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The Effect of Stimulated Brillouin Scattering on WDM-PON

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Introduction

The existing TDM-PON (Time-Division Multiplexing Passive Optical Network) technologies like EPON (Ethernet PON) or GPON (Gigabit PON) have limitations of bandwidth due to the concept of time division [1]. The bit rate can only be enlarged increasing the speed of the common channel (10G EPON). Another way of achieving the bandwidth growth is the use of WDM (Wavelength Division Multiplexing) technology [5]. The main problem of the WDM-PON is the ability to use the existing cable plant with high losses due to power splitters. Hybrid TDM/WDM-PON conception is the only way of upgrading of the existing technologies [4]. However, there is a lack of power budget to enlarge a number of wavelengths and the splitting ratio. The easiest way of enlarging the power margin is the increase of inserted power. One of the main limitations is SBS (Stimulated Brillouin Scattering), which scatters all the power after the threshold [2, 3].

Brillouin scattering arises from the interaction of light with propagating density waves or acoustic phonons. Of the two types (Raman and Brillouin) of nonlinear scattering events SBS is recognized as the dominant optical fiber nonlinearity [2]. At high enough input powers (can be at a level of 7 dBm for narrow spectrum lasers), SBS will convert transmitted light in the fiber to a scattered, Stokes-shifted (down shifted) reflection well above typical Rayleigh scattering power levels. As illustrated in Fig. 1 this phenomena arises from the interaction between the optical field and acoustic phonons in the fiber, driven through an electrostrictive process where the medium becomes more dense in regions of high optical density [2]. As shown in Fig. 1 an incident optical field of sufficient intensity interferes with ubiquitously scattered optical fields, which give rise to density and pressure variations (electrostriction). The incident optical field then scatters of the refractive index perturbations as a result of the aforementioned density variations. Typical values of a Brillouin frequency shift in optical fiber at 1550 nm range approximately between 9 and 12 GHz.

Achieving the SBS threshold, all the pumping light becomes scattered, and there are no ability to insert extra power into optical fiber. This problem is quite complicated in cases where high optical powers must be used (Cable Television, PON, long-haul networks).

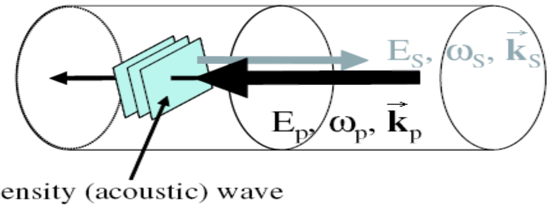

Fig. 1. Schematic diagram of the stimulated Brillouin scattering

Process (Fig. 1) in an optical fiber (where $\omega_{p,S}$ and $\overrightarrow{k_{p,S}}$ are the optical frequencies and wave vectors of the pump and Stokes shifted fields, respectively. $E_{p,S}$ are optical field intensities) [2].

System Design and Simulation

Brillouin threshold is calculated using “classical” formulas for CW (Continuous-Wave) and ASK (Amplitude Shift Keying) operation [2, 3]

$$P_{th}^{CW} = \frac{21A_e}{L_{eff}g_B}\left(\frac{\Delta\vartheta_B+\Delta\vartheta_S}{\Delta\vartheta_B}\right), \tag{1}$$

$$P_{th}^{ASK} = \frac{P_{th}^{CW}}{1-\frac{B}{2\Delta\vartheta_B}\left(1-e^{-\frac{\Delta\vartheta_B}{B}}\right)},. \tag{2}$$

where A_e is the effective area of the optical fiber (81µm^2), and $\Delta\vartheta_B$ is the full-width-at-half-maximum (FWHM) Brillouin linewidth (20 MHz), $\Delta\vartheta_S$ - laser FWHM (50 MHz). L_{eff} is the effective length and g_B is a coefficient depending on various material parameters ($4\cdot10^{-11}$ m/W) [2]. The formula (2) also contains the bitrate B of ASK (Non-return-to-Zero code was used). If bitrate $\rightarrow \infty$ (after $\approx$ 500 Mbit/s the results are the same), threshold improvement $\rightarrow$ 3 dB. The scheme (Fig.2) was made to check this theoretical formula. It contains laser source with FWHM of 50 MHz, EDFA (Erbium Doped Fiber Amplifier) with a possibility to fix output power with 0.1 dB step, 20 km of standard single mode fiber (G.652) and OSA(Optical Spectrum Analyzer) with power meter.

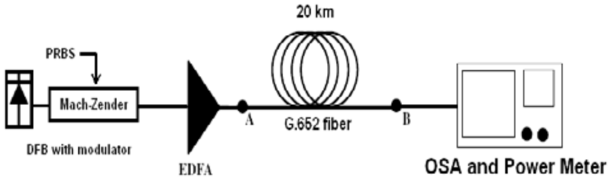

Fig. 2. Schematic diagram of experiment

Input power was linearly increased and output (with power meter) controlled. There were made 4 experiments: CW mode of operation and ASK mode with NRZ coding and PRBS (Pseudo Random Bit Sequence) 10^{23}-1 at a bitrate of 1.25, 2.5 and 10 Gbit/s. You can see the results on Fig. 3a. Fig. 3b shows theoretical SBS threshold values for CW and ASK operating modes.

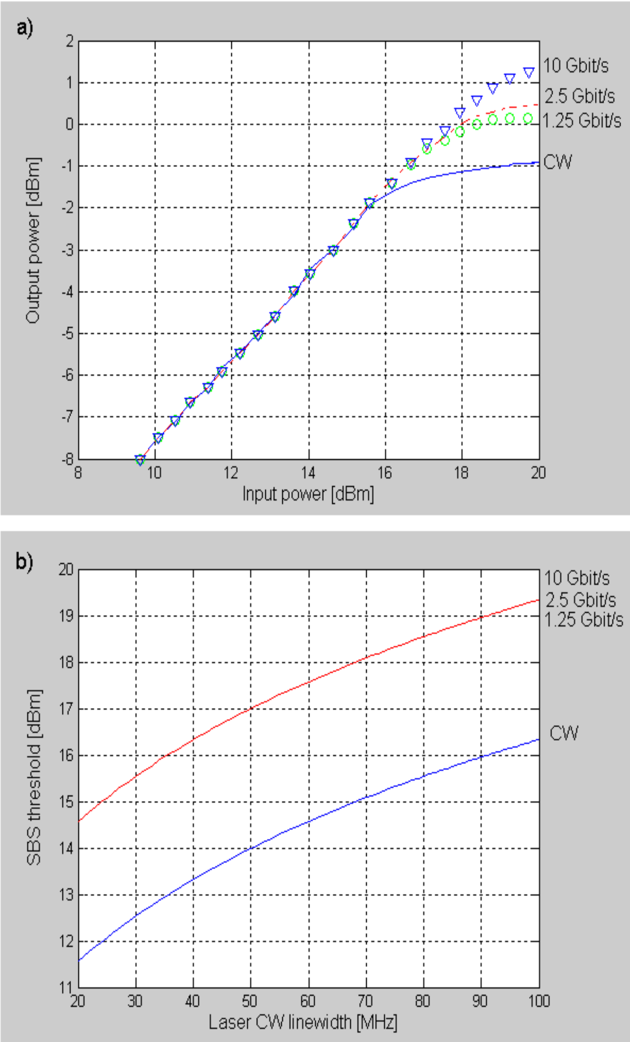

Fig. 3. SBS threshold measurement (a); SBS threshold calculated data (b)

SBS threshold was evaluated as the input power where the second derivative of the output power is minimal. It is seen that practical results, especially in the case of ASK, are not equal with theoretical evaluation (1, 2). It can be explained in the way, that theoretical formula (2) doesn't take into account PRBS used in experiment. Power meter showed us the average power, but logical "0" in the pattern can cause the power fluctuations at a small period of time, that we see as a threshold increasing. The expression (2) also cannot be used in exact calculations, because if bitrate exceeds 500 Mbit/s, the difference of CW and ASK threshold is 3 dB. Fig. 3 and Table 1 show us that threshold difference is not equal after ≈ 500 Mbit/s and doesn't achieve 3 dB at least till 10 Gbit/s.

Table 1. SBS threshold comparison

Bitrate [Gbit/s]	**CW**	**1.25**	**2.5**	**10**
Theoretical results[dBm]	14	17	17	17
Practical results[dBm]	15.5	16.9	17.2	18

The second goal of the research was to find out TDM/WDM PON limitations of power budget and amount of clients induced by SBS. Fig. 4 shows us the configuration of the system [6].

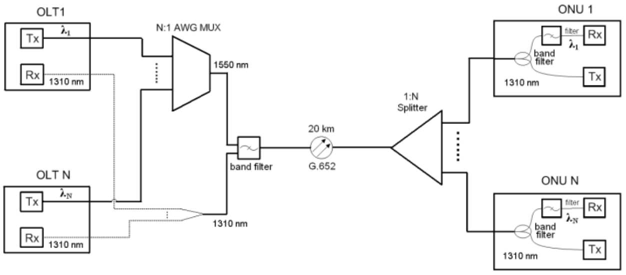

Fig. 4. Schematic diagram of TDM/WDM PON

Classical PON realization is expanded with AWG (Arrayed Waveguide Grating) on OLT (Optical Line Terminal) side and two filters on OLT and ONU (Optical Network Unit) sides to divide Downstream (C-band) from Upstream (O-band). Standard components were chosen to make the system less complicated and easy to install. All the component IL (Insertion Loss) and technical data are viewed in the Table 2. 16-channel system was chosen using standard splitting ratio for EPON 1×16.

Table 2. Technical specification

Fiber length	20 km
Laser output power (Downstream)	variable
Laser output power (Upstream)	14.2 dBm
1:16 splitter IL	13,2 dB
1:16 AWG IL	3,5 dB
Filter IL	2.4 dB
APD (downstream) sensitivity (theoretical)	-24 dBm
APD (upstream) sensitivity (FEC) including dispersion (chirp) loss and SOA noise [6]	-23.8 dBm
Fiber attenuation (downstream 1550 nm)	0,25 dB/km
Fiber attenuation (upstream 1310 nm)	0.4 dB/km
Splicing loss	1 dB

The aim is to find the maximum available input power and upgrading properties for 16-channel WDM-PON system using OptSim simulation. It is based on maximum available power budget evaluation for 16-channles (16-λ simultaneously). The power increase can be achieved using either EDFA or high power lasers. The SBS calculation in OptSim was précised, due to lack of ability to calculate SBS threshold for modulated signals. It must be noted that the total power of all channels doesn't affect on SBS threshold, which is calculated only for separate channel. Input power of all 16 channels was linearly increased and output power evaluated. CW threshold for 16-λ system is not equal to theoretical data, but ASK (10 Gbit/s) threshold can be used in practical calculation of maximal upper limit (difference between measurement is only 0.05 dB).

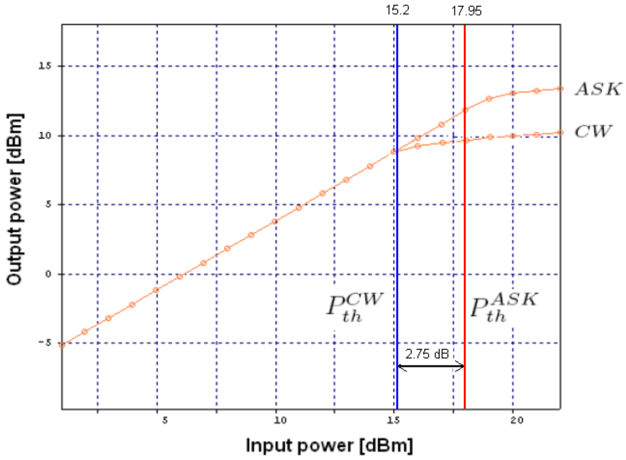

Fig. 5. Investigation of SBS threshold for 16-λ system

Maximal upper limit for inserted power is 18 dBm. To calculate power budget we need data for sensitivity (downstream channel) in presence of dispersion and non-linear distortion, which is worse than theoretical value. The simulation was made for low power case (3 dBm per λ) and high power (18 dBm per λ), where the degradation of power budget is higher (Fig.6).

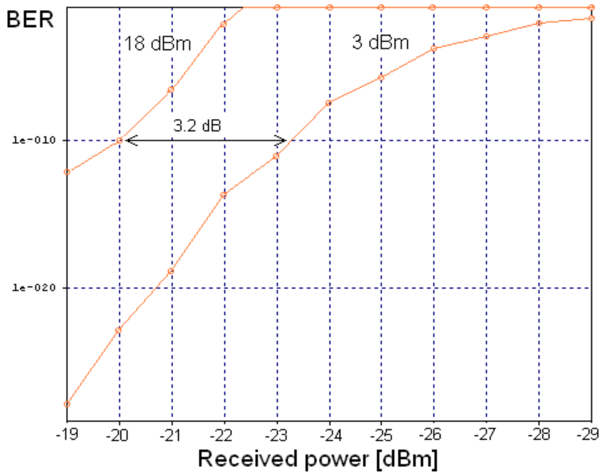

Fig. 6. Sensitivity degradation

We can see, that received power difference to achieve BER < $1 \cdot 10^{-10}$ is 3.2 dB for 3 and 18 dBm laser output power scenario due to OSNR (Optical Signal-to-Noise Ratio) degradation caused by nonlinear effects. 0.75 dB difference between theoretical and calculated sensitivity can be explained as the effect of dispersion and inter-channel crosstalk.

Maximal available power budget for upstream in O-Band is 38 dB (with FEC – Forward Error Correction) including 11.4 dB extra power margin. Insertion loss for downstream 16-channel case in C-band with power margin 2 dB is 27.1 dB. Laser output power must be at least 3.9 dBm. Taking into account sensitivity degradation maximal possible power budget for downstream can achieve 38 dB as in upstream case (10.9 dB extra margin comparing with minimal needed input power per one channel).

Conclusions

Theoretical expression for SBS threshold evaluation for CW mode (1) is only suitable for lasers with FWHM much less than Brillouin linewidth (20 MHz for G.652 in our experiment). Practical results for 50 MHz CW mode (that is more usual for commercially available lasers) showed the difference of 1.5 dB. The expression for ASK mode (2) cannot be used for signals (NRZ coding) with bitrate more than ≈ 500 Mbit/s. Practical results show, that 3 dB difference (in (2) if bitrate → ∞ threshold difference → 3 dB) is not achieved even for bitrate of 10 Gbit/s. Practical difference between CW mode and 10 Gbit/s ASK mode is 2.5 dB. Optsim simulation (after specifying the parameters) for 16-channel WDM-PON system also showed the nonequality of the results for CW mode, however ASK mode was correct and can be used for 32 and 64-channel simulations.

For maximal available power budget calculation was chosen 16-channel WDM-PON system. 1×16 splitting ratio was chosen due to EPON standard and its possible future upgrade. Downstream was composed of 16-λ per each customer and upstream of 1 channel in O-band (1310 nm) with the use of SOA (Semiconductor Optical Amplifier) and time division multiplexing [6]. Upstream maximal power budget is 38 dB (extra power margin 11.4 dB) with the use of FEC (receiver theoretical sensitivity degradation of dispersion and SOA noise is 3.2 dB). The simulation showed that for downstream realization insertion loss (including splicing, filter, splitting losses, power margin and fiber attenuation is 27.1 dB). Minimum needed laser output power to ensure stable working is 3.9 dBm. Taking into account degradation of sensitivity due to nonlinear effects and OSNR degradation (3.2 dB concerning minimal practical achievable -23.2 dBm), maximal available power budget is 38 dB for downstream. It grants extra margin of 10.9 dB concerning with minimal requirements. It is clear that it is not obligatory to use maximum output power (either using EDFA or high power lasers).

Proposed system can ensure downstream bitrate of 10 Gbit/s and upstream bitrate of 0.625 Gbit/s per user. This solution has comfort downstream/upstream bitrate attitude 16/1 for high definition TV and telephony, ultra fast internet applications and next generation online gaming. Presence of extra power margin can increase the splitting ratio by the factor of 2 for upstream (1×32) and increase channel number till 32-λ. For total power budget it will be only decrease of 6 dB. In spite of presence of extra dB limit, there is no availability of extra splitting ratio increasing, due to extra nonlinear penalty for budget (32 and 64-channel realizations will obviously have degradation of sensitivity higher, than 16-λ realization) as also 32/1 and even 64/1 downstream/upstream bitrate attitude is not suitable for modern bandwidth demand. High cost of components (high power lasers and EDFA) will not make the system attractive from commercial point of view.

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The existing TDM-PON (Time-Division Multiplexing Passive Optical Network) technologies like EPON (Ethernet PON) or GPON (Gigabit PON) have limitations of bandwidth due to the concept of time division .The bit rate can only be enlarged increasing the speed of the common channel (10G EPON). Another way of achieving the bandwidth growth is the use of WDM (Wavelength Division Multiplexing) technology .The main problem of the WDM-PON is the ability to use the existing cable plant with high losses due to power splitters. Hybrid TDM/WDM-PON conception is the only way of upgrading of the existing technologies. However, there is a lack of power budget to enlarge a number of wavelengths and the splitting ratio. The easiest way of enlarging the power margin is the increase of inserted power. The main limitation is SBS (Stimulated Brillouin Scattering), which scatters all the power after the threshold. The paper contains: SBS threshold measurement and comparison with theoretical data, the evaluation On-Off Keying effect on SBS threshold, calculation of maximum power budget and channel (client) number limited by SBS for 16-channel TDM/WDM-PON system based on SBS threshold measurement data. Ill. 6, bibl. 6, tabl. 2 (in English; abstracts in English, Russian and Lithuanian).

И. Ляшук. Влияние ВРМБ на WDM-PON // Электроника и электротехника. – Каунас: Технология, 2010. – № 7(103). – С. 105–108.

В существующих технологиях TDM-PON (Time-Division Multiplexing Passive Optical Network – Пассивная оптическая сеть с временным уплотнением), EPON (Ethernet PON) и GPON (Gigabit PON- гигабитный PON) имеются ограничения скорости из-за концепции временного уплотнения. Скорость может быть увеличена только поднимая скорость общего потока (10G EPON). Другой способ достижения роста скорости – это использование технологии WDM (Wavelength Division Multiplexing – уплотнение по длине волны). Главная проблема WDM-PON – это необходимость работы в существующей кабельной сети с большим затуханием разветвителей мощности. Гибридная концепция TDM/WDM-PON – единственный способ модернизации существующих технологий. Однако существует нехватка бюджета мощности для увеличения числа длин волн и коэффициента ветвления. Самый лёгкий способ увеличения бюджета – это увеличение мощности лазера. Главное ограничение – это SBS (Stimulated Brillouin Scattering – стимулированное рассеивание Брюльена), которое рассеивает всю мощность после определённого порога. Публикация состоит из измерения рубежа SBS и сравнения с теоретическими данными, оценка влияния модуляции интенсивности на рубеж SBS, расчёт максимального бюджета мощности и числа каналов (вероятное), ограниченных SBS на основе шетнадцати канальной системы TDM/WDM-PON, основываясь на результатах эксперимента. Ил. 6, библ. 6, табл. 2 (на английском языке; рефераты на английском, русском и литовском яз.).

I. Ļašuks. Pasyvinių optinių tinklų įtaka signalų sutankinimui // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 7(103). – P. 105–108.

Analizuojama pasyvinės optinės sistemos taikymo technologija, kuriant naujos kartos multipleksinius optinius įtaisus ir didinant naudojamų lazerių galią. Pateikiami teoriniai kanalų skaičiaus parinkimo ir šešiolikos kanalų sistemų signalams sutankinti įvertinimo skaičiavimai. Rezultatai patikrinti eksperimentiškai. Il. 6, bibl. 6, lent. 2 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).