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# Raman-assisted Vector Brillouin Optical Time Domain Analysis

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## ABSTRACT

Raman-assistance (RA) has become a promising technique to enhance the sensing range of standard Brillouin Optical Time Domain Analysis (BOTDA) fiber sensors due to its ability to amplify in a distributed way all the interacting signals within the fiber. Unfortunately, Raman amplification introduces a great amount of Relative Intensity Noise (RIN) to the detected low-frequency probe wave. This RIN transfer problem has been widely identified as a major limitation in RA-BOTDA. In Vector Brillouin Optical Time Domain Analysis (VBOTDA) the detected signal is transferred to a high-frequency carrier where the Raman RIN transfer turns out to be much less harmful. In this work we demonstrate, for the first time to our knowledge, Raman-assistance in a VBOTDA. Our results show significant reduction of the RIN transfer effect in RA-VBOTDA compared to standard RA-BOTDA, making this type of scheme particularly interesting for long range distributed sensing.

**Keywords:** Brillouin scattering, distributed optic fiber sensor, Raman scattering, phase measurement, temperature sensing, strain sensing.

## 1. INTRODUCTION

The request for long-range (> 50 km) distributed fiber optic sensors for civil structure monitoring is progressively increasing every day due to the availability of new infrastructures crossing large unmanned areas. One of the preferred techniques for the distributed monitoring of large civil structures is Brillouin Optical Time Domain Analysis (BOTDA) [1]. However, a standard BOTDA can only range up to approximately 50 km. To achieve longer distances, range increasing techniques should be applied. Among these, one of the preferred techniques is Raman-assistance, either using first-order pumping [2] or second-order pumping [3], [4]. These methods can help to achieve 100 km sensing range [5] and beyond [4] maintaining a considerably high resolution (2-3 meter) without any special kind of data treatment.

Unfortunately, distributed Raman amplification introduces Relative Intensity Noise (RIN) transfer to the detected signal. This RIN transfer appears to be stronger at lower frequencies (< 200 MHz) [5], which is the frequency region where the detection scheme of a standard BOTDA operates. The transferred quasi-periodic noise turns out to be extremely difficult to completely average out in the acquisition scheme, and sometimes digital filtering techniques are necessary for high-performance applications [6]. Overall, RIN transfer has been identified by many authors [7] as a major limitation in the performance of long-range and high resolution Raman-assisted BOTDA sensors.

Vector Brillouin Optical Time Domain Analysis (VBOTDA) [8], [9] transfers the detected signal to a high-frequency carrier region (> 500 MHz) where the RIN transfer from the Raman pump to the probe signal should be strongly attenuated. The origin of this RIN transfer reduction lies in the large walk-off times between the Raman pumps and the BOTDA signals induced by chromatic dispersion (several periods of the carrier signal in VBOTDA). This causes any noise perturbation in the Raman pump to slip along several signal periods, amplifying the whole signal more homogeneously and reducing significantly its deleterious effect. So in principle this scheme can be used to strongly reduce RIN transfer drawbacks when enhancing the range of a distributed fiber optic sensor.

In this work we demonstrate, for the first time, Raman assistance in a VBOTDA. We provide experimental data showing that RIN transfer in a VBOTDA can be reduced by more than 10 dB over a conventional BOTDA in a bi-directional Raman amplification scheme. The results shown illustrate the potential of this technique for long-range measurements.

## 2. EXPERIMENTAL SETUP

A VBOTDA is very similar to a standard BOTDA: a pulsed pump wave interacts locally with a frequency shifted counter-propagating signal through Stimulated Brillouin Scattering (SBS). Instead of a continuous-wave probe, in VBOTDA the probe is phase modulated (PM) to create two sidebands. The frequency arrangement is done so that one of the sidebands of the PM signal falls in the SBS gain region [8]. This causes a local conversion of phase to amplitude modulation (AM), that can be easily detected by a high-bandwidth photo-detector. Amplitude and phase information can be obtained this way, even allowing real-time measurements [10]. Typical modulation frequencies of the PM signal can reach several hundred MHz without significant chromatic dispersion impairments. As mentioned before, for Raman assistance this turns out to be extremely interesting to avoid RIN transfer effects.

The developed experimental setup is mainly based on introducing a first-order bi-directional Raman amplification module to the VBOTDA developed in [8]. The employed system can be observed in Figure 1.

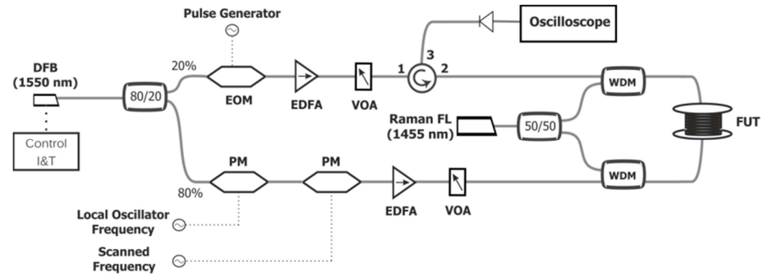

Figure 1. Experimental setup of the VBOTDA system assisted by first-order Raman amplification. DFB: Distributed FeedBack Laser Diode; EDFA: Erbium Doped-Fiber Amplifier; EOM: Electro-Optical Modulator; PM: Phase Modulator; VOA: Variable Optical Attenuator; WDM: Wavelength Division Multiplexer; FUT: Fiber Under Test; FL: Fiber Laser. Because of oscilloscope memory limitation, for a measurement over the full fiber length, the probe time of flight signal is logged with a microwave spectrum analyzer in 0 frequency span mode. Conversely for studying a short fiber section, we use an oscilloscope which has a higher analysis bandwidth. Oscilloscope can be sometimes replaced by a spectrum analyzer.

A low-noise ~500 kHz Distributed-FeedBack (DFB) laser diode emitting at 1550 nm is split to obtain both pump and probe waves. The pump wave is achieved by pulsing the continuous output of the DFB with 200 ns pulses (20 meter resolution) and afterwards amplified through an Erbium Doped Fiber Amplifier (EDFA) to obtain pulses with ~3.5 mW peak power. On the probe wave side, two phase modulators are employed. The first one, labeled as the Local Oscillator ($F_{LO}$) , the detected frequency, is fixed at 750 MHz, which is far enough from the RIN transfer region. The other one can be tuned in the 10 GHz range and allows to scan over the Brillouin Gain Spectrum (BGS). These two modulators develop a probe spectrum for the BGS scan at $\pm F_{BGS} = \pm(F_S+F_{LO})$. By tuning the $F_S$ frequency so the $F_{BGS}$ frequency is located around the BGS, $-F_{BGS}$ will be located in the gain regime while $+F_{BGS}$ will be in the loss regime [11]. This unbalance will disrupt the phase modulation equilibrium provoking an amplitude beat note at the $F_{LO}$ frequency. This frequency can be detected in the high-bandwidth detector and demodulated, providing information of both gain and phase of the BGS. The probe signal power is also amplified in this case to obtain a power level ~40 μW. This level ensures a good signal level at the detection side while still avoiding undesired non-linear effects as well as pump depletion. The distributed Raman amplification is developed through a FL emitting at 1455 nm which amplifies all the signals within the fiber. These lasers are nowadays the ones that can provide enough power in order to provide a considerable range extension, although, as stated, they introduce a great amount of RIN transfer (RIN of the FL is -110 dBc/Hz).

Besides confirming the RIN transfer reduction, the system was also tested as a temperature sensor. 84.5 km of fiber were monitored, formed by three spools spanning 40 km, 42.5 km and 2 km respectively. All three reels had a maximum Brillouin Frequency Shift (BFS) of 10.866 GHz at 20 ºC. The resolution of the system, set at 20 meters, was considerably low due to system limitations, although it is not a significant drawback in this work since the reduction of RIN transfer can be equally tested under these conditions (it mainly affects the probe detection).

# 3. RESULTS

The verification of the RIN transfer reduction was developed by measuring the whole frequency spectrum of the probe signal with and without the distributed Raman amplification. As a simple test, the bi-directional Raman amplification was set at 550 mW, which means 275 mW of Raman amplification on the probe side. Figure 2 shows the FFT$^2$ (squared Fast Fourier Transform) representation of the detected probe wave RIN noise as a function of frequency. As it can be clearly seen, at low frequencies (< 200 MHz), where a standard BOTDA operates, the probe RIN level increases around 30 dB when the Raman pump is turned ON (blue trace). By setting the probe wave at 750 MHz it can be seen that the noise increase given by Raman pumping is reduced until 20 dB, which implies a 10 dB reduction in terms of transferred noise. As long as the frequency increases the noise is reduced even more (15 dB reduction at 1 GHz). At higher frequencies the chromatic dispersion effect introduces a non-negligible PM-AM conversion in the probe signal [11], and would therefore restricts the VBOTDA dynamic range accordingly. Therefore, it is necessary to find a proper trade-off between the RIN reduction achieved and the dynamic range reduction caused by chromatic dispersion. For the experimental settings, we have set $F_{LO}$ = 750 MHz.

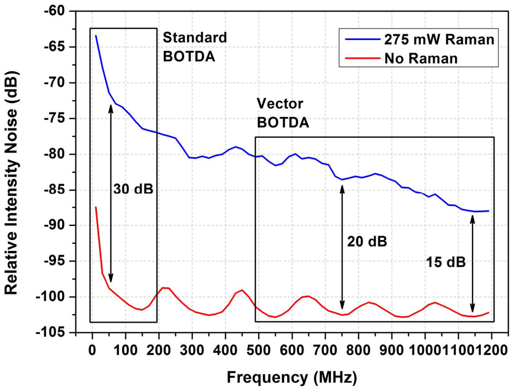

Figure 2. Comparison of the RIN transfer to the probe wave when the Raman pump is OFF (red trace) and when the amplification is set at 550 mw in a bi-directional configuration (275 mW for the probe signal).

Once the RIN transfer reduction was proved and selected 750 MHz as the proper modulation for our purposes, the performance of the Raman-assisted VBOTDA as a sensor was tested. In order to do that, the last 2 km of the total 84.5 km were introduced in a temperature controlled oven. The first 82.5 km of fiber were kept at 20 ºC constant controlled temperature, which generated a maximum BFS at 10.866 GHz, while the heated fiber was set at 60 ºC. The 40 ºC temperature difference is translated as approximately 52 MHz of frequency shift (1.3 MHz/ºC)[8]; thus, we expect at 82.5 km a 20 meter gain transition from 10.866 GHz until 10.918 GHz.

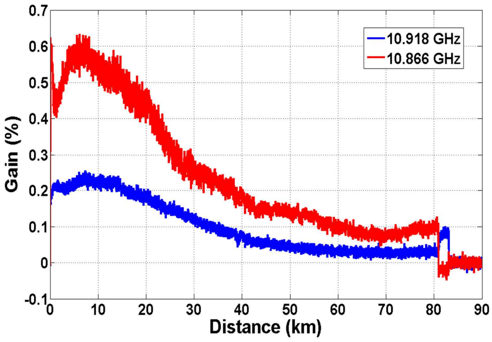

Figure 3. Whole trace measurement (spectrum analyzer) for 10.866 GHz (red trace) and 10.92 GHz (blue trace). At the expected location (82.5 km) a clear gain transition is observed, and the maximum gain at the fiber end is shifted as expected.

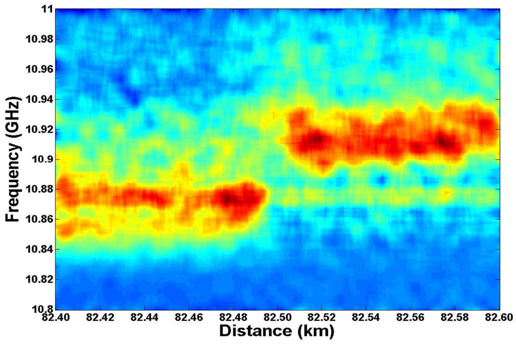

Figure 4. 200 meter zoom (oscilloscope) at the heated fiber transition zone. A 20 meter transition can be seen at the expected location from 10.866 GHz until 10.918 GHz, which corresponds to the 40 ºC difference (0.0013 GHz/ºC).

In Figure 3, it can be seen the whole 84.5 km traces (82.5 km + 2 km) at the frequencies of 10.866 GHz and 10.918 GHz (corresponding to the BG shift at 20 ºC and 60 ºC). The acquisition is done with 500 averages. A clear gain shift in the end of the fiber is noticeable, and the contrast between the heated and non-heated section is very good. As it can be observed, no RIN transfer is noticeable even with the relatively low number of employed averages. A detailed sweep of the transition between the heated and non-heated sections is seen in Figure 4. A complete switch of the gain position can be seen around the position of 82.5 km. Visibly, the complete gain switch is achieved in 20 meters, confirming the aforementioned resolution values. This measurement was developed in a 200 meter span through an oscilloscope. The measurement was developed trying to obtain a neat trace with the minimum number of averages possible, so as to illustrate the good RIN transfer capabilities of the setup. In this case 512 averages were employed.

## 4. CONCLUSIONS

In this work we have demonstrated for the first time first-order Raman assistance in a VBOTDA. Compared to a standard BOTDA, the VBOTDA uses a high-frequency (> 500 MHz) modulated probe wave. In terms of Raman assistance, this allows reducing considerably the RIN transfer effect to the detected amplified probe wave, which is one of the major limitations in Raman-assisted Brillouin distributed sensors. The measured noise reduction can be as large as 10 dB. Further reduction could be achieved at higher frequencies; however a trade-off remains to be found because chromatic dispersion will at the end cause some undesired PM-AM conversion in the probe wave and reduces the dynamic range of the measurement. The performance of the setup as a sensor was neatly verified with furthermore very low averaging (~500) compared to a standard BOTDA, proving the potential of this technique in long-range distributed measurements.

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