Practical Considerations on using Gaussian Shape Pulses in phi-OTDR Systems

Felipe Maia[1], Pedro O. Mariz de Carvalho[2], Sérgio Barcelos[2] and Luis Ynoquio Herrera[3]
[1]*Fiberwork Optical Communications Ltda., Campinas SP 13087-010, Brazil,*
[2]*Future Photonics, Sunnyvale CA, 94089 USA*
[3]*Photonics Innovation Institute - Campinas SP 13087-010, Brazil*
luis.herrera@itech.org.br

Abstract: This paper experimentally demonstrates practical advantages and limitations on using Gaussian shape pulses for phi-OTDRs systems by measuring the SNR of the detected vibration in the far end of a standard single mode fiber.

1. Introduction

Distributed Acoustic Sensing (DAS) based on Phi-OTDR techniques can lead the development of innovative technologies for a growing number of applications in areas such as: intrusion detection, oil and gas exploration, structure health monitoring, railway monitoring, hydrocarbon pipeline integrity and safety monitoring [1], and many others. To achieve high sensitivity in acoustic vibration detection, DAS uses Narrow-Linewidth Lasers (NLL) to generate coherent optical pulses. These pulses, when injected into an optical fiber, generate Rayleigh backscattering, and this scattered signal carries the light phase delay distribution along the whole fiber. The phase delay change, $\Delta\phi$, can be described by the following equation [1]:

$$\Delta\phi = \beta L \frac{\Delta L}{L} + L\left(\frac{\partial\beta}{\partial n}\right)\Delta n + L\left(\frac{\partial\beta}{\partial d}\right)\Delta d \qquad (1)$$

where, n, d, L are the core refractive index, core diameter and length of the fiber, respectively.

To reach longer fiber distances, while maintaining sensitivity and high spatial resolution, higher pulse peak powers must be used. The level of this power, however, is limited by nonlinear effects like Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS), Self-Phase Modulation and, specially, Modulation Instability (MI) [2]. The use of Gaussian pulse instead of Square ones, has been demonstrated for MI mitigation [3]. This paper shows practical advantages and limitations on using Gaussian shape optical pulses in phi-OTDR systems. We experimentally demonstrate that using Gaussian pulses improves the signal to noise ratio (SNR) of the detected phi-OTDR trace around the "blind zones" produced by MI. This improvement however doesn't mean the OTDR's dynamic range (DR) gets higher; indeed, the improvement is mainly of the first kilometers of the fiber.

2. Principle

MI is a non-linear effect, also known as "degenerate Four Wave Mixing", and is described as the interaction between the signal to be amplified, the spontaneous emission (ASE) generated by the optical amplifier within the signal band, and the ASE generated outside the signal band. This effect generates Stokes and anti-Stokes spectral sidebands, whose frequency shift, υ_s, depends on the optical power, P_i, as describe in the following equation [2].

$$v_s = \frac{1}{2\pi}\sqrt{\frac{2\gamma P_i}{|\beta_2|}} \qquad (2)$$

where β_2 and γ are the Group Velocity Dispersion (GVD) and the nonlinear parameter of the fiber, respectively. MI produces "blind zones" on the phi-OTDR traces [2–4], where the detected power level is greatly reduced and consequently the SNR of the detected vibration is degraded.

3. Experimental Setup

Fig. 1 (left) shows the experimental setup. The "optical pulse generator" block creates Gaussian or Squares pulses, with 1kHz of repetition rate. A CW light of the NLL is amplitude modulated using an Acousto-Optic Modulator (AOM_1), whose electrical modulation signal (Gaussian or Square) comes from an Arbitrary Function Generator (AFG). The created optical pulses are amplified by an Erbium Doped Fiber Amplifier ($EDFA_1$) and filtered to diminish the own EDFA's ASE. The AMO_2, also controlled by the AFG, is used to increase the amplitude extinction ration (ER) of the pulse, thus avoiding undesired coherent Rayleigh noise [5]. A variable optical attenuator (VOA) controls the peak power, whose level and shape are monitored by an oscilloscope (OSC) via the photodetector PD_1. The FUT is composed by three optical fibers (9.5, 10.5 and 1.1 km) and two piezoelectric fiber stretchers which simulate vibration points. Both stretchers are modulated by a 50 Hz sinusoidal signal. The "detection and processing" block amplifies the backscattered signal by using the $EDFA_2$, filters the ASE and finally detects and processes the signal by using the PD_2 and the OSC, respectively. Fig. 1 (right) shows the shape and peak power, of detected optical pulses by mean of the calibrated (Optical Power ∝ Voltage) PD_1. The full-width-at-half-maximum (FWHM) of 80 ns (the spatial resolution) were kept the same for both, the Square and the Gaussian, cases.

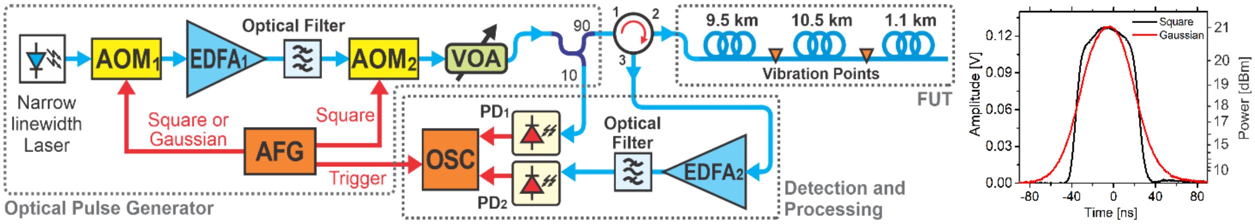

Fig. 1: (left) Experimental Setup and, (right) detected pulse shapes and peak powers using the calibrated (Optical Power ∝ Voltage) PD_1

4. Results

To show how MI behaves for the Gaussian and Square pulses, we selected different peak powers in our experiments. Fig. 2 shows the phi-OTDR trace for two optical peak powers, for (a) Gaussian and (b) square pulse. Note that MI is shown ("blind zones") when a square pulse of 29.0 dBm is used, and the use of the Gaussian pulse is less affected.

A tool to show MI in a clearer way is to compute the trace "Visibility" [3]. Though Visibility shows a clearer figure, it isn't a quantitative tool; however, it helps to understand other measurement types, such as SNR, for instance. Fig. 2 (c) and (d) shows the visibilities for four different peak powers (Square and Gaussian cases), where the Gaussians robustness against MI is clearly shown. When a 25.5 dBm peak power is used (red traces), the MI is not present in any of the cases. As the power grows, MI appears in the square pulse case, showing its typical "blind zones" whose positions and severity depends on the optical power [4]. So, for example, for 29.0 dBm (black trace), two "blind zones" are visualized, one between 7.5 and 9 km and the other between 12 and 13 km.

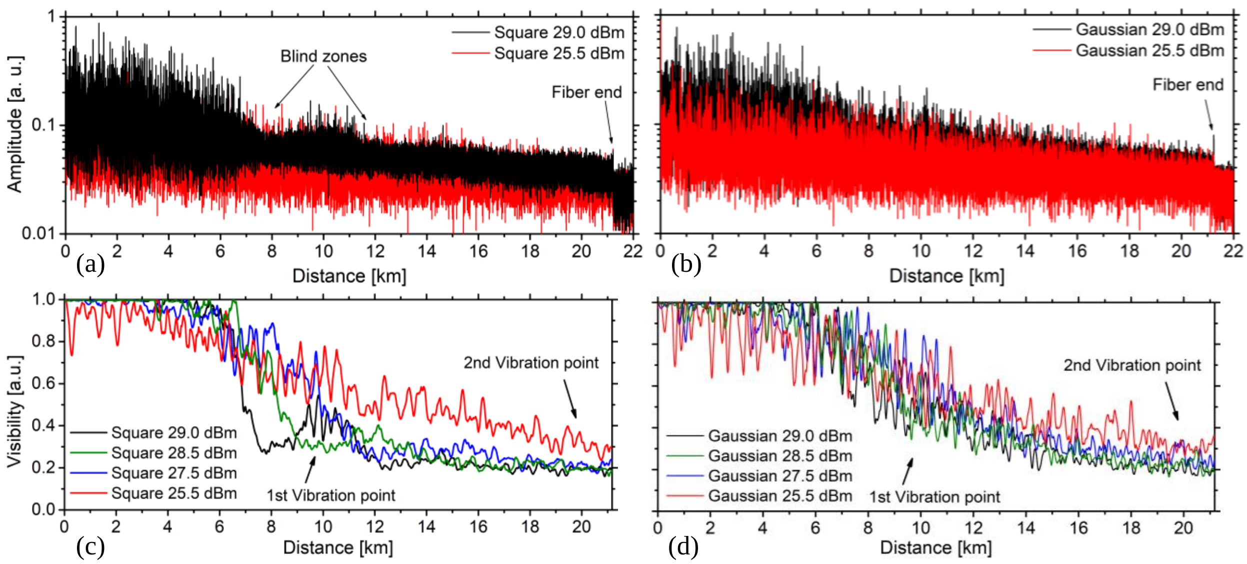

Fig. 2: phi-OTDR trace for two different pulse powers for (a) Square and (b) Gaussian pulse. Visibility for four different pulse powers for (c) Square and (d) Gaussian pulse

A better analysis tool is to measure the SNR of the detected vibration signal. Fig. 3 (a) shows the frequency spectrum of a detected 50 Hz vibration at 9.5 km, for Square and Gaussian pulses with the same peak power. The harmonics are due to phi-OTDR non-linear response. The SNR is calculated by adding up the harmonic powers and dividing it by the mean noise power. As higher harmonics have negligible power, we have selected only the first 5 harmonics in this calculation. Note that phi-OTDR fading could mask the actual SNR values. Thus, we performed a lot of trace acquisitions to obtain more reliable SNR values. For each computed SNR, we acquired 480 measurements; each measurement lasts 30 seconds, summing up 4 hours for each SNR final value. Besides, the 480 acquisitions for each SNR were distributed along different days and times to obtain a more realistic scenario.

First we compare the SNR of a vibration point at 9.5 km, when using 28.5 dBm peak power. At this power, a "blind zone" occurs around the selected vibration point (green trace of the Fig. 2 (c)). The SNR histogram comparison is shown in Fig. 3 (b); the mean SNR values are 29.9 and 23.7 dB, and the standard deviations 3.3 and 4.1 dB for Gaussian and Square pulses, respectively. The improvement in the Gaussian case, however, occurs around the "blind zones", and this does not mean that all positions in the probed fiber have the same level of improvement. Our experiments also show, as explained below, that Gaussian pulses do not improve the phi-OTDR's dynamic range, that is, longer fibers cannot be probed. This results contradict a statement in [3], where it is suggested that the probed fiber length could be doubled. To show this, we performed the measurements in the far end of the fiber, at 20 km, as shown in Fig. 3 (c). This figure shows the SNR mean and standard deviation of a detected vibration when using 8 different pulse peak powers.

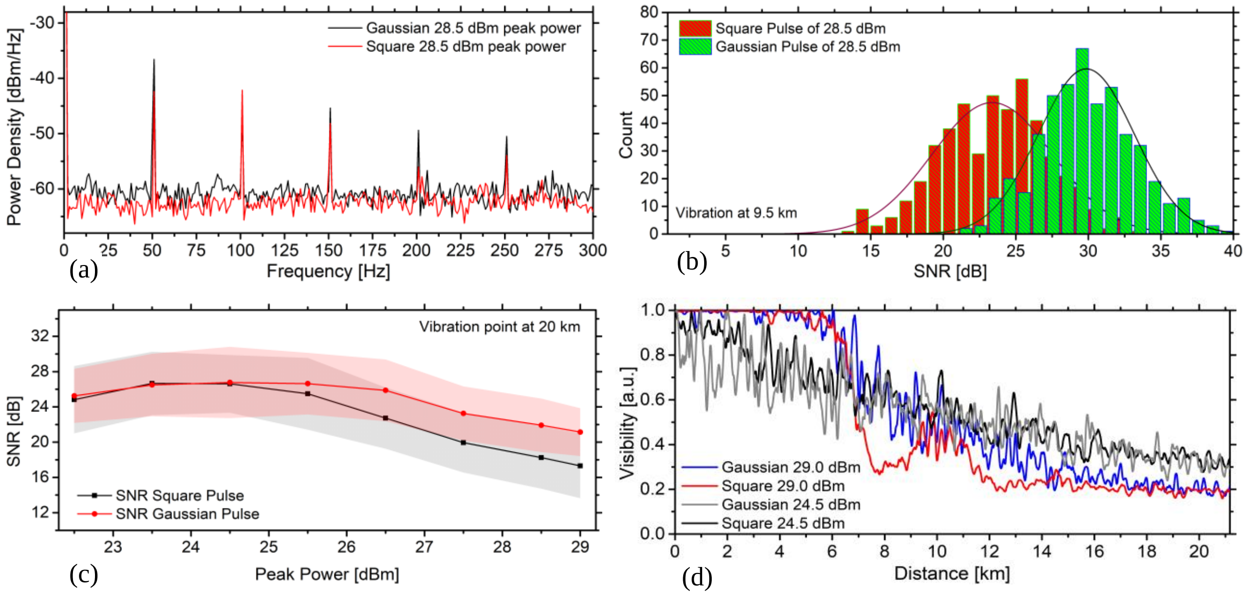

Fig. 3: (a) Frequency spectrum of a 50 Hz vibration detected at 9.5 km, (b) SNR histogram of 480 acquisitions for 28.5 dBm Square and Gaussian pulses, (c) SNR mean (solid line) and standard deviation (hatched area) for eight pulse peak powers, for Square (black) and Gaussian (red) pulse shapes and (d) Visibility comparison of Gaussian and Square pulses for two different peak powers

Fig. 3 (c) shows a power limit, around 24 dBm, for which the SNR gets its highest value, 26 dB. Note that this power level does not produce MI, neither for Gaussian nor for Square pulse. As the peak power increases above 24.0 dBm the SNR diminishes when using Square pulses. However, the SNR for the Gaussian case remains almost stable up to 26.5 dBm; after that, it decreases in the same fashion as the Square case. Besides, at higher powers, the SNR of the Gaussian case is around 4 dB above the Square one; however, both cases are below the maximum SNR of 26 dB.

It is clear that longer fibers cannot be probed since the SNR does no increase for higher peak powers, and at most it keeps the same value for a range of peak powers in the Gaussian case. Moreover, the SNR improvement is predominantly in the first kilometers of the fiber, and its value is better in and near the "blind zones". Our statement is also confirmed by comparing the Visibilities for 29.0 and 24.5 dBm peak powers, as shown in Fig. 3 (d). In this case, the Visibility improves for higher powers, but the improvement occurs in the first 6 km of the probed fiber. The use of a Gaussian pulse improves the visibility beyond 6 km, and the improvement is greater in the "blind zones".

4. Conclusions

This paper experimentally shows practical considerations when using optical Gaussian pulses in phi-OTDR systems. Although Gaussian pulses offers an increase on the detected SNR in the nearest end of the fiber, this improvement does not mean that higher dynamic range can be achieved, consequently no longer fibers can be monitored. Nonetheless, Gaussian pulses are useful when, for instance, tiny vibrations need to be detected in the near end of the fiber.

6. References

[1] Rao, Y., Wang, Z., Wu, H. et al., Recent Advances in Phase-Sensitive Optical Time Domain Reflectometry (Φ-OTDR). Photonic Sens 11, 1–30 (2021). DOI: 10.1007/s13320-021-0619-4

[2] Nesterov, E. T. et al, Experimental study of influence of nonlinear effects on phase- sensitive optical time-domain reflectometer operating range, J. Phys.: Conf. Ser. 584 012028, (2015), DOI:10.1088/1742-6596/584/1/012028

[3] Maria R. Fernández-Ruiz, et al., Phase-sensitive OTDR probe pulse shapes robust against modulation-instability fading. Opt. Lett. 41, 5756-5759 (2016)

[4] Hugo F. Martins, et al., Modulation instability-induced fading in phase-sensitive optical time-domain reflectometry. Opt. Lett. 38, 872-874 (2013)

[5] Hugo F. Martins, et al., Coherent Noise Reduction in High Visibility Phase-Sensitive Optical Time Domain Reflectometer for Distributed Sensing of Ultrasonic Waves. J. Lightwave Technol. 31, 3631-3637 (2013)