Repeaterless Brillouin OTDR Sensing over 250 km using Erbium doped Fiber Amplifier

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Abstract: We demonstrate a Brillouin OTDR sensing range of 251 km using two sections of remotely pumped Erbium doped fiber amplifiers. The temperature shift is measured with an accuracy of 3.3°C at 251 km.

1. Introduction

As part of the ongoing transition towards cleaner and renewable energy sources, implementation of offshore wind and solar farms are becoming widespread. Distributed fiber-optic sensors (DFOS) are used to monitor the high voltage power cables that transport the generated green energy to the coasts. DFOS systems based on Brillouin scattering can achieve long sensing range due to high Brillouin scattering in optical fibers [1]. Brillouin Optical Time Domain Reflectometry (BOTDR) systems based on spontaneous Brillouin scattering can sense temperature and strain changes in fiber at a length of 100 km [2]. Using distributed Raman amplification and remotely pumped Erbium doped fiber (EDF) amplification, the sensing range of repeater-less BOTDR sensing can be increased to 250 km [3]. In distributed Raman amplifier schemes, pump depletion and dispersion in the sensing fiber can cause significant deformation of the probe pulse. Such a deformed probe pulse can cause a spectral shift in the back scattered Brillouin field, which is detrimental to sensing systems that rely on Brillouin frequency shift, as this shift could incorrectly be interpreted as a temperature or strain change in the sensing fiber [4]. This problem of Brillouin spectral shift is also analysed in distributed Raman amplifier assisted BOTDA (Brillouin Time Domain Analysis) systems and a solution is demonstrated using a compensating pulse with a wavelength different than the sensing pulse [5]. Introducing such compensating pulses in BOTDR systems is rather complicated, and hence we propose a repeater-less BOTDR system which only use EDF amplifiers to extend the sensing range over 250 km. Two EDF amplification sections are implemented at appropriate positions of the sensing fiber span to simultaneously amplify the back-scattered Brillouin signals and the forward propagating pump signal.

Using the implemented setup, the Brillouin frequency shift with temperature change is measured at a remote distance of 251 km with a measurement accuracy of 3.3 °C. In this paper we demonstrate, to the best of our knowledge, the longest sensing range of all reported repeater-less BOTDR systems using a relatively simple EDF amplifier setup, which only requires single ended access to the fiber.

2. EDF assisted BOTDR system

The experimental setup is shown in Fig1. A commercial BOTDR interrogator (OTS4 series from Luna Innovations) is used for the measurement. OTS4 is set to generate a seven bit coded pulse sequence at 1550 nm with peak power of 150 mW [6]. The pulse width used is 200 ns, which corresponds to a spatial resolution of 20 m. Standard subsea telecommunication fibers (Ultra low loss TeraWave® SCUBA) of effective area (A_{eff}) 150 µm^2 (SCUBA-150) and 80 µm^2 (SCUBA-80) are used as the sensing fibers. The attenuation of the two fibers are 0.1499 dB/km and 0.160 dB/km at 1550 nm respectively [7]. The two EDFs (OFS Rightwave LP980) [8] are spliced to the sensing fiber at 90 km and 140 km of the sensing fiber. The EDFs are remotely pumped using a combination of 1455 nm and 1480 nm continuous wave pumps. The pump signal is propagated through a parallel ultra low loss SCUBA-150 fiber up to 140 km. SCUBA-80 fiber is placed in the last part of the span, so that the smaller A_{eff} of the fiber gives a larger Brillouin coupling.

The required EDF length is determined using a continuous wave (CW) EDF model which is described in [9]. A CW model is employed here, even though the probe is pulsed with the reason that the probe pulse does not deplete

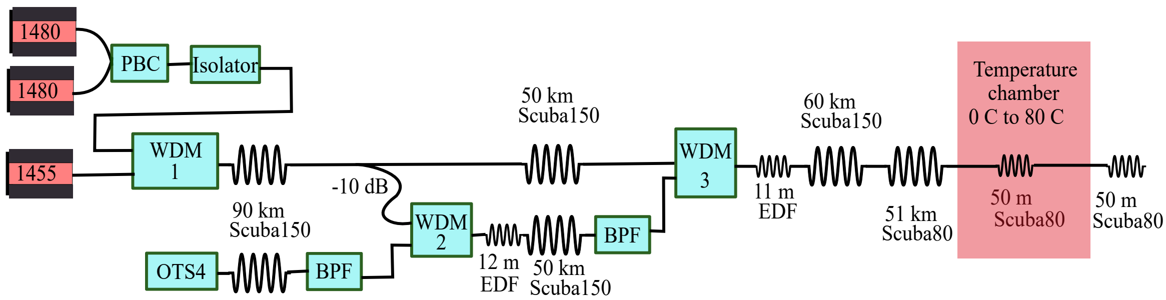

Fig. 1. Experimental setup used for long distance BOTDR using two EDF sections. 1480/ 1455: pump lasers, PBC: polarization beam combiner, OTS4: Brillouin OTDR, BPF: band pass filter, WDM: wavelength division multiplexer, EDF: Erbium doped fiber.

the Erbium amplifier with the parameters used in the configuration. Hence, the gain of the amplifier is calculated as the small signal gain of the CW model. The total pump power available after the first WDM (WDM1) is 1.54 W and the pump power launched to both EDF section is 2.5 mW. At this pump power, the model predicts a maximum gain of 7 dB for an EDF length around 10.3 m as shown in Fig 2a. There is more 1480 nm pump power available at the second EDF, which gives a higher gain compared to first EDF. For the experimental setup the two EDF lengths are chosen as 12 m and 11 m.

3. Results

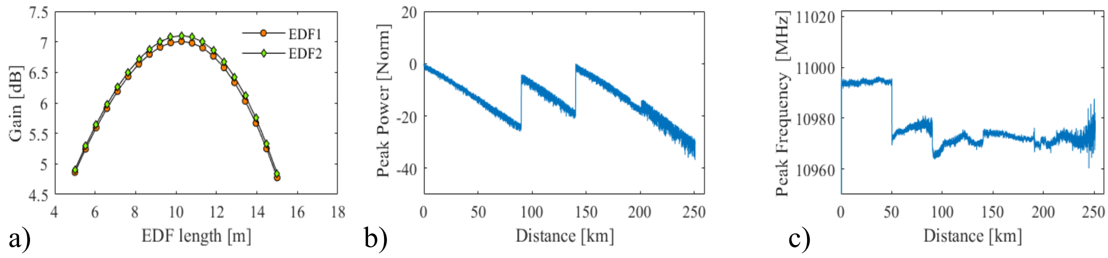

Fig. 2. (a) Modelled EDF gain (b) Measured Brillouin peak power and c) Peak frequency along the sensing fiber length.

The back-scattered Brillouin spectra are measured using OTS4 at a sampling interval of 1 m. The Brillouin peak frequencies and peak powers along the fiber span are obtained by fitting a Lorentzian function to the measured spectra. The BOTDR results for the 251 km fiber are shown in Fig 2b and c. The signal amplification provided by the EDF fiber can be seen at 90 km and 140 km. The total measured gain for both forward and backward propagating signal is around 18 dB. Hence the measured gain in one direction is 9 dB, which is larger than the gain predicted by the theoretical model. The variations in the fiber parameters used in the model could be the reason for this discrepancy. An increase in the Brillouin peak power is clearly visible after 200 km in Fig 2b, which is due to low A_{eff} of SCUBA-80 fiber. The measured Brillouin peak frequencies along the length of the sensing fiber is shown in Fig 2c. The peak frequencies change between the different fiber sections due to the in-built strain from the spooling of the fiber. The results shown in Fig 2b and c are obtained using a measurement time of 96 minutes. A reduction of measurement time to 20 minutes still enables a sensing range of 238 km, where the calculated standard deviation in peak frequency is 5 MHz.

3.1. Remote temperature sensing at 251 km

A 50 m of SCUBA-80 fiber at the remote end of 251 km is placed inside a temperature chamber in a loose coil and the last 50 m is placed outside the chamber at room temperature as shown in the schematic in Fig 1. The chamber temperature is changed from 0 °C to 80 °C. The measured peak frequencies at different temperatures are shown in Fig 3a. The shift in Brillouin peak frequencies with temperature at 251.9 km is clearly visible. The measurements are done with a sampling interval of 1m, hence there are 50 points corresponding to the 50 m fiber length placed in the temperature chamber. As the spatial resolution of the measurement is around 20 m, out of these 50 measurement points, only 31 points between 251.891 km to 251.922 km are chosen to calculate

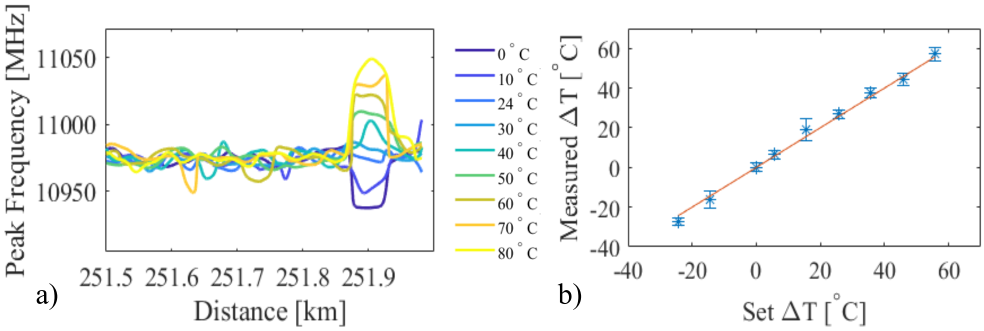

Fig. 3. (a) Brillouin Peak frequency shift with temperature at 251.9 km (b) Measured temperature shift as a function of actual temperature shift.

the average frequency shift for each temperature setting. The measured frequency shift ($\Delta\nu$) can be translated to the measured temperature change from room temperature (ΔT_{meas}) using the relation $\Delta T_{meas} = \Delta\nu/C_T$, if the temperature shift coefficient (C_T) of SCUBA-80 fiber is known. This value is obtained as 1.28 MHz/°C, by a more accurate measurement, at a spatial resolution of 10 m, on a short 50 m SCUBA-80 fiber in a loose coil connected 1 km after the OTS4 interrogator. The measured temperature change (ΔT_{meas}) is plotted against the actual temperature change in the chamber in Fig 3b, together with the standard deviation of the measurement. The accuracy of measured temperature, compared to actual set temperature in the chamber varies from 0.7 °C to 3.3 °C for ΔT between -24.3 °C to 55.7 °C.

4. Conclusion

The temperature sensing using single side interrogated Brillouin OTDR is demonstrated at a length of 251 km at an accuracy of 3.3 °C. Two Erbium doped fiber amplifier sections are implemented to amplify the probe pulses and the back scattered Brillouin signal. Distributed Raman amplification is deliberately avoided by propagating the pump signal through a separate fiber, which helps to avoid incorrect temperature measurements due to pulse deformation.

Acknowledgement

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