a multicast a to jak v měřeních, tak i prostřednictvím simulaci.

Summary

This bachelor thesis studies the effects of four-wave mixing and its application. In theoretical part, properties of four wave mixing and its subsequent phenomena, such as stimulated Brillouin scattering and Kerr effect are studied. Then application in multicasting and parametric amplification is given. In practical part four wave mixing and multicasting, both via practical measurements and simulations is then examined.

Content:

Abbreviations:

GVD	Group Velocity Dispersion
ZDWL	Zero Dispersion Wavelength
SPM	Self-Phase Modulation
HNLF	Highly Non-Linear Fiber
FWM	Four-Wave Mixing
DFWM	Degenerate Four-Wave Mixing
FOPA	Fiber-Optic Parametric Amplifier
SOA	Semiconductor Optical Amplifier
EDFA	Erbium-Doped Fiber Amplifier
SBS	Stimulated Brillouin Scattering
OSA	Optical Spectrum Analyzer

1. Introduction

In the modern era of communications one of the most important aspects is the capacity of communication channel and its transparency towards transferred data (its format). Therefore fiber optics introduces one of the most significant medium for high speed and high capacity data transfer. Almost all (originally metallic) backbone networks are completely substituted by optical networks. Including signal regenerators, that also work in the optical domain. Such solution means advantage in speed and capacity of data channel.

Optical data transfer is in its nature different than transfer through metallic medium and therefore in this thesis I will study all-optical networks and related phenomena, especially nonlinear effects in fiber optics.

In this work I focus on four wave mixing (FWM). In theoretical part I will describe phenomena connected with FWM. This fundamental knowledge will be further required to understand application of FWM. In application based chapter I will study three applications – parametric amplification, all-optical wavelength conversion and multicasting. Measurements will afterwards verify the multicasting application with focus on stimulated Brillouin scattering suppression, channel allocation, polarization and pump setup.

2. Theoretical background

In this chapter I will study FWM and phenomena of chromatic dispersion, Kerr effect, stimulated Brillouin scattering (SBS) the chapter will be concluded with brief description of nonlinear fibers.

2.1 Chromatic Dispersion

Dispersion causes widening of optical pulse which can cause problems especially with further detection or processing of the given signal. In this chapter I will only cover chromatic dispersion as it represents the most important influence of single mode fibers (SMF). Chromatic dispersion is composed of two components, material dispersion and waveguide dispersion.

The nature of material dispersion lies in variability of refraction index, which is wavelength dependent. Optical pulse launched into an optical fiber does not have a single (chromatic) wavelength, but consists of a span of wavelengths – characterized by spectral width $\Delta\lambda$ – and therefore each of these wavelengths propagates in different index of refractivity. This dispersion causes broadening of pulse in time domain [1, 2]:

$$\Delta T = DL\Delta\lambda \tag{2.1.1}$$

where D is dispersion parameter, L is fiber length and $\Delta\lambda$ is spectral width generated by the optical source. For dispersion D it applies [1]:

$$D = -\frac{2\pi c}{\lambda^2}\beta_2 \tag{2.1.2}$$

where β_2 is the Group Velocity Dispersion (GVD), Dispersion slope $S = \frac{\partial D}{\partial \lambda}$ and can be written as [1]:

$$S = \left(\frac{2\pi c}{\lambda^2}\right)\beta_3 + \left(\frac{4\pi c}{\lambda^3}\right)\beta_2 \tag{2.1.3}$$

It is important to note, that for optical fibers there are certain wavelengths for which chromatic dispersion can be equal to zero. These wavelengths are called zero dispersion wavelengths (ZDWL). For conventional silica-based optical fibers such wavelength is positioned around 1300nm [2]. Entire situation is demonstrated in figure 2.1.1:

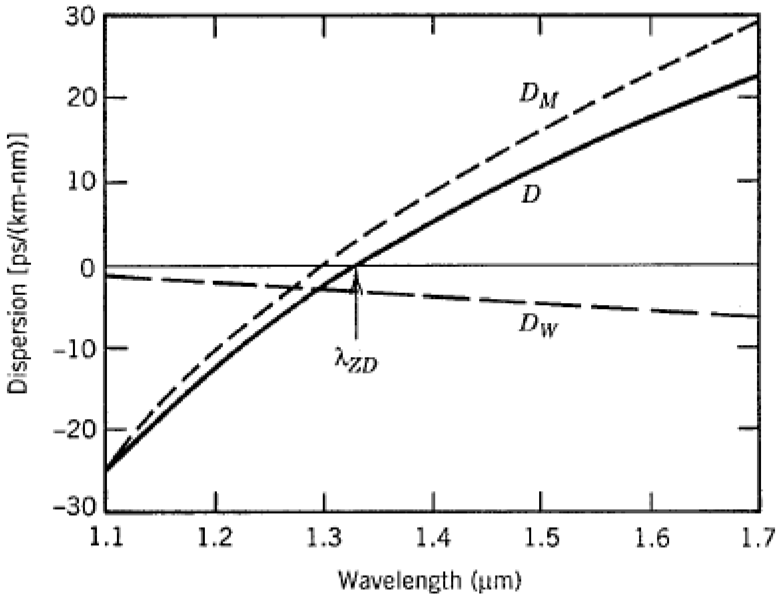

Fig 2.1.1: Chromatic dispersion and its components, waveguide dispersion D_W and material dispersion D_M [2].

2.2 Kerr Effect

In practice refractive index is not only frequency dependent, but also depends on optical power (or intensity of light) [1]. As a result, optical fibers exhibit nonlinearity when increasing optical power (optical intensity). For refractive index applies [2]:

$$n = n_1 + n_2 I \tag{2.2.1}$$

Where n_1 is frequency dependent component and n_2 is nonlinear component of refractive index that depends upon light intensity I. Therefore the signal itself will change refractive index of medium in which it propagates based upon its own intensity. Nonlinear coefficient γ describing the magnitude of this effect can be defined as [1]:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{2.2.2}$$

Where A_{eff} is effective fiber area. For conventional silica based fibers γ is in order of 1 – 5 $W^{-1}km^{-1}$. Nonlinear part of refractive index n_2 is much smaller than linear (n_2 is in order of 10^{-20} [2]) and therefore at smaller intensities can be neglected [2].

2.3 Self-Phase Modulation

Self-Phase Modulation (SPM) is a nonlinear effect that is directly resulting from the Kerr effect. Kerr effect also influences the propagation constant β', that in turn is dependent upon optical power [2].

$$\beta' = \beta + k_0 n_2 \frac{P}{A_{eff}} = \beta + \gamma P \quad (2.3.1)$$

Therefore change in the refractive index causes nonlinear phase shift Φ_{NL}, given as [2, 1]:

$$\Phi_{NL} = \int_0^L (\beta' - \beta) dz = \gamma P L \quad (2.3.2)$$

Because signal modulates refractive index of material it passes and thus influence by amplitude its own phase, this phenomena is called Self-Phase Modulation. This phase modulation also cases a frequency chirp, that is dependent on the shape of pulse propagating through fiber and generally causes pulse broadening [2].

2.4 Four-wave mixing

Four-wave mixing (FWM) is a nonlinear phenomenon in which at least two optical signals are fed in a nonlinear medium. It results in generation of new optical signals at wavelengths different of the two input signals [4].

If three optical signals are launched into a fiber with frequencies ω_1, ω_2 and ω_3 they will interact with each other and a new signal will emerge at ω_4 that is called idler [1]. For these signals it applies $\omega_1 + \omega_2 = \omega_3 + \omega_4$ [2]. Interaction of these three (four) signals can result in a large number (M) of newly created idlers at differences of frequencies of original signals [1]. We can receive a number of newly created idlers by solving [1]:

$$M = \frac{(N^3 - N^2)}{2} \quad (2.4.1)$$

where N is number of optical signals sent into fiber.

If two pump signals are frequency matched ($\omega_1 = \omega_2$) then phenomena is called degenerate four-wave mixing (DFWM) [3].

In case of DFWM where ω_1 and ω_2 are degenerated and $\omega_1 = \omega_2 = \omega_p$ (they have same frequency but different wave vector [4]) then $\omega_3 = \omega_s$ will force pump to give one photon to signal ω_s and one to idler ω_i [1]. As result exchange of energy occurs. Whole situation can be seen in figure 2.4.1.

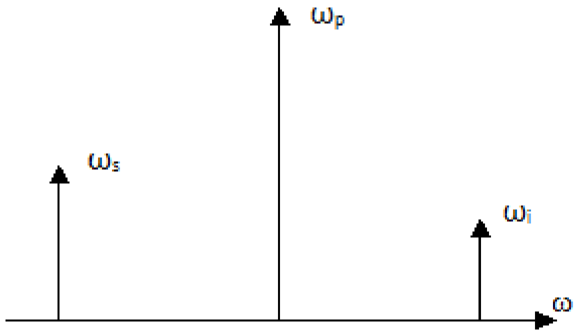

Fig. 2.4.1: Degenerated four-wave mixing

These three signals (waves) can be described by their field intensities as [1]:

$$E_{(x,y,z)} = f(x,y)\frac{1}{2}\left[A_p(z)\exp(i\beta_p z - i\omega_p t) + A_s(z)\exp(i\beta_s z - i\omega_s t) + A_i(z)\exp(i\beta_i z - i\omega_i t) + c\right] \quad (2.4.2)$$

By applying nonlinear Schrödinger equation to amplitudes *A(z)* we can receive expressions [1]:

$$\frac{dA_p}{dz} = i\gamma\left[\left(\left|A_p\right|^2 + 2(|A_s|^2 + |A_i|^2)\right) A_p + 2A_sA_iA_p^*\exp(i\Delta\beta z)\right] \quad (2.4.3)$$

$$\frac{dA_s}{dz} = i\gamma\left[\left(|A_s|^2 + 2(\left|A_p\right|^2 + |A_i|^2)\right) A_s + A_i^*A_p^{2*}\exp(-i\Delta\beta z)\right] \quad (2.4.4)$$

$$\frac{dA_i}{dz} = i\gamma\left[\left(|A_i|^2 + 2(\left|A_p\right|^2 + |A_s|^2)\right) A_i + A_s^*A_p^{2*}\exp(-i\Delta\beta z)\right] \quad (2.4.5)$$

Where $A_p(z)$ is amplitude of pump signal, $A_s(z)$ is amplitude of signal at ω_s and $A_s(z)$ is amplitude of signal of created idler. $\gamma = \frac{\omega_p}{c}\cdot\frac{n2}{A_{eff}}$ is nonlinear coefficient [3] and $\Delta\beta$ is difference of propagation constants [3]:

$$\Delta\beta = \beta_s + \beta_i - 2\beta_p \quad (2.4.6)$$

2.5 Stimulated Brillouin scattering

Stimulated Brillouin scattering (SBS) converts transmitted light launched into fiber into counter-propagating lightwave with Stokes-shift (down shifted) frequency [1, 2, 7]. Frequency downshift is around 10 – 14 GHz [1, 2]. SBS is caused by excited co-propagating acoustic wave due to of nonlinearity caused changes in the material density with applied high optical power. It is a process where material becomes more compressed when electric field is present. Such process is called electrostriction [2].

SBS is dominant optical fiber nonlinearity [7]. Intensity of light scattered through SBS increases exponentially after power threshold needed for SBS to occur is reached [2]. Power threshold is described in [1]:

$$P_{th} = \frac{21kA_{eff}}{g_0L_{eff}}\left(\frac{\Delta\nu_B+\Delta\nu_P}{\Delta\nu_B}\right) \tag{2.5.1}$$

where k is polarization factor between 1 and 2, $A_{eff}$is effective fiber area, g_0 is Brillouin gain coefficient, $L_{eff}$is effective interaction length, $\Delta\nu_B$is Brillouin line width and $\Delta\nu_P$is pump spectral light.

SBS induces limitation to optical communication systems by reducing maximum usable power. These limitations mainly apply to amplifiers (such as parametric amplifiers or Raman amplifiers) and lasers [7]. High power is also needed for transparent wavelength conversion and efficient phase conjugation [1]. Effects of SBS on signal power can be seen in figure 2.5.1 [8]:

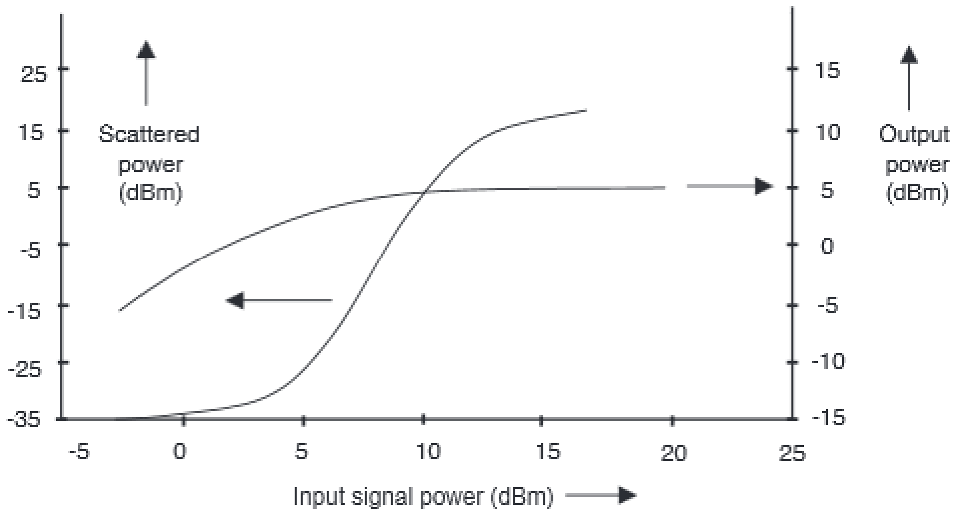

Fig 2.5.1: Effect of SBS on signal power [8].

SBS can be suppressed by broadening spectrum width (which reduces overall power in carrier wave) [7], as can be seen in equation 2.5.1, and such technique is very common [1, 7]. However such approach is limited by dispersion limitation given by spectrum broadening.

Power threshold is also dependent upon data format – for instance a single pulse with short width would not induce SBS, contrary to a bit stream. Typical value of SBS power threshold is ~5 mW [2].

2.6 Nonlinear fibers

As described in Chapter 2.2, nonlinearity of the optical fiber is dependent on intensity of optical signal (optical power) and the magnitude of the nonlinearity can be described by (2.2.2). Highly Nonlinear Fibers (HNLFs) are developed to enhance the use of nonlinear effects (such as Four-wave mixing).

HNLF has higher nonlinearity coefficient γ than ordinary fibers and can reach an order of $30W^{-1}km^{-1}$ [1]. As equation (2.2.2) implies to reach higher nonlinearity we either have to use different material (and as result change refractive index) or change construction of optical fiber (change A_{eff}).

To change refractive index we can dope core with i.e. GeO_2 [1]. Dispersion shifted HNLF with shifted ZDWL to wavelengths around 1550 nm have been developed. They are manufactured by doping both core and cladding. Such solution can have a disadvantage of higher fiber attenuation [1]. Profile of refractive index of such fiber can be seen in figure 2.6.1:

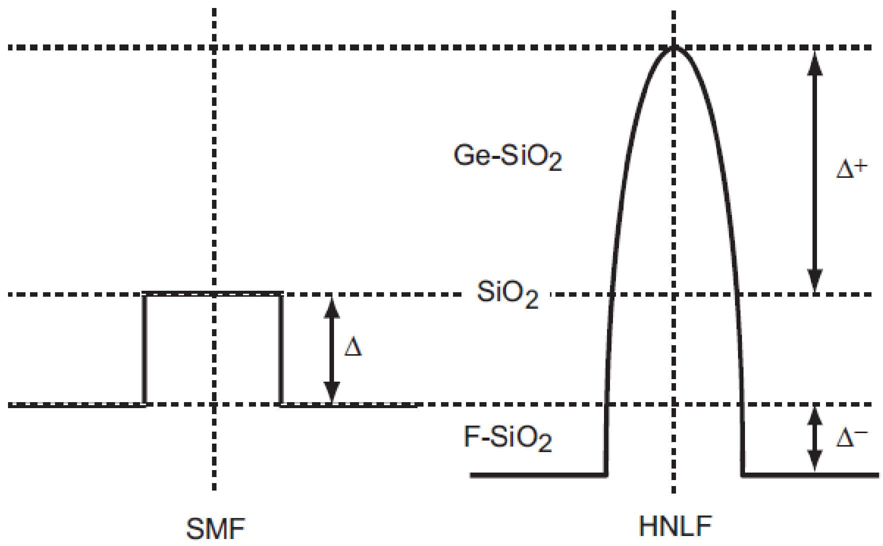

Fig. 2.6.1: Profile of refractive index of SMF and HNLF [1].

Second possibility is to decrease A_{eff} which is more complicated as it becomes more difficult to couple signal into a fiber with narrower A_{eff} (reason stands in smaller numeric aperture). It is also more challenging to manufacture such fiber as it requires more precise drawing process. Both doping of core and reduction of A_{eff} are used in HNLF [1].

Another method to acquire high nonlinearity coefficient γ is to use specialty optical fibers. Such fibers can be i.e. microstructured fibers [1]. Microstructured fibers have small air holes in the cladding. By using such fibers and changing the configuration of air holes, their size and distance between them or by doping core we can achieve fibers with both high coefficient γ and large enough A_{eff} to be able to easily couple signal into fiber. Their disadvantage however lies in attenuation [1].

3. Applications

In this chapter I will extend theoretical background of previous chapter. I will study possible applications of FWM that are relevant for this bachelor thesis. Between these applications belong parametric amplification, all-optical wavelength conversion and multicasting.

3.1 Parametric amplifier

Parametric amplifier is a device capable of i.e. amplification, wave conversion or time division demultiplexing [1, 6]. Fiber-Based Optical Parametric Amplifiers (FOPAs) are based on FWM effect. Advantage of such application is simple construction consisting of pump, input signal (data) and a length of highly nonlinear fiber (HNLF) [6]. Schematics can be seen in figure 3.1.1:

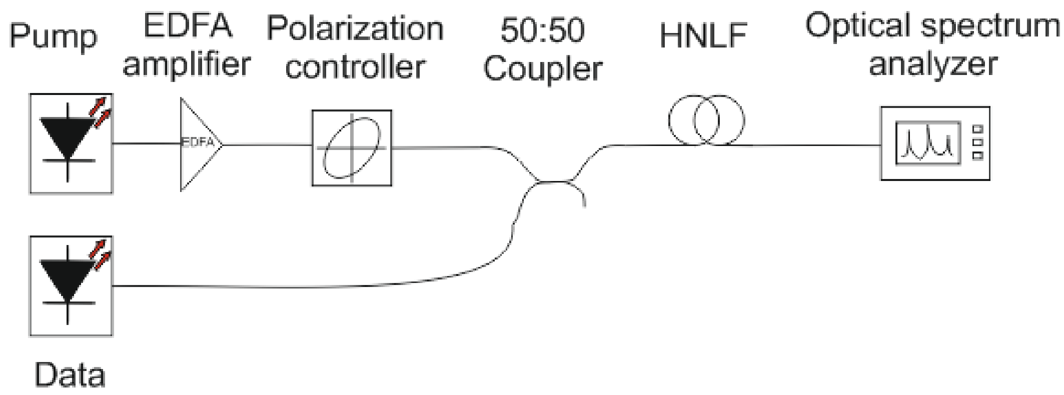

Fig. 3.1.1: Construction of FOPA amplifier

FWM will occur in nonlinear media and in this case in HNLF. Because there are two input signals DFWM will occur. Similar situation is demonstrated in figure 2.4.1. Amplification itself will occur by pump transferring one photon to signal and one to idler from the pump signal [1, 6].

Therefore degree of amplification is highly dependent upon power of the pump. For this reason it is common to amplify pump signal with EDFA amplifier. Because of high power of pump signal a problem with stimulated Brillouin scattering will limit the use of amplifier. Therefore it is required to suppress SBS by i.e. phase modulating pump signal [6].

Degree of amplification is also dependent upon phase matching of both signals (data and pump). Signals that are phase matched are amplified most whereas other signals are attenuated. This technique is especially useful for noise suppression.

Advantage of such amplifier is high amplification (up to 70dB) [1]. Another advantage is fast response time that is shorter than 10 fs [1. 6].

3.2 All-optical wavelength conversion

Wavelength conversion is a process in which signal with given wavelength is converted into signal with a different wavelength [2]. There are several methods for wavelength conversion, but I will address only wavelength conversion using FWM.

In this process properties of FWM are used, especially newly created idler that is a copy of original signal [1]. Whole system is than consisted of semiconductor amplifier (or another nonlinear media) into which pump signal (ω_p) and data signal (ω_s) we want to convert, are launched.

After FWM will occur a filter is used that will filter all signals except one converted [2]. Schematics of entire system can be seen in figure 3.2.1:

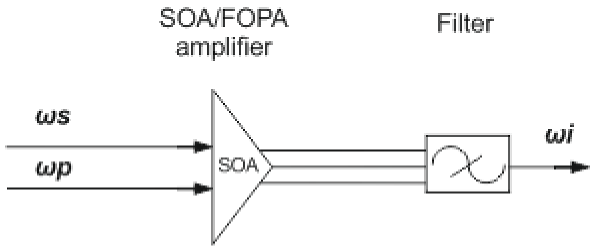

Fig. 3.2.1: Wavelength conversion using FWM, SOA (Semiconductor Optical Amplifier)/FOPA (Fiber Optical Parametric Amplifier)

In this process data signal ω_s and pump signal ω_p are lunched into amplifier. Because of nonlinear environment DFWM will occur. Converted signal is then idler ω_i. Pump wavelength is used to control converted wavelength. Therefore [2]:

$$\omega_p = \frac{\omega_{s+}\omega_i}{2} \tag{3.2.1}$$

If semiconductor amplifier is used, nonlinearity is caused by fast intraband relaxation (shorter than 0.1 ps). As a result it is possible to receive a frequency shift up to 10 THz (a wavelength shift over 80 nm). Because of that it is possible to achieve a bit rate up to 100 Gb/s. Another advantage is high conversion efficiency, where with use of amplifier it is even possible to achieve signal amplification [2].

If HNLF is used as FOPA amplifier it is possible to achieve up to 60 nm wavelength shift [1]. Another advantage is data transparency and wavelength conversion is bit rate independent, which is caused by FOPA fast response time [1].

Disadvantage of wavelength conversion using FWM can be usage of tunable laser and high attenuation while coupling pump and data signal into amplifier for conversion [2].

3.3 Multicasting

Multicasting is a method when the input data signal is copied and transmitted to multiple outputs at once. Here I will address only multicast method using wavelength multiplexing (WDM) based on FWM. In this case one signal of given wavelength is copied to several wavelengths [5].

For wavelength multiplex an all-optical wavelength conversion is used using properties of FWM [5]. Similar to Chapter 3.2, here we also need to use nonlinear media such as SOA or HNLF. At the output of amplifier we will receive original signal and as its copy, idler [1, 5]. In this case again DFWM is used. It has been proven that 1x16 multicast is possible with data rates up to 40 Gb/s NRZ (Non Return to Zero). However such solution present a problem where 16 lasers have to be used and signal phase is not preserved [5].

Another solution can be using FWM, where two pumps and a signal are converted to several wavelengths. It has been achieved 1x6 multicast with data speed up to 10 Gb/s while preserving signal phase. This method produces nine idlers altogether, but only six preserve phase information [5].

4. Experimental campaign

In this part I will verify the application of FWM for multicasting. At first a simple FWM setup will be measured and then I will further optimize this setup for better performance. Then I will verify effects of SBS and SBS frequency modulation as its suppression.

4.1 Measurement configuration

In these measurements I focused on FWM in real conditions and then further tuned laser and system setup to improve performance. Since there is a possibility of damaging an optical-spectrum analyzer (OSA), I had to use optical attenuator. This does not affect FWM, but it will affect its visualization by OSA.

Setup was as follows. I used a single tunable laser (TL) with multiple outputs one being pump signal at 16 dBm, one being and data signal at 6 dBm. Pump signal was polarization controlled (PC) and both signals were then coupled in a 50:50 coupler connected to HNLF. Output was then attenuated by a 99:1 coupler (20 dB) and displayed by OSA. Each component was also separately measured to obtain precise information about their insertion losses. As power source I used tunable laser ID-Photonics Cobrite DX and optical spectrum analyzer EXFO F13 -500. Entire measurements scheme with components insertion losses can be seen in figure 4.1.1:

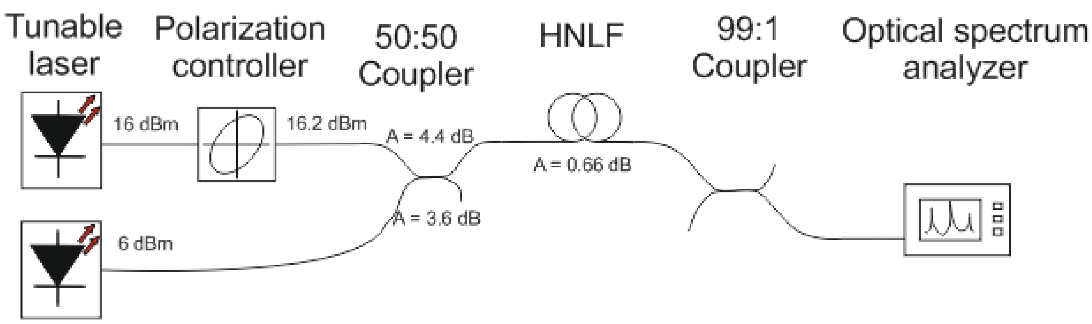

Fig. 4.1.1: Basic measurement setup with actual components attenuation

When measured with this setup DFWM was obvious and therefore I focused on improving performance. First was to establish proper wavelengths and relative position of pump and data signals to have optimal power of idler signal. To achieve that I tuned polarization controller to reach highest idler power and then continued with tuning wavelength of both pump and data signal. Results of basic DFWM with one pump and one data signal can be seen in figure 4.1.2 (note that these results are 20 dB attenuated):

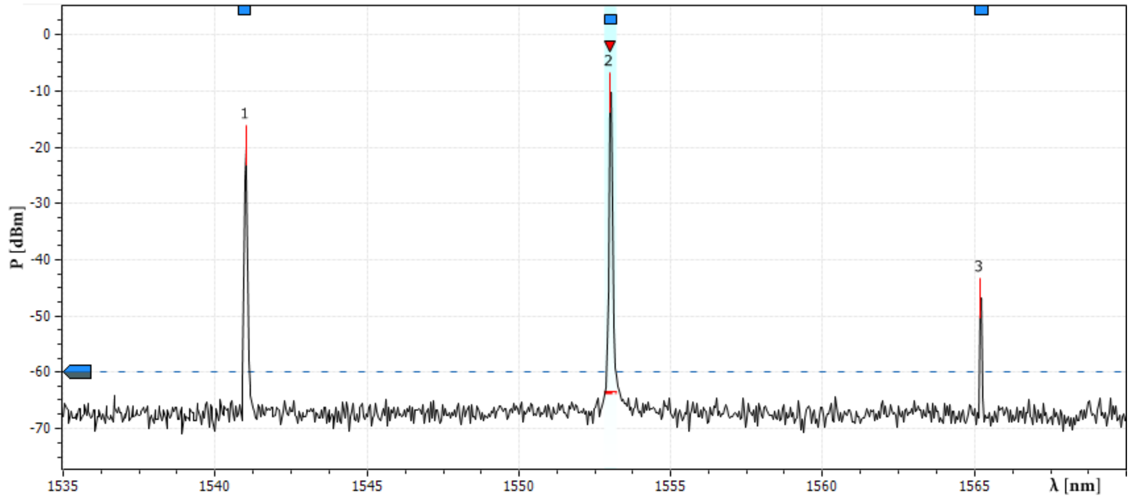

Fig. 4.1.2: Basic FWM with one pump one data signal and created idler

Measurements results can be seen in table 4.1.3:

Pump signal wavelength [nm]	Data signal wavelength [nm]	Idler signal wavelength [nm]	Idler signal power [dBm]
1553	1552	1554	-23.41
	1551	1555	-23.43
	1550	1556	-23.50
1554	1553	1555	-23.33
	1552	1556	-23.44
	1551	1557	-23.44
1555	1554	1556	-23.49
	1553	1557	-23.46
	1552	1558	-23.54
1556	1555	1557	-23.31
	1554	1558	-23.46
	1553	1559	-23.43
1557	1556	1558	-23.57
	1555	1559	-23.51
	1554	1560	-23.57
1558	1557	1559	-23.57
	1556	1560	-23.63
	1555	1561	-23.62
1559	1558	1560	-23.69
	1557	1561	-23.69
	1556	1562	-23.88
1560	1559	1561	-23.74
	1558	1562	-23.89
	1557	1563	-23.85
1561	1560	1562	-23.85
	1559	1563	-23.81
	1558	1564	-23.92
1562	1561	1563	-23.88
	1560	1564	-23.97
	1559	1565	-23.96
1563	1562	1564	-23.95
	1561	1565	-23.95
	1560	1566	-23.98
1564	1563	1565	-24.02
	1562	1566	-24.07
	1561	1567	-24.07

Table 4.1.3: Results of basic FWM setup.

From results it appeared that ZWDL for this fiber was at 1556 nm. Therefore I used it as reference for further measures.

Next part was to determine position of data signal relative to optimal position of pump signal. For that purpose pump was set to fixed 1556 nm and I was only tuning data signal wavelength. From measurements taken it can be seen that optimal data signal position was at 1555 nm. Measurements results can be seen in table 4.1.4:

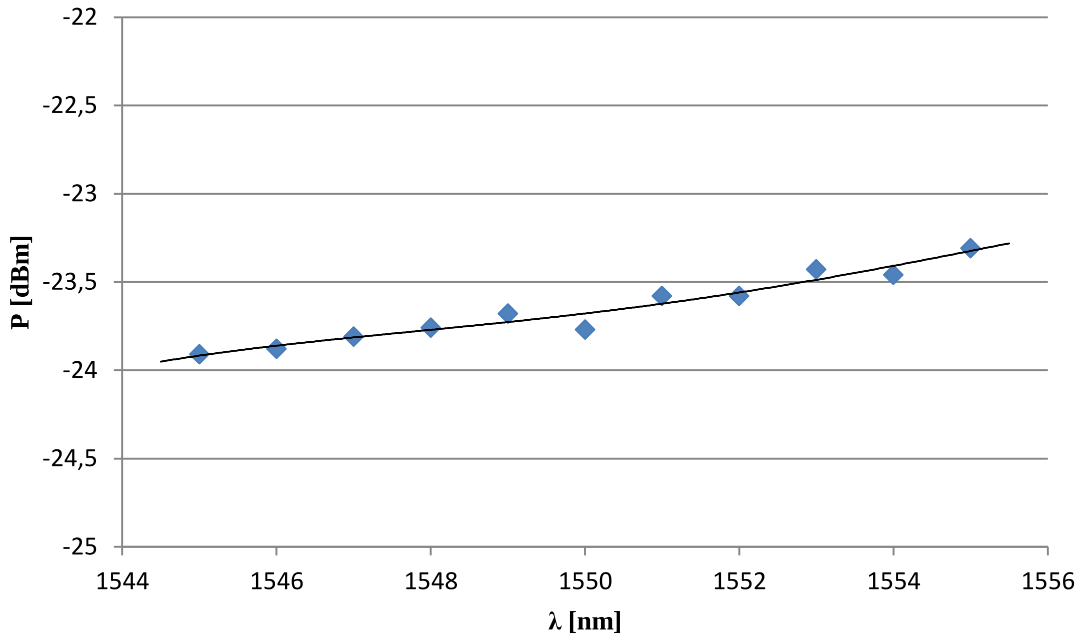

Table 4.1.4: Idler's strength dependency on the position of the data signal with respect to the pump signal

From the progression of the idler signal it was obvious that the closer the two signals are, the better their given product is. Therefore I carried out another measurement with longer separation of 12 nm between data signal and pump signal to determine if separation between two signals in previous measurement was affecting the resulting idler's strength or if idler's strength was more affected by distance from ZWDL. Results of that measurement can be seen in table 4.1.5:

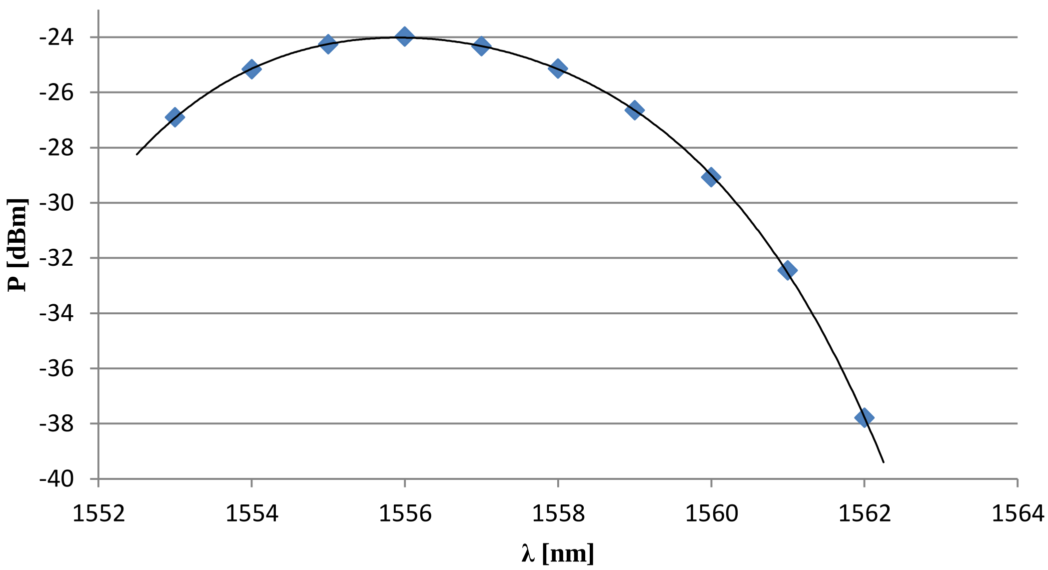

Table 4.1.5: Idler's power dependent on wavelength separation from ZWDL

From results of the two previous measurements I deducted that chosen separation (12 nm) between data signal and pump signal has small effect on resulting product (for chosen distance) while placement of signal near ZWDL is crucial for optimal idler signal power.

4.2 Effect of stimulated Brillouin scattering

Since SBS is of major concern with parametric amplifiers I tested its effect and effect of SBS suppression. Laser that I used included internal signal modulation up to 1000 MHz that suppressed SBS. To measure SBS I had to modify previous setup and include another coupler, a power meter and an EDFA amplifier. In this case pump and data signals are set to 6 dBm. EDFA amplifier would amplify pump signal to 20 dBm. Both signals would be merged by previously used 50:50 coupler and then sent through 99:1 coupler to HNLF. 99:1 coupler is used to measure SBS as there is power meter connected to 1% input and would measure power returning from HNLF. This power would be 20 dB attenuated. As previously new components were each tested for their insertion loss. Entire measurement scheme with component insertion losses can be seen in figure 4.2.1:

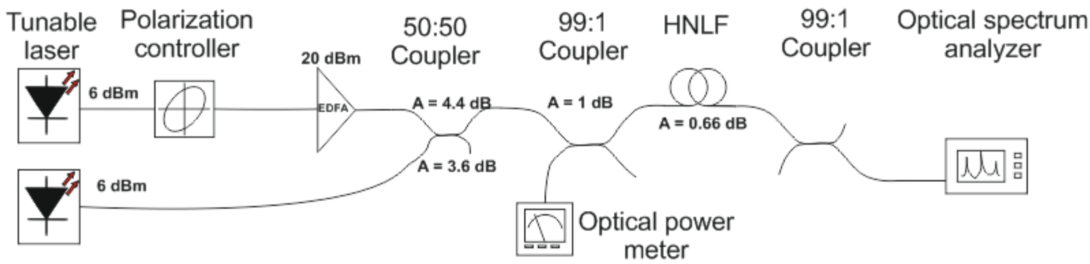

Fig. 4.2.1: Setup for SBS measuring with 6 dBm data signal power.

Measurement results can be seen in table 4.2.2:

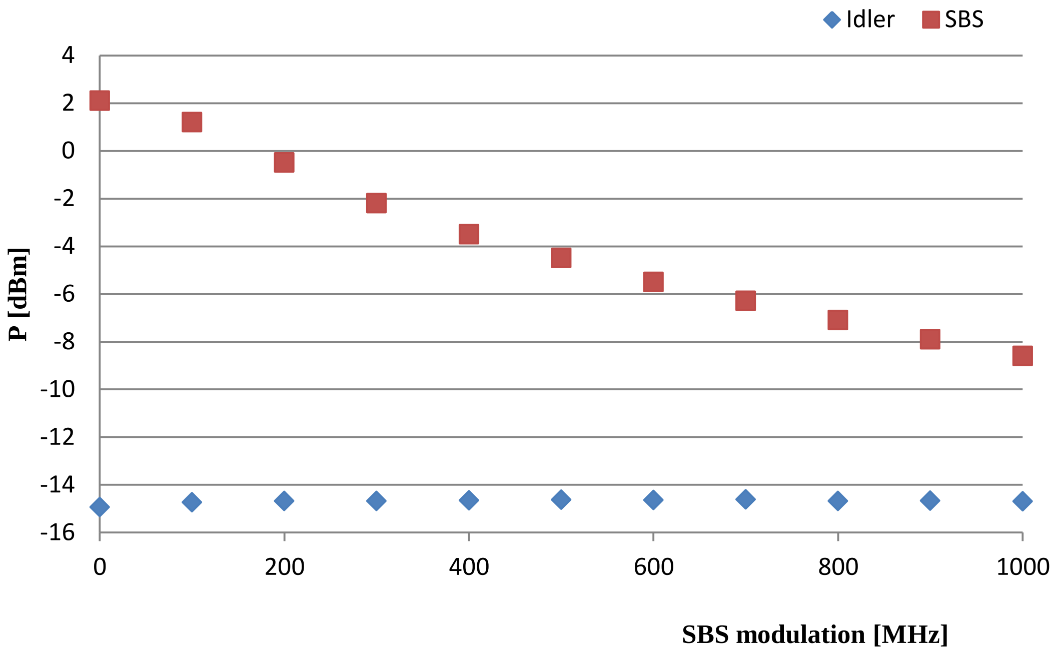

Table 4.2.2: Effect of SBS with 6 dBm data signal

Results show that SBS suppression works as SBS power is attenuated from 2.41 dBm to -7.59 dBm. However SBS itself is not an issue as there is only 0.24 dB gain between no SBS suppression and best possible SBS suppression. That is possibly a result of low power of either pump or data signal. Therefore I modified the setup to allow higher data signal power.

For that, data signal is set to 16 dBm and first 50:50 coupler is replaced by 99:1 coupler with insertion loss of 0.2 dB. Rest of the setup is the same. Entire setup can be seen if figure 4.2.3:

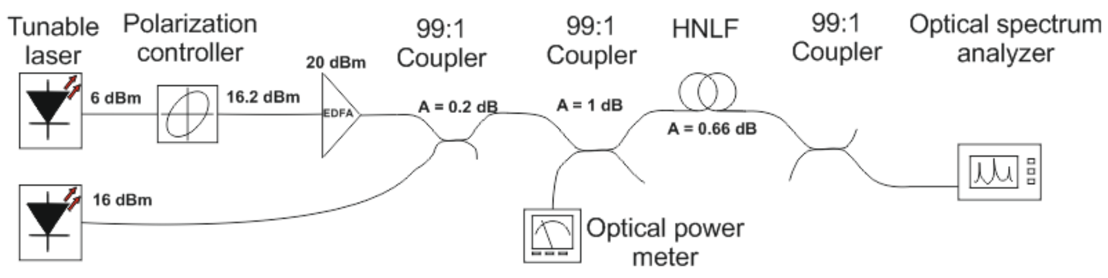

Fig. 4.2.3: Setup for SBS measuring with 16 dBm data signal power.

Measurements results can be seen in table 4.2.4:

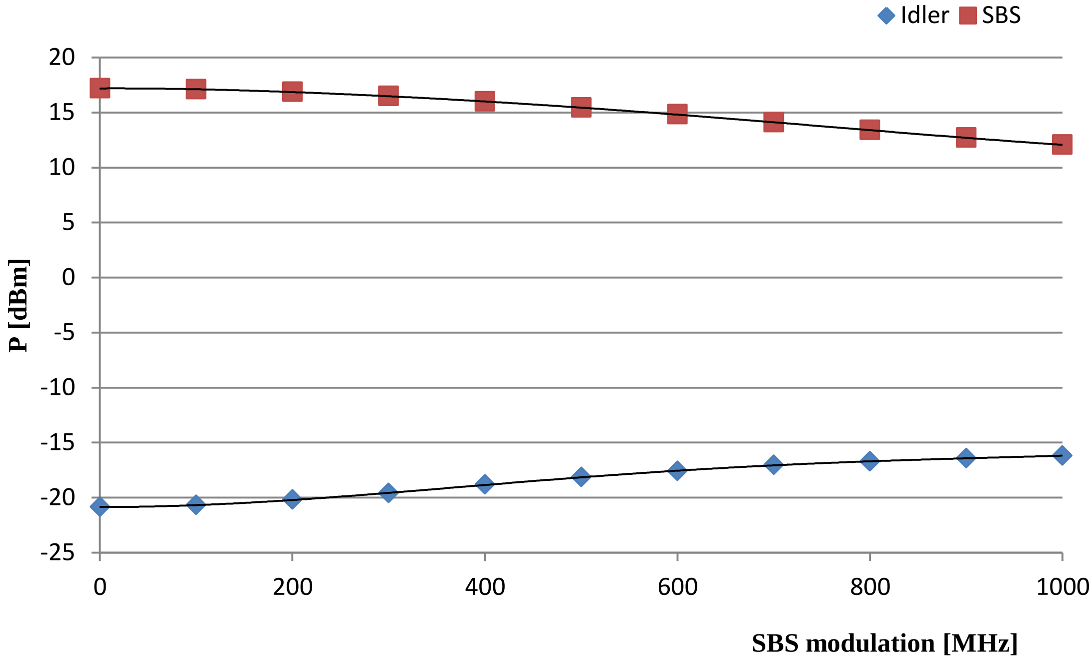

Table 4.2.4: Effect of SBS with 16 dBm data signal

As can be seen from results, power attenuation of SBS suppression is the same as in previous case but the power magnitude of SBS is much higher, resulting in attenuation of idler signal. Therefore SBS suppression is required as it has improved signal by 4.66 dB.

Along with SBS it became apparent that FWM is working surprisingly well and therefore I made measurements to determine how idler's strength would deteriorate with distance between pump and data signal. For that purpose I used setup as can be seen in figure 11.1 with fixed position of pump at 1556 nm. Then I tuned data signal and noted idler's strength. Results can be seen in table 4.2.5:

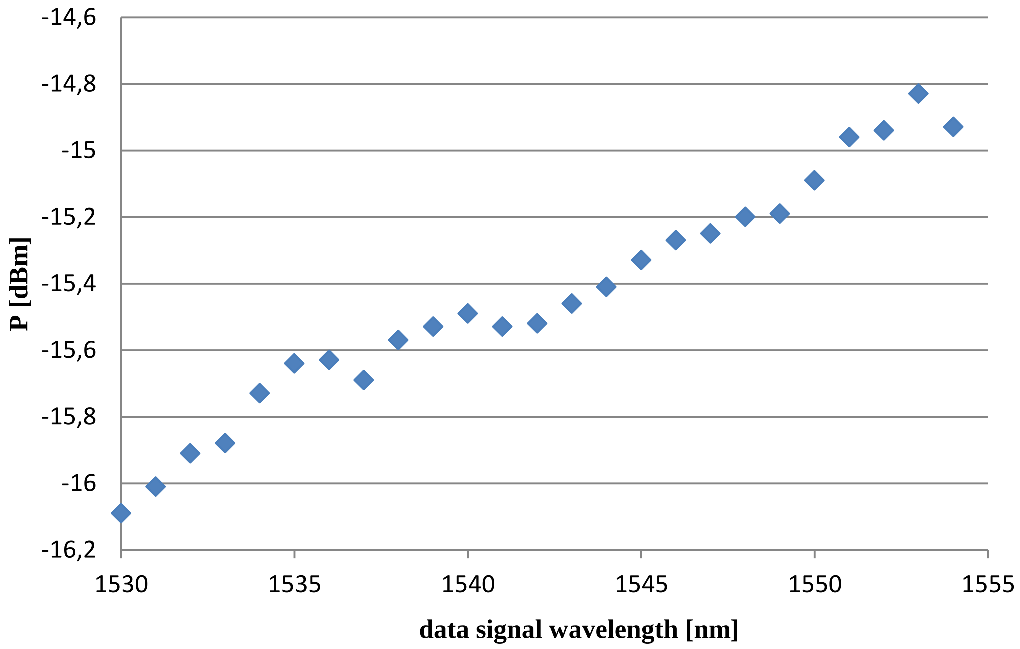

Table 4.2.5: Effect of distance between pump and data signal on idler's power level

4.3 Multicasting

For multicasting I used two pump signals and one data signal. For pump signals I used tunable laser ID-Photonics Cobrite DX and laser diode for data signal. Both pump signals are set to 6 dBm and coupled in a 50:50 coupler with 3.57 dB insertion loss. They are then amplified to 20 dB with EDFA amplifier and coupled with data signal set to 16 dBm in 99:1 coupler with insertion loss of 0.2 dB. This coupler is then connected to another 99:1 coupler with insertion loss of 1 dB. That coupler is then connected to HNLF and output of HNLF is attenuated by 99:1 coupler and sent into OSA. Entire measurement scheme with component insertion losses can be seen in figure 4.3.1:

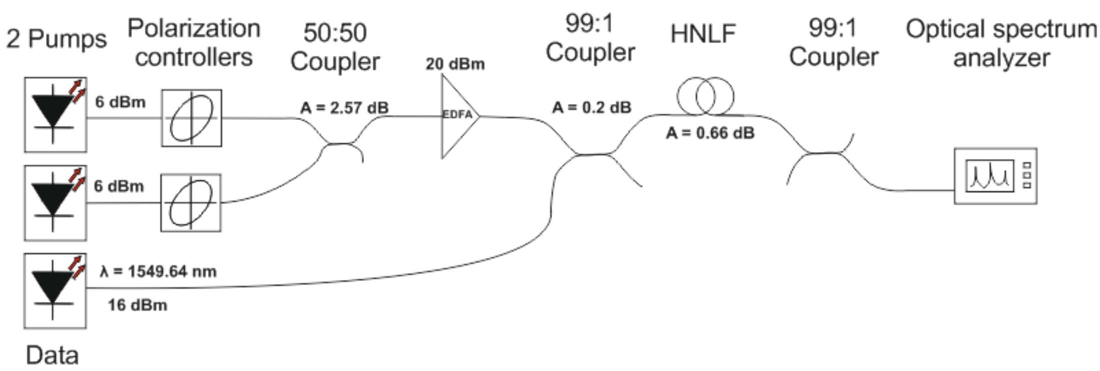

Fig. 4.3.1: Setup for multicasting with signal powers and insertion losses.

Measurements results can be seen in table 4.3.2:

Pump 1 signal wavelength [nm]	Pump 2 signal wavelength [nm]	Idler 1 signal wavelength [nm]	Idler 2 signal wavelength [nm]	Idler 1 signal power [dBm]	Idler 2 signal power [dBm]
1556	1540	-	-	-	-
1556	1542	-	1562.38	-	-16.90
1556	1543	-	-	-	-
1556	1544	1538.36	1562.38	-37.74	-17.35
1556	1545	1540.36	1562.38	-35.07	-17.32
1556	1546	1542.31	1562.35	-33.27	-17.45
1557	1540	-	1564.40	-	-16.62
1558	1540	-	1566.42	-	-16.66
1559	1540	-	1568.44	-	-16.86
1560	1540	-	1570.47	-	-18.21
1561	1540	-	1572.50	-	-20.79
1562	1540	-	1574.53	-	-27.41
1563	1540	-	1576.56	-	-36.56
1564	1560	1570.46	1578.59	-27.73	-35.42
1565	1560	1570.47	-	-28.22	-
1565	1561	1572.49	-	-30.75	-
1565	1562	1574.53	-	-36.82	-
1565	1563	-	-	-	-
1565	1564	1579.60	-	-37.80	-

Table 4.3.2: Positions of data carrying idlers and their strength

These results only show idlers created through pump signals as they are of the highest optical power. Many other idlers are possible, though there emerges a problem, when in sheer number of idlers it is difficult to determine which idlers carry information and which is just copy of pump signals. This situation can be seen in figure 4.3.3; note that slope of noise is given by EDFA amplifier and all results are 20 dB attenuated:

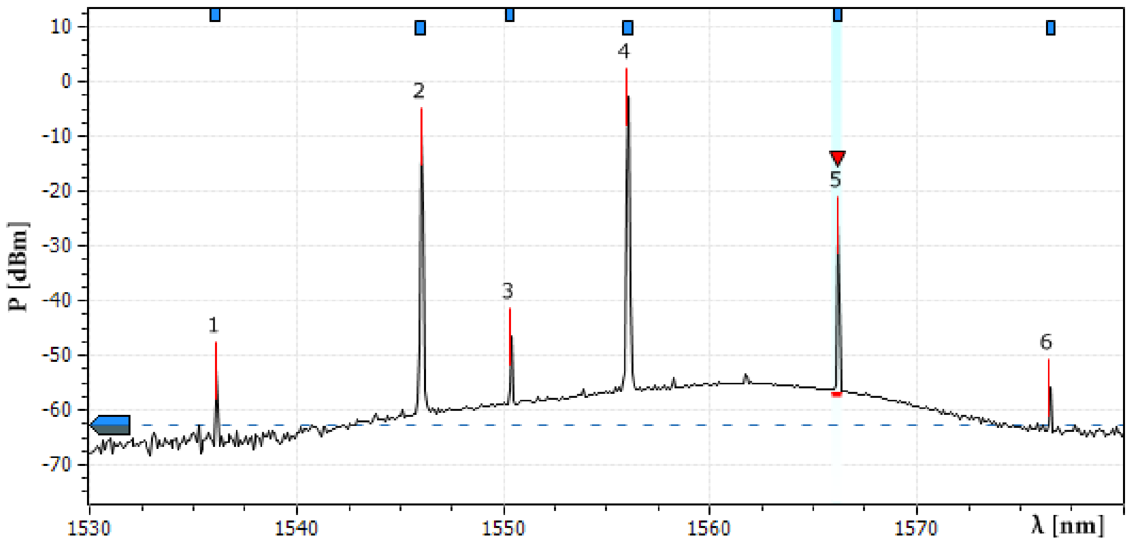

Fig. 4.3.3: Output of basic multicast signal with multitude of idlers. Signals 4 and 7 are pump signals and signal 5 is data signal.

To reduce number of copies of pumps I used two PCs to tune polarization of pump signals in such way that they will be polarization independent and will created the least amount of idlers. This situation can be seen in figure 4.3.4 (note that results are 20 dB attenuated):

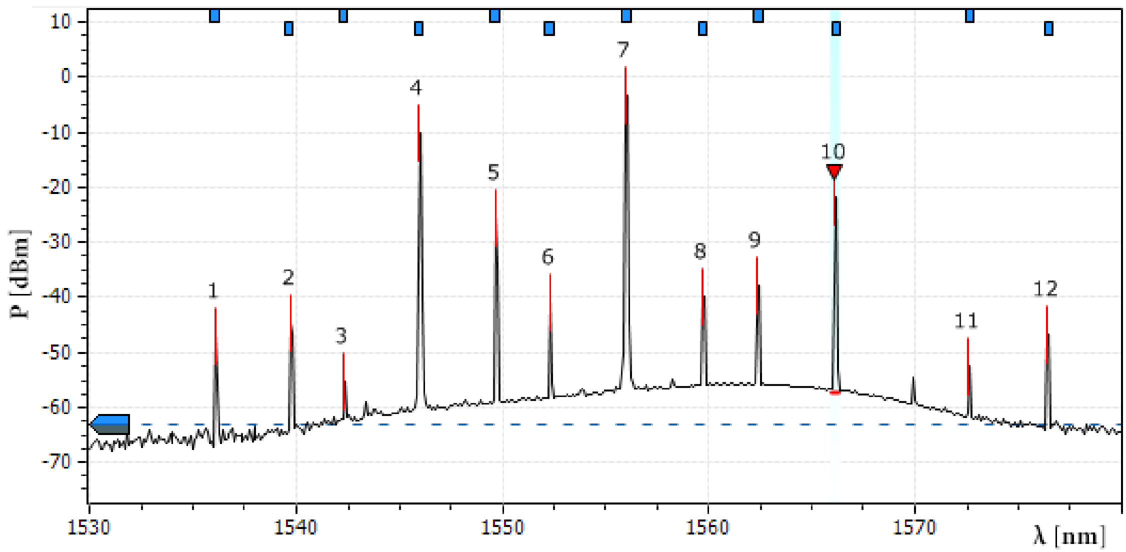

Fig. 4.3.4: Two polarization independent pump signals at 2 and 4 and their idlers.

As I had only non-tunable laser diode with given wavelength of 1549.64 nm I tuned the position of both pumps to achieve highest number of idlers that would carry data. As can be seen from measured results in table 4.3.2, only several configurations give two such idlers and thus achieving only 1x2 multicast. It is important to note, that shown results are 20 dB attenuated and therefore many more idlers might be possible. Also there is a given restriction of EDFA amplifier as it only amplifies through C band and other idlers should be appear at shorter wavelengths. Results with two data carrying idlers can be seen in figure 4.3.5 (note that results are 20 dB attenuated):

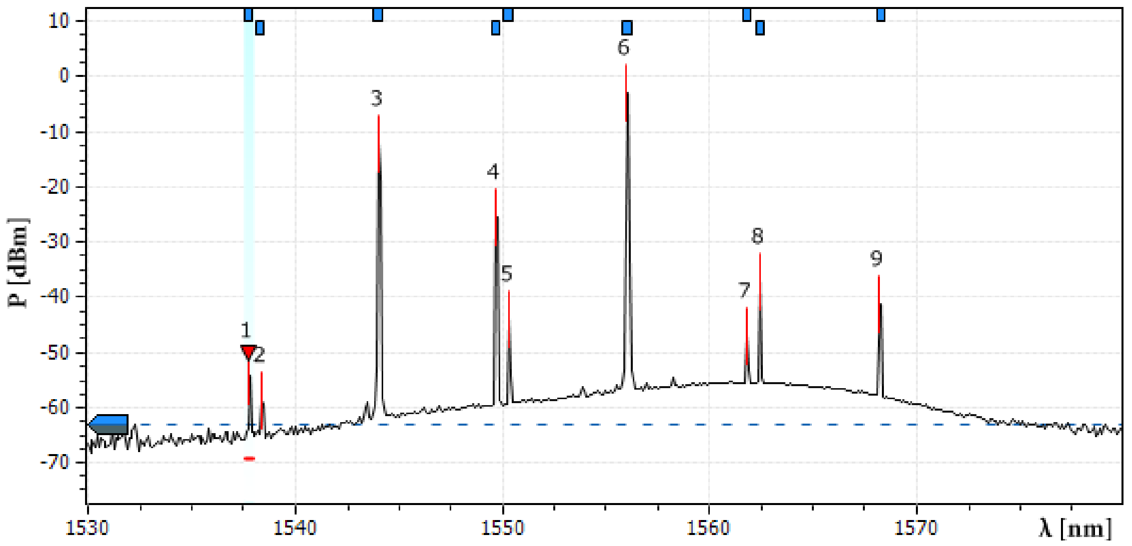

Fig. 4.3.5: Multicast with two data carrying idlers at 2 and 8, pump signals at 3 and 6 and data signal at 4.

As can be seen in figure 4.3.5 pump signals are marked as 3 and 6 (difference in power is given by EDFA amplifier, where 3 is less amplified than 6 due to its wavelength), data signal is 4 and its idlers are 2 and 8.

Since I used laser diode as data signal, it has an unfortunate effect of having additional spectral line at downshifted wavelength and it is denoted as signal 1. Signal 5 is then its copy through pump 3 and signal 7 is copy of signal 5 through pump 6. Signal 9 is copy of pump 3 through pump 6. However none of these signals carries any data.

5. Simulations

In this part I will demonstrate simulations of basic DFWM and FWM for multicasting in order to verify measurements. For these simulations OptiSystem software was used.

5.1 Basic setup simulation

In this basic setup I compared performance results of simulations and measurements of DFWM.

At first, I had to create entire setup using Optiwave OptiSystem. Setup is similar to figure 4.1.1. There are two continuous wave lasers, each with polarization controller (pump and data signals have the same polarization). Both signals are coupled in 50:50 coupler that is connected to HNLF. HNLF parameters were given by measured HNLF. Results are then displayed in OSA. This setup can be seen in figure 5.1.1:

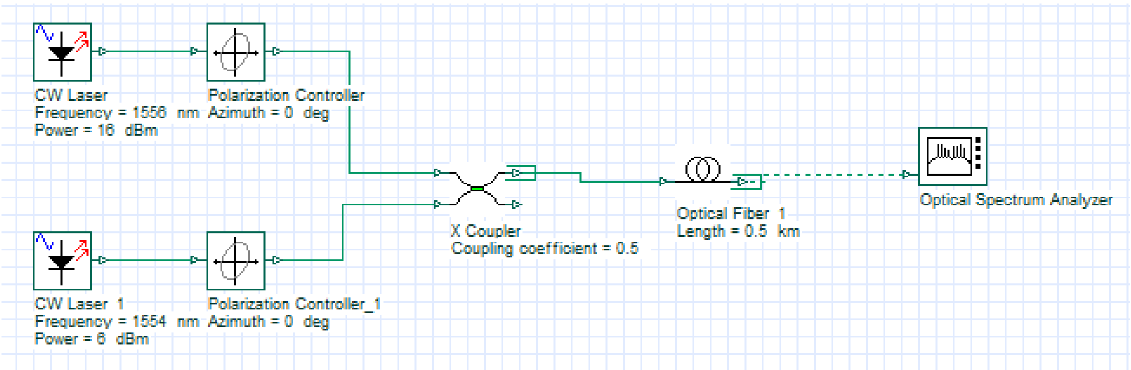

Fig. 5.1.1: Basic simulations setup of FWM.

Results of simulation of basic FWM can be seen in figure 5.1.2:

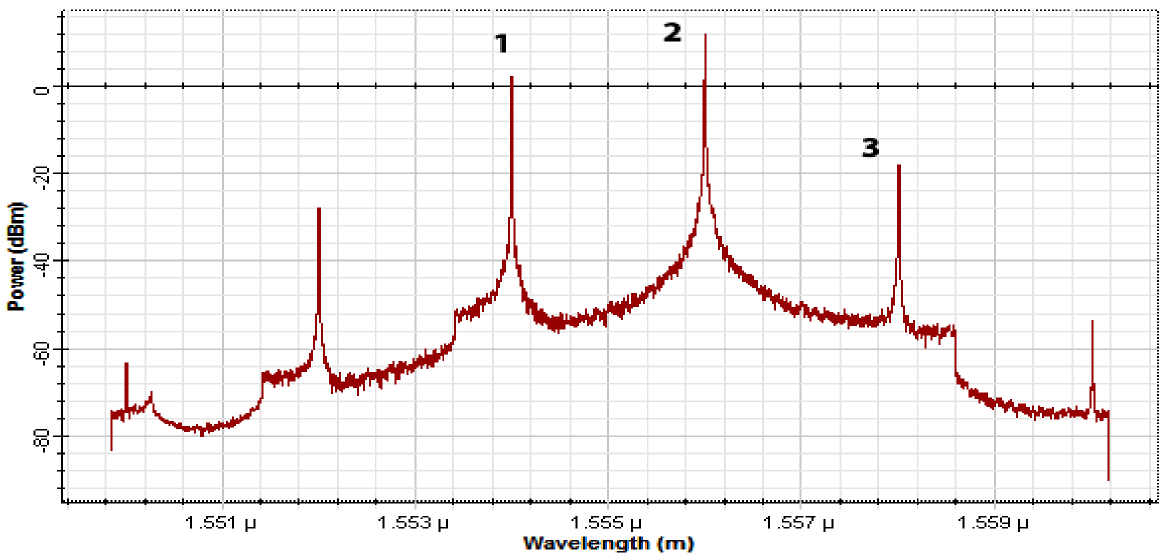

Fig. 5.1.2: Results of basic FWM simulation with pump at 1556 nm and data signal at 1554 nm.

In comparison with figure 4.1.2 the results are different, as there are more idlers. As can be seen in figure 5.1.2 signal 1 is pump signal at 1556 nm, signal 2 is data signal at 1554 nm and signal 3 at 1558 nm is idler of signal 1 through pump 2. Out of all the other signals only idler 3 is relevant as it carries the information. Other signals are copies of pump and carry no information. As simulated idler is more than 5 dB stronger than measured. Therefore more idlers are created.

5.2 Multicast simulation

For these simulations I used similar setup as can be seen in figure 4.3.1. The setup consists of three continuous wave lasers all of them with polarization controllers. Two pump signals at 6 dBm are coupled in 50:50 coupler and amplified to 20 dBm with EDFA. This signal is then coupled with data signal at 15.2 dBm in 99:1 coupler, with data connected to 1% input. Output of this coupler is then connected to HNLF and results are displayed on OSA. Entire schematics can be seen in figure 5.2.1:

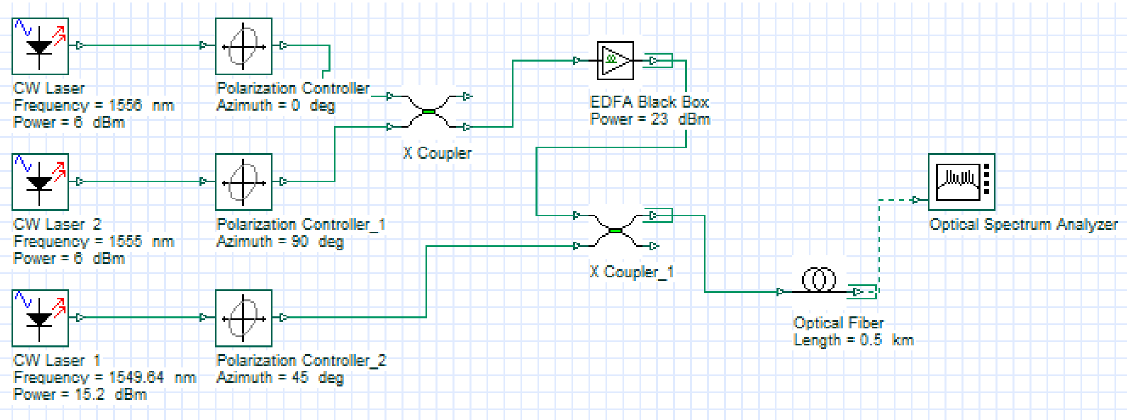

Fig. 5.2.1: Setup for multicast simulations.

For these simulations I set one pump to 1556 nm and tuned wavelength of second pump. Data signal is set to fixed 1549.64 nm. As can be seen in fig 5.2.1 pump polarizations have difference of 90°. Data signal than has polarization of 45°. This is to have both pumps with orthogonal polarization (as to not create idlers with each other), but for data signal to interact with pumps. As in case of measurements, without this polarization control there is created a large number of irrelevant idlers, which carry no information. This situation can be seen in figure 5.2.2:

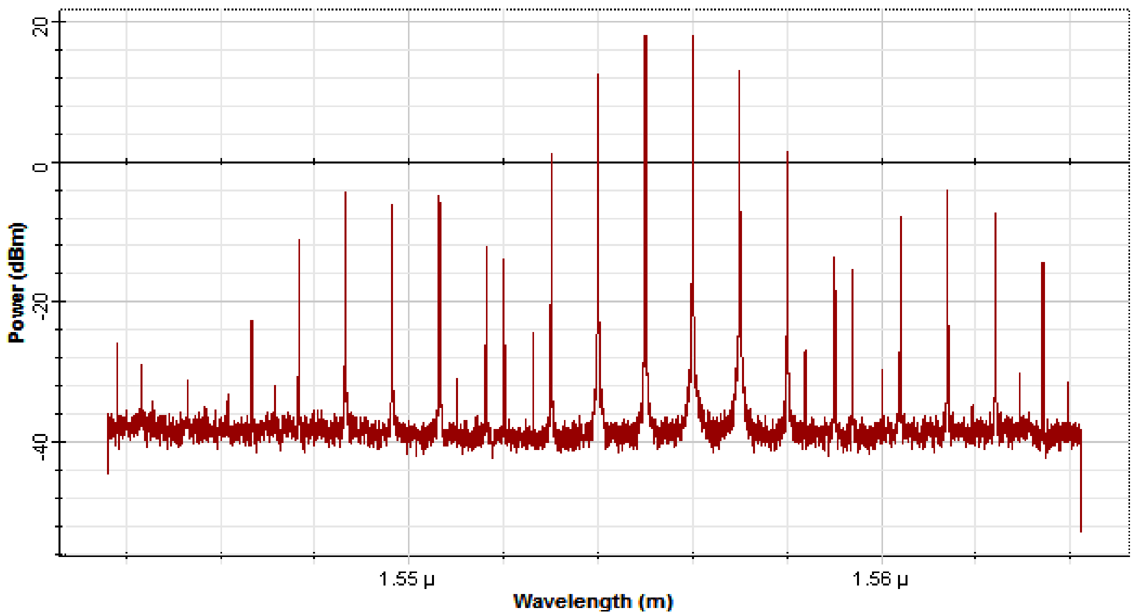

Fig. 5.2.2: Multicast when all three input signals have same polarization.

Simulation results of multicast can be seen in table 5.2.3 and in figure 5.2.4:

Pump1 signal wavelength [nm]	**Pump2 signal wavelength [nm]**	**Idler 1 signal wavelength [nm]**	**Idler 2 signal wavelength [nm]**	**Idler 1 signal power [dBm]**	**Idler 2 signal power [dBm]**
1556	1558	1562,34	1564,41	-13,95	-14,22
1556	1557	1562,41	1564,44	-13,77	-13,24
1556	1555	1562,39	1560,39	-12,8	-14,11
1556	1554	1562,39	1558,37	-12,35	-14,91
1556	1553	1562,39	1556,36	-12,46	-15,42
1556	1552	1562,39	1554,34	-12	-16,03
1556	1551	1562,4	1552,36	-11,64	-16,04
1556	1548	-	1546,35	-	-15,9
1556	1547	-	1544,43	-	-15,19
1556	1546	-	1542,37	-	-15,31
1556	1545	-	1540,37	-	-15,03

Table 5.2.3: Results of multicast simulation.

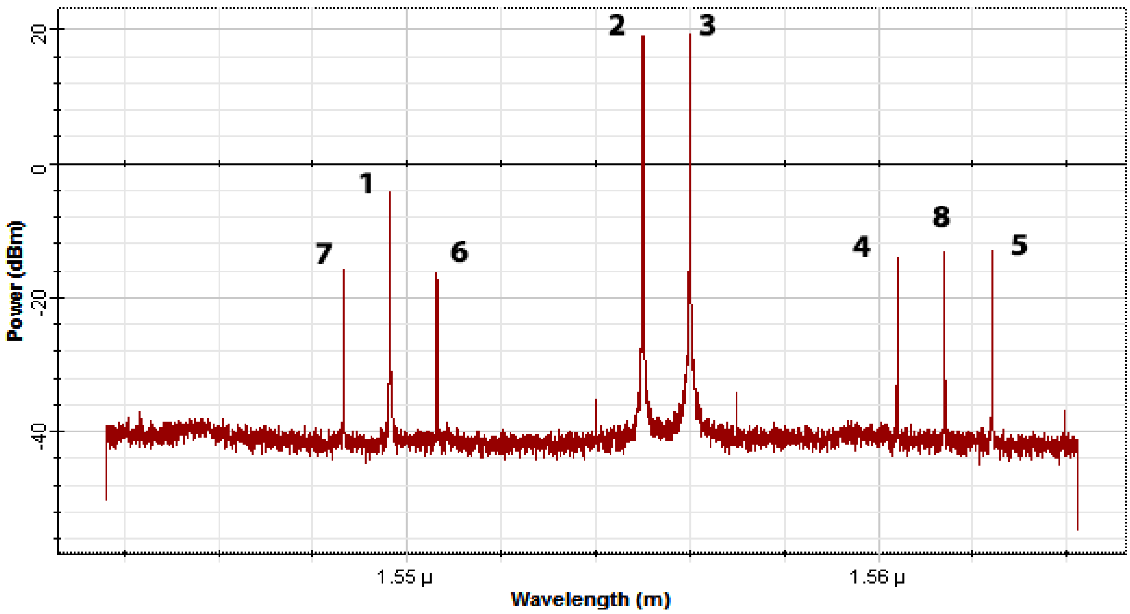

Fig. 5.2.4: Demonstration of multicast simulation.

In figure 5.2.4 it can be seen that results are similar as in basic DFWM setup, simulation shows better results in idler's power. Apart from power gain, there is large number of data carrying idlers, not present in measurements.

As can be seen in figure 5.2.4 signal 1 is data signal, signals 2 and 3 are pump signals. Signal 4 is data carrying idler, created through signal 2 and signal 5 is second data carrying idler created through signal 3.

As opposed to measurements, there is signal 6 that is copy of signal 4 through pump 3. Signal 7 is copy of signal 5 through pump 2. Signal 8 is copy of signal 6 through pump 3. All of these newly created idlers carry data information and therefore 1x5 multicast is achieved.

Such large number of data carrying idlers can be caused by higher power of all created idlers (as conditions of simulation are ideal) and resulted higher power of both pumps. Some idlers even receive power gain. As for example idler 8 which has gain of more than 3 dB over idler 6. Therefore new idlers are likely to be created.

6. Conclusion

In this bachelor thesis I studied nonlinear optical effects and FWM in particular. Critical conditions of efficient FWM stands in achieving high optical power, where the largest limitation will be in SBS.

To overcome SBS limitation I used signal modulation built into signal generating laser. As it has proved at low optical power (6 dBm) SBS suppression worked well (suppression up to 11 dB), and the SBS effect was negligible (difference of 0.24 dB). With higher optical power (16 dBm) SBS became more apparent but internal laser modulation would improve results only to some degree (difference over 4 dB).

For the purpose of this bachelor thesis such measures were sufficient but for efficient application of FWM with higher optical power, more advanced methods would be required. As SBS is limiting factor in construction of devices using FWM such as parametric amplifiers, multicast and wavelength convertors. For that, further analyses would be required.

Other issues were introduced when I implemented multicast. First issue was polarization control. If both pump signals have similar polarization, they interact to such degree that it caused a large number of irrelevant idlers. As these idlers are copies of pumps and as such carry no information.

This problem was solved by setting orthogonal polarization of both pumps with data polarization being random with respect to both pumps. In this case pump signals have almost no interaction between each other and so they create almost no unwanted idlers. Since data signal has polarization in between two pump signals, it still interacts with them.

Another problem with multicast was usage of EDFA amplifier. EDFA has limited wavelength range for amplification as well as a slope instead of flat amplification (can be seen in figure 4.3.3) in ideal case. This caused only certain configurations of pumps wavelengths to allow for two data carrying idlers. Despite that, 1x2 multicast was achieved.

Finally simulations presented higher idlers optical power as well as significantly more idlers. That was most apparent in multicast simulations where 1x5 multicast was achieved and even optical power gain was present between idlers.

7. References

[1] Toroundis, Thomas. *Fiber Optic Parametric Amplifiers in Single and Multi Wavelength Applications*. Göteborg, Sweden, 2006. Thesis for the degree of Doctor of Philosophy. CHALMERS UNIVERSITY OF TECHNOLOGY.

[2] Agrawal Govind P. *Fiber-optic communication systems*. 3rd ed. New York: Wiley-Interscience, 2002. ISBN 04-712-2114-7.

[3] Aso, Osamu, Masateru Tadakuma and Shu Namikhi. Four-Wave Mixing in Optical Fibers and Its Applications. *Furukawa Review, No. 19. 2000* [online]. [cit. 2013-12-26]. Dostupné z: http://furukawa.jp/review/fr019/fr19_12.pdf

[4] Marciu, Daniela. Optical Limiting and Degenerate Four-Wave Mixing in Novel Fullerenes. Blacksburg, Virginia, 1999. Dissertation. Virginia Polytechnic Institute and State University. Dostupné z: http://scholar.lib.vt.edu/theses/available/etd-022299-083514/unrestricted/CHAPTER3.PDF

[5] Pu, Minhao, Hao Hu, Hua Ji, Michael Galili, Leif K. Oxenløwe, Palle Jeppesen, Jørn M. Hvam and Kresten Yvind. One-to-six WDM multicasting of DPSK signals based on dual-pump four-wave mixing in a silicon waveguide. Optics express, Vol. 19, Issue 24, pp. 24448-24453 (2011) .

[6] Applications of Fiber-Based Optical Parametric Amplifiers. In: *IEEE Photonics Society* LEOS Newsletter, vol. 16, no.5, [online]. 2002 [cit. 2014-12-26]. Dostupné z: http://photonicssociety.org/newsletters/oct02/hansryd.html

[7] Ruffin, Boh. Stimulated Brillouin Scattering: An Overview of Measurements, System Impairments, and Applications. [online] 2004 [cit. 2014-05-12]. Dostupné z: http://www.corning.com/docs/corporate/discovery_center/innovation_library/2004/NTRNTR100886_NIST_SOFM_Ruffin.pdf

[8] S. P. Singh, R. Gangwar, and N. Singh. “Nonlinear scattering effects in optical fibers”, Progress In Electromagnetics Research, Vol. 74, 379-405, 2007