Impact of GAWBS in Communication Systems

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Abstract: Guided acoustic wave Brillouin scattering (GAWBS) in modern communication system is overviewed. We discuss induced penalties, GAWBS scattering coefficient estimation, GAWBS detection, compensation, and modeling of various aspects of GAWBS.

1. Introduction

Optical communication technology is improving over time. Current technology is quite mature: the transmission fiber has low loss, the optical amplifiers use low loss components reducing the amplifier noise figure, advanced modulation formats with nonlinearity compensation further improves channel SNR. As the technology improves, the amount of noise generated by transmission systems goes down. Previously unimportant noise sources become noticeable. One of such sources is Guided Acoustic Wave Brillouin Scattering or GAWBS.

The first observation of GAWBS effect in a single mode fiber was done in 1985 [1]. Since that time the importance of this effect for single mode transmission systems was not greatly discussed due to smallness of the effect and difficulty of its observation. It is only in recent works [2] for submarine transmission systems and [3] for single span systems the importance of GAWBS in modern communication systems was noticed. It has been shown that for long haul communication systems the effect is sufficiently large to have up to about 0.5dB penalty at the system nonlinear optimum [2] and is an important part of the system budget [4]. The effect is large enough to ask practical question if it can be compensated somehow, at least partially. The prospects of GAWBS compensation are discussed in [3] for the single span systems and in [5] for the submarine systems. While [2] gives simple description and prediction of GAWBS scattering coefficient and provides measured value for 150 μm^2 modern communication fiber, publications [6 - 8] greatly expand theoretical aspects and have measured values for various modern fibers [6].

In this work we overview the physics of GAWBS and the mechanism of penalty creation for modern communication systems. We will discuss GAWBS scattering coefficient and its dependence on fiber effective area. We also demonstrate that it is possible to observe GAWBS effect directly in communication channel and talk about prospects of GAWBS compensation difficulties for future communication systems.

2. Estimation of GAWBS penalty

GAWBS effect can be described as light scattered by thermally excited acoustic modes in glass volume of a fiber. While communication fibers also have plastic coating, as the results show, the coating impact is minor, and the modal structure of a glass cylinder can be used as good approximation.

There are several types of waves possible in solid glass – shear waves, compression waves and hybrid waves combining both types. The largest scattering is expected from compression of the glass, since it is the change of the glass density that gives the largest contribution for the refractive index change. We are also mostly interested in those acoustic modes of the glass cylinder that have maximum in glass density time-variation at the center of the fiber. This is where the light is concentrated – in the core of the single mode fiber. This leads us to well-known solution of the wave equation for glass density deviation $\delta\rho$ in axially symmetric system:

$$\delta\rho_{m,n}^{mode}(r,z,t) = J_0(\mu_n r)\cdot\cos\left(\Omega_{m,n}t\right)\cdot\cos\left(K_m z\right) \tag{1}$$

Here m and n are the radial and longitudinal indices of the modes, μ_n and K_m are the radial and longitudinal propagation constants respectively and J_0 is the zero order Bessel function. Since we are interested in forward scattering by the modes with oscillation frequency less than 1GHz, the fiber diameter and synchronism condition require longitudinal propagation constant to be significantly smaller than the radial constant. Under such condition the longitudinal dependence and longitudinal modal index can be simply ignored in all estimations. This greatly simplifies estimations, and the relative scattering strength can be calculated as overlap integral between the optical field and the acoustic field of Eq. (1) ignoring z dependence. In these estimations it is important to assume equal excitation of each mode, as it is expected in thermal equilibrium, see [2] for details.

The estimation of the relative scattering strength coefficient by each mode and the dependence of the total scattering coefficient on effective area of the transmission fiber are shown in Figs. 1 and 2. The effective area dependence appears due to change of the modal shape with effective area of the fiber impacting the overlap integral. The dependence shown in Fig. 2 is close to inversely proportionality with effective area. Work [8] has theoretically demonstrated that this dependence becomes inverse of Aeff under some reasonable assumptions. The dependence is important in prediction of performance for different transmission fibers. However, one cannot make conclusion that the penalty is smaller for large effective area fibers. The signal power at nonlinear optimum is larger for the large effective area fibers, resulting in the ratio of the GAWBS scattered power to the ASE generated by amplifiers and to the nonlinear noise to be nearly constant. The performance penalty is thus nearly independent from the effective area.

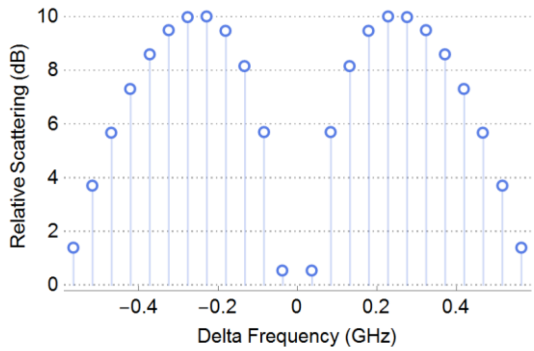

Fig. 1. Relative Scattering Strength

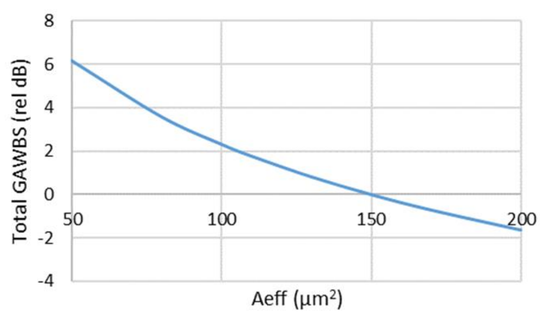

Fig 2. Dependence on effective area relative to Aeff=150μm^2

While it is possible to calculate total GAWBS scattering coefficient from the first principles, it is difficult to accurately operate with the exact modal structure of the fiber with (typically multilayer) coating. One can experimentally measure GAWBS scattering coefficient by sending CW light with narrow spectrum into transmission system that can be either single span [3, 6] or multi-span [2]. Each method has its advantages and disadvantages and all of them benefit from advanced DSP techniques for compensation of laser instability and for separation of GAWBS scattered signal from the noise. Fig. 3 shows an example of such measurement, where the CW laser line is removed for clarity. One can notice that the modal structure although not identical is very similar to that shown in Fig. 1. This confirms the assumption that reasonable estimations and conclusions can be done operating only with the compression modes described by Eq. (1).

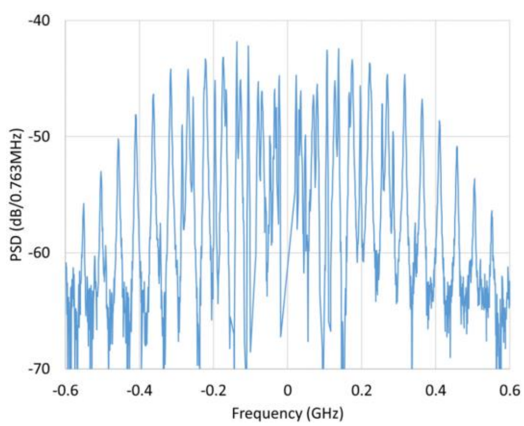

Fig. 3. GAWBS induced scattering spectrum

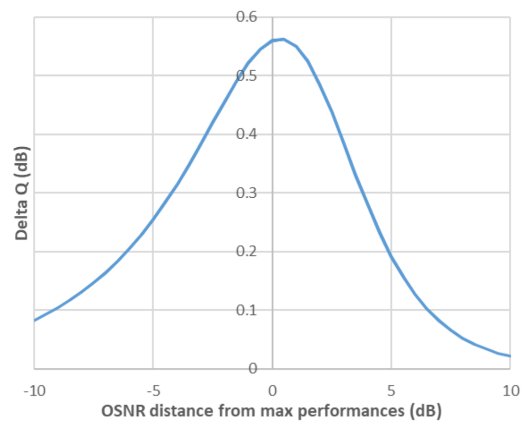

Fig. 4. Expected penalty due to GAWBS

The total GAWBS scattering coefficient can be obtained as summation over all modal peaks. The value of the total coefficient varies from fiber to fiber, and it is around -32dB/Mm for 150 μm^2 fiber [2, 6]. For the long transmission systems (> 2000km for 33GBaud channels) the GAWBS noise can be assumed to be Gaussian and uncorrelated to the signal. The impact of GAWBS on system performance can be accounted in calculation of effective SNR:

$$SNRe = \frac{S}{ASE + \gamma \cdot L \cdot S + P_{NLI}} \qquad (2)$$

Here S is the signal power, γ is the total GAWBS scattering coefficient, L is the system length, ASE and P_{NLI} are the ASE and the nonlinear interference noise powers. Assuming nonlinear noise power to be proportional to the cube of the signal power, we can best fit the pre-emphasis curve of our past experiment [9] with Eq. (2). After that SNRe performance penalty can be calculated from the measured value of the total GAWBS scattering coefficient and converted to Q-penalty based on format properties. Fig. 4 shows expected penalty due to GAWBS versus distance from the nonlinear optimum measured in dB of OSNR. One can vary the transmission distance L in Eq. (2) assuming that the ASE and nonlinear powers are proportional to the distance. It is interesting result that the GAWBS penalty at the nonlinear optimum does not depend on the transmission distance under these assumptions. This result and the previous statement (there is no penalty dependence on effective area) lead to the conclusion that the penalty is rather constant across different systems if they have similar fiber loss, amplifier NF and span lengths. These parameters tend not to vary a lot from system to system.

3. GAWBS Detection in Modulated Channel and GAWBS Compensation

The estimations and discissions above are based on the measurements of GAWBS effect performed with CW laser. While special care was taken in [2] to make sure that the measured effect is linear (the scattering coefficient does not depend on distance and signal power), and thus expected to have the same scattering strength for an actual information carrying modulated channel, it is a good idea to confirm presence of GAWBS in the actual channel. Another motivation is the related to the goal of GAWBS compensation – the detection problem is easier, and if we can not detect GAWBS we have little chance compensating it.

We come up with the "GAWBS searcher" transformation [5] to be applied on received optical field:

$$Seacher(\Delta\omega) = |\mathcal{F}(Im[E_{sb}^*(t) \cdot N(t)])| \tag{3}$$

Here $\mathcal{F}$ is the Fourier transform, E_{sb}^* is the optical field after standard DSP chain and before de-mapper at the receiver filtered by band-pass filter (3GHz in our work). N is the noise which is defined as the difference between expected and received signal. Applying this searcher to the received optical channel we were able to see GAWBS lines like that shown in Fig. 3, thus conclusively demonstrating the presence of the effect in the actual channel.

Since GAWBS generates frequency shifted replicas of the channel, a compensator based on frequency shifted equalizer was suggested [5]:

$$\begin{gathered} E_i^{\text{out}} = E_i^{\text{in}} + \sum_n \sum_{k=-N..N} \sum_{j=x,y} h_{i,j}^{k,n} \cdot E_{j+k}^{\text{in}} \times e^{i\Omega_n t} \\ h_{i,j}^{k,n} += \mu \cdot (Target_i - E_i^{\text{out}}) \cdot \left(E_{j+k}^{in}\right)^* \cdot e^{-i\Omega_n (t+kT)} \end{gathered} \tag{4}$$

Here Ω_n is the GAWBS shift frequency with index n, k is the tap delay index, j is the polarization index, i is the time index, and μ is the equalizer gain coefficient. The target $Target$ can be either known (data aided equalization) or obtained via hard decision (decision directed equalization). We have been able to demonstrate that when all targets are known in advance, then this equalizer partially compensates GAWBS in both synthetic data and in experimental data. The GAWBS searcher analysis also demonstrates reduction of the GAWBS peaks. However, with decision directed equalization we were unable to demonstrate performance improvement in experimental data, although we could do so with synthetic data by artificially lowering ASE noise generated by the system. The conclusion is that feedback signal is just too noisy, and the frequency shifted equalizer can not track GAWBS scattering fast enough with feedback based on hard decisions.

4. Conclusion

GAWBS effect produces noticeable penalty in long haul transmission links. The penalty is nearly independent of system length and fiber effective area. Since the amount of the scattered power is smaller than typical ASE and nonlinear noise power, it is difficult or impossible to extract good feedback signal to drive GAWBS compensators. Therefore, GAWBS penalty is important penalty to account in system performance estimations.

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