Raman-based Distributed Temperature Sensor using Simplex Code and Gain Controlled EDFA

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ABSTRACT

In this work we present a comparison between simplex coded and optical amplified simplex coded Raman based Distributed Temperature Sensing (DTS). An increase in performance is demonstrated using erbium doped fiber amplifier (EDFA) with proper gain control scheme that allows a DTS operates with simplex code. Using 63-bit simplex code and gain controlled EDFA we demonstrated the temperature resolution and dynamic range improvement in 16 °C @ 10 km and 4 dB, respectively.

Keywords: DTS, Simplex Code, Gain Controlled EDFA, AGC.

1. INTRODUCTION

Fiber-based Distributed Temperature Sensor (DTS) have been used in different areas, most common application includes power cable temperature monitoring, fire detection and pipeline leakage detection systems[1, 2]. The optical fiber passivity allows using DTS systems in explosive atmospheres, nuclear power plants and environments with high electromagnetic interference (EMI)[3].

Raman-based DTS techniques are based mainly on Optical Time Domain Reflectometry (OTDR), and the temperature measurement is implemented by the ratio of Stokes and anti-Stokes (AS) backscattering signals[4]. Several efforts have been made to increase the Raman-based DTS system performance[5, 6] in the past years. Almost all of these developments aim to increase the signal-to-noise ratio (SNR) of the anti-Stokes backscattering signal, once this signal has some drawbacks, such as very low optical power and poor SNR.

Erbium Doped Fiber Amplifiers (EDFA) have been widely used to improve the range in optical telecommunications networks[7], but for coded OTDR application other amplification technique such as lumped Raman amplifier (LRA) have been used due to the waveform distortion caused by the slow transient effect of EDFA[6]. Although LRA proved be a suitable solution to improve the DTS performance, this amplifier is more expensive than EDFAs, which are a common technology nowadays.

In this work, we explore simplex code amplified by a gain controlled EDFA in order to improve the anti-Stokes backscattering SNR. We also demonstrate for the first time to our knowledge that EDFA with gain control enables increasing the backscattering SNR without distortion due to low frequency transients.

2. RAMAN BASED DTS AND GAIN CONTROLLED EDFA

The temperature estimation on Raman based DTS is performed by monitoring the backscattering intensity of Stokes (I_{ST}) and anti-Stokes (I_{AS}) caused by a high intensity pulsed laser. This ratio can be approximately expressed as $\left(I_{AS}/I_{ST}\right) \propto \exp\left(h\Delta\nu/kT\right)$, where h is the Planck constant, k the Boltzmann constant, T the absolute temperature, and $\Delta\nu$ the separation between Raman anti-Stokes and Stokes light frequencies[4].

The anti-Stokes is more sensitive to the temperature variation than the Stokes backscattering but it is difficult to be detected due to its very low optical power and consequent poor SNR. Typically, the anti-Stokes backscattering optical power is around 30 dB below the Rayleigh backscattering used in conventional OTDR equipment. Thus, to improve Raman-based DTS performance some techniques[5,6] have been used in order to increase the backscattering traces SNR.

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Coding techniques provide significant SNR improvements. The code gain is defined as the ratio of SNR obtained with coded OTDR to the SNR obtained with conventional OTDR using the same number of measured traces. For simplex coding the code gain (G_{code}) can be quantified as $G_{code} = (L+1)/(2\sqrt{L})$, where L is the code length[6].

Performance enhancement of coded DTS was previously demonstrated using simplex code and a co-pumped lumped Raman amplifier[6]. Although LRA proved to be a good approach, this amplifier uses a long dispersion shift fiber (DSF) and a high power fiber Raman laser witch increase the size, cost and power consumption of the amplifier. On the other hand, EDFAs are widely used in optical telecommunication networks, few meters of erbium doped fiber and low power pump laser (200 mW) can be used to achieve the desired optical gain. Thus, EDFAs present low size, cost and power consumption when compared with LRAs.

Unfortunately, EDFAs present waveform distortion caused by the slow transient effect in typical burst signals such as simplex coded OTDR signals. These effects can be mitigated by a gain control scheme implemented in the EDFA. This method will be described in the next section.

3. EXPERIMENTAL SETUP

Figure 1 shows the experimental setup block diagram used to explore the DTS system based on simplex code and EDFA amplification. A field programmable gate array (FPGA) was used to modulate a Fabry Perot laser diode at 1536 nm (80 mW, 10 nm FWHM) according to the simplex code pattern and 100ns pulse width. The light pulses, amplified by a gain controlled EDFA, were injected into the fiber link through an optical circulator, the backscattered signals were filtered by a band pass filter (1445 - 1475 nm), used to avoid amplified stimulated emission (ASE) in the Raman anti-Stokes backscattering, and then coupled to the receiver. The receiver block was composed by an InGaAs avalanche photodiode (APD), a transimpedance amplifier (TIA) and electrical amplifier stages. After the receiver we used a Analog to Digital Converter (ADC) (200 MHz; 50 MS/s) embedded in a oscilloscope, the traces acquired were stored in a PC by a self-developed LabView Virtual Instrument (VI) and, processed using a Matlab script. The optical sensing link was composed by four spools of standard single mode fiber (SSMF) with lengths 3.9 km, 4.9 km, 19.8 km and 3.8 km. Spool #2 and spool #4 were exposed to a high temperature (80º C) and the others spools were left at room temperature (25º C).

Figure 2 shows the all-optical EDFA automatic gain control (AGC) block diagram, which was mounted using two identical add/drop centered at 1554.6 nm. The technique is based on a feedback loop where part of the amplified spontaneous emission (ASE), is dropped by the Add/Drop #2, passes through optical attenuator and is coupled back into its input by Add/Drop #1. The dropped channel is amplified by the EDFA and once again dropped by the Add/Drop #2 for a new feedback cycle. After several cycles, this control channel acquires enough power becoming a laser in the loop and compete with the Fabry Perot laser for the EDFA gain. As a result, assuming an appropriate loop attenuation level, the control channel power responds in accordance to the power fluctuations of the simplex code pattern, maintaining the EDFA gain practically constant at 1536 nm.

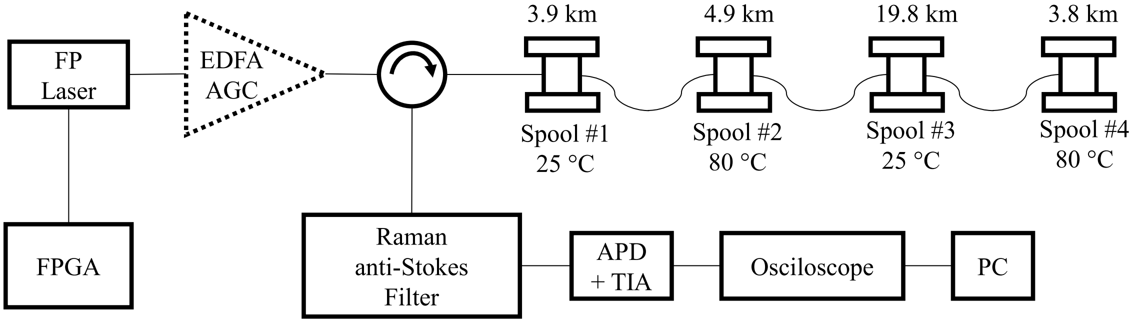

Figure 1: Experimental set-up block diagram

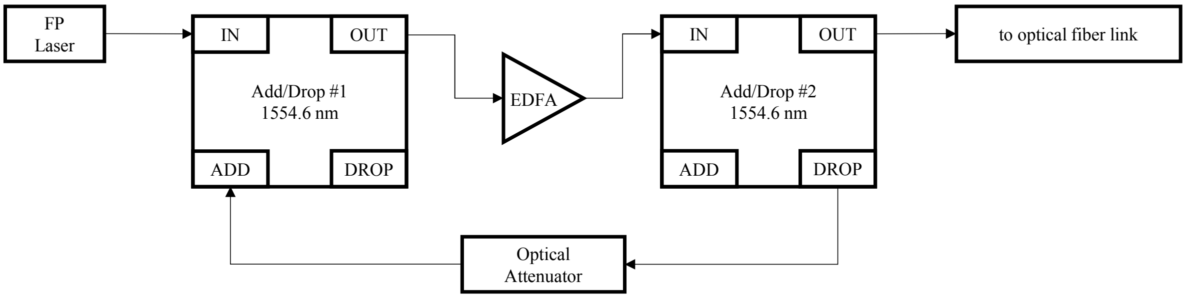

Figure 2: All-optical gain controlled EDFA block diagram

4. RESULTS

Figure 3 (a) reports the optical spectrum measured at the end of the optical link. Fabry Perot laser peaks can be observed at the 1530 nm region, the control channel (1554.6 nm) created by the add/drops is attenuated because this channel is dropped before the optical link.

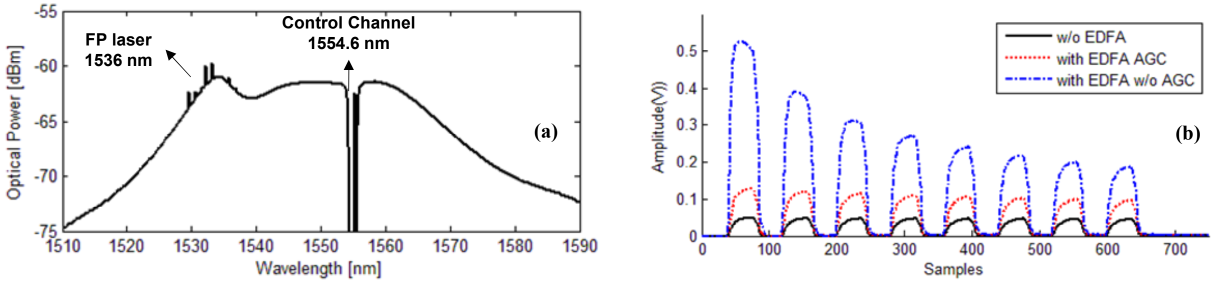

Figure 3: (a) Optical spectrum measured at the end of optical link and (b) EDFA gain control effect for a 15-bit simplex code word

Figure 3 (b) shows the results of the amplified coded pulsed laser in three conditions (without EDFA, with EDFA with AGC and EDFA without AGC) measured at the end of the fiber-sensing link using a 15-bit burst signal. The EDFA distortion is evident when the EDFA without AGC is implemented to amplify the simplex code burst signal, this distortion is strongly reduced when the AGC is employed. The attenuation on the control channel was adjusted to decrease the EDFA distortion and maintain the signal gain. In order to achieve the result shown in the Figure 3 (b) a 3 dB attenuation was applied to the control channel.

Figure 4 (a) shows the flatness gain in the bit sequence versus feedback loop attenuation. The flatness gain was measured as the gain variation on the amplitude of the first and the last simplex code bit 1 using a 15-bit simplex code word. As can be seen in the Figure 4 (a) flatness gain is better when the attenuation is low, but it implies that more optical power is used to control the EDFA gain.

In order to verify the SNR improvement provided by the gain controlled EDFA, the temperature estimation was performed using simplex coded OTDR and simplex coded OTDR with EDFA. Figure 4 (b) shows the traces of anti-Stokes backscattering after the decoding processes, in this case spools #1 and #3 (3.9 km and 19.8 km, respectively) were kept at room temperature and the spools #2 and #4 (4.9 km and 3.8 km, respectively) were heated at 80°C using a temperature controlled chamber. The enhancement in the dynamic range obtained was around 4 dB measured at the background noise.

In this experiment we acquired anti-Stokes traces using 100 ns pulse width, 63-bit simplex code and a total number of 63000 acquired traces (63x1000) being 1000 time averaging a single code word. Each trace spent 100 ms to be acquired, mainly limited by the processing time. Total processing time can be greatly reduced by the use of embedded processing instead of an oscilloscope as an ADC and a VI to trace averaging.

Figure 4 (c) shows the root-mean-square (RMS) temperature resolution versus distance for two approaches (simplex code and simplex code with EDFA), the enhancement in the temperature resolution when the second technique is used is clear. Using simplex code a 10°C temperature resolution is achieved for distances smaller than 4 km, the same resolution when the amplification is used can be obtained at 10km.

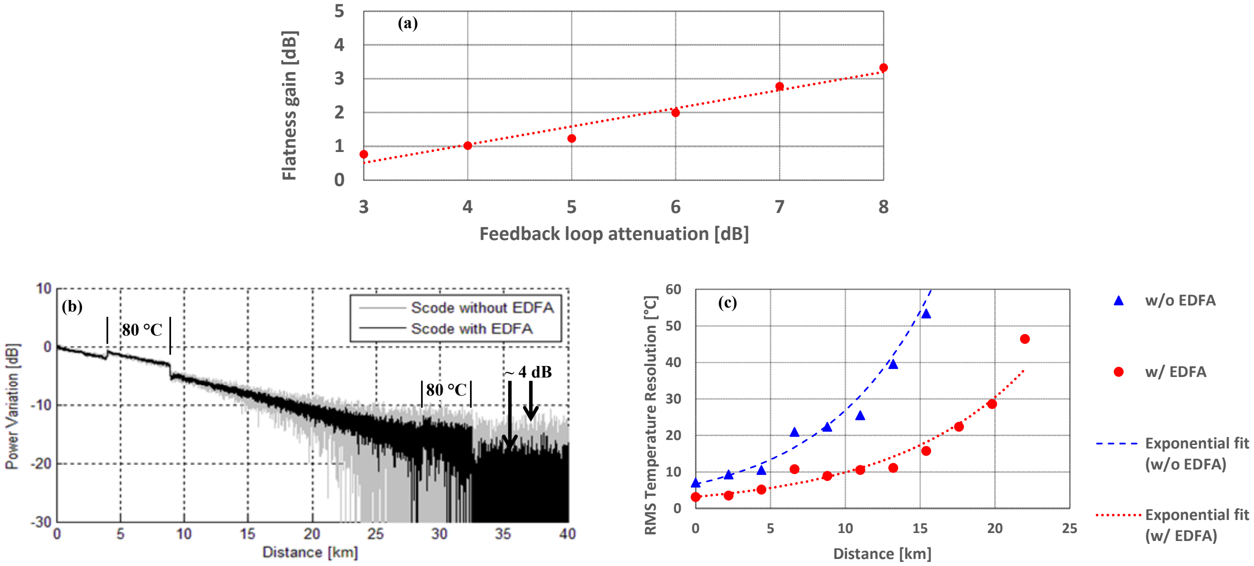

Figure 4: (a) Flatness gain and feedback loop attenuation (b) 63-bit simplex code anti-Stokes traces and (c) RMS temperature resolution.

5. CONCLUSION

We have demonstrated the performance enhancement on Raman-based DTS using 63-bit simplex code and an all-optical gain controlled EDFA implemented using commercial add/drops and an optical attenuator. Experiments showed an improvement around 4 dB in the dynamic range and 16 °C @ 10 km in the temperature resolution when compared with the system without amplification.

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