140 km Brillouin optical time domain reflectometry based on single-photon detector.

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ABSTRACT

Extending the range of distributed fiber sensors is one of the major challenges in the development of offshore wind turbines in order to monitor the transmitted electrical power inside the cables. Here we report a novel technique allowing to monitor the fiber up to 140 km, with a spatial resolution of 20 m in single-ended. Our method relies on the Brillouin anti-Stokes backscattering measurements that directly depend on the temperature along the optical fiber. The actual commercial devices have a range of 75 km. As a consequence, long infrastructures can't be monitored in single-ended. Here the proposed method allows us to monitor the temperature without the need for an amplification module.

Keywords: Fiber optics sensors, Brillouin scattering, Photon counting, Optical sensing and sensors.

1. INTRODUCTION

During the last years, the transport of energy via the development of offshore wind turbines has experienced strong growth. Monitoring the temperature along these infrastructures is essential to optimize the power inside the power cables 1–3. One solution consists in placing an optical fiber along the submarine power cables and monitoring the distributed temperature along the infrastructure. Different techniques allow measuring the temperature, Brillouin optical time domain analysis (BOTDA) 4–9, Raman DTS 10–12, Brillouin optical correlation-domain reflectometry (BOCDR)13, 14 and Brillouin optical time domain reflectometry (BOTDR) 15–19. Current infrastructure is getting longer and longer and approaching 150 km, but commercial BOTDRs are only limited to 75 km. It is therefore necessary to extend the range of these sensors, to be able to monitor the infrastructure from 75 km up to the end. One solution consists of using a single-photon avalanche diode (SPAD) in gated mode with a very low noise level (-120 dBm) 20. The method presented here, based on SPAD is able to measure the Brillouin signal up to 140 km, with a spatial resolution of 20 m in single-ended, without optical amplification along the optical fibre 1, 21–23.

2. EXPERIMENTAL CONFIGURATION

Brillouin optical time domain reflectometers are based on spontaneous Brillouin scattering. Brillouin backscattering intensity and frequency depend on the temperature and the strain[1] along the optical fiber. Our configuration is based on a continuous tunable laser at 1547.8 nm is used as a pump and a semiconductor optical amplifier (SOA) generates optical pulses of 200 ns, with a peak power of 13.6 dBm. Optical isolators are used before and after the SOA to avoid a laser effect, which results in a reduction of the extinction rate of the generated pulses. A standard telecommunication fiber (G-652) is used as a fiber under test. The backscattered light is filtered through a fiber Bragg grating (FBG) in order to remove the Rayleigh scattering and the Brillouin Stokes scattering. We only keep the Brillouin anti-Stokes scattering. In this configuration, we only measure the intensity variation, by positioning the Brillouin anti-Stokes signal at the center of the FBG response. As a consequence, we are not sensitive to the frequency variation. For the detection, we use a single-photon avalanche detector (SPAD) in gated mode (100 ns), in order to scan the backscattered light along the optical fiber. The SPAD has an efficiency of 20%.

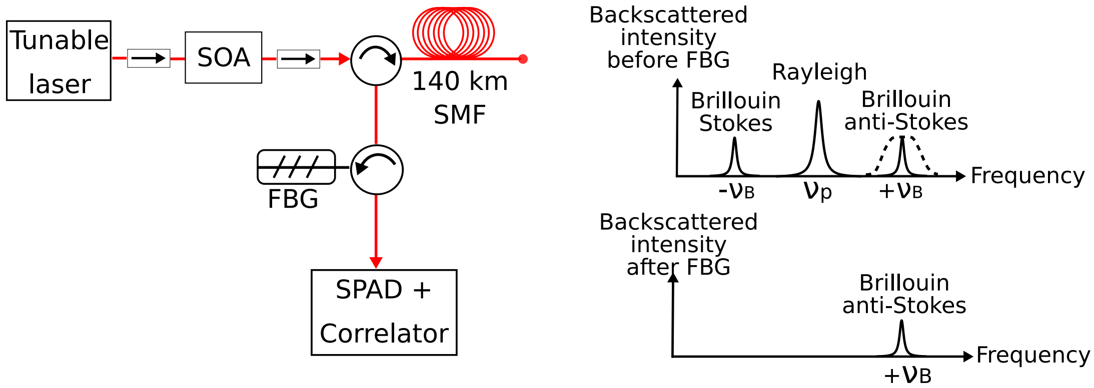

Figure 1. Experimental setup (left). Backscattered light spectrum before and after the Fiber Bragg Grating (right). SOA: semiconductor optical amplifier, SMF: single-mode fiber, FBG: fiber Bragg grating, SPAD: single-photon avalanche detector.

3. EXPERIMENTAL RESULTS

3.1 Measurement of Brillouin power along the optical fiber

By measuring the Brillouin anti-Stokes intensity, we can deduce the temperature fluctuation, by compensating fiber optic losses (0.19 dB/km) and using the temperature coefficient (0.38%/°C). In the following figure, we show the Brillouin anti-Stokes count rate as a function of the distance and the temperature variation for a 20 m spatial resolution and 4 hours of acquisition time.

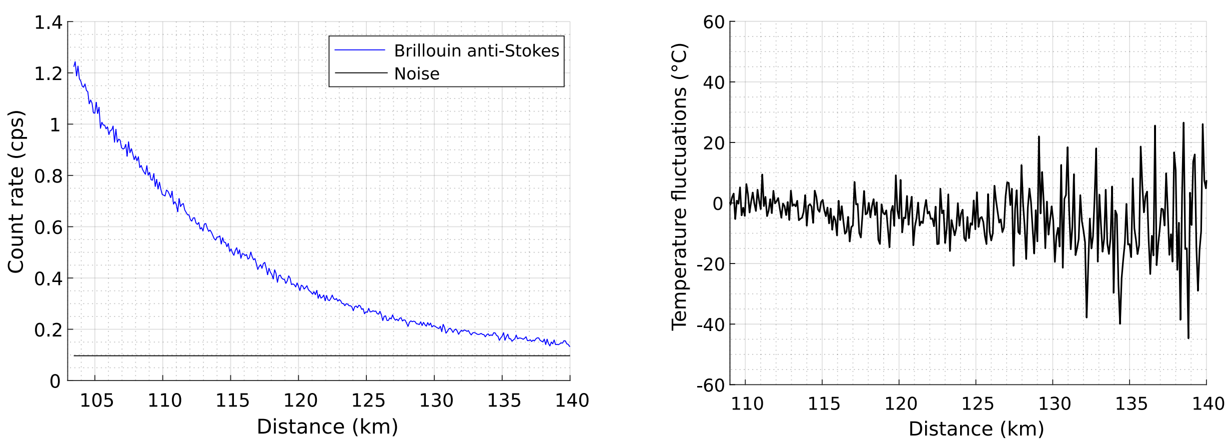

Figure 2. Count rate detection for a 1 hour measurement (left) and temperature profile deduced (right) for a 4 hours acquisition time and a spatial resolution of 20m.

In Fig. 2 (left) the Brillouin anti-Stokes count rate is shown in blue, as a function of the distance. The attenuation of the signal is due to the optical losses in the optical fiber (0.19 dB/km at 1550 nm). In black, we show the noise of the detection system. The noise of the system is composed of 2 main noises. The first one is the optical noise, that comes from the amplified spontaneous emission (ASE) from the SOA. The second one is specific to the SPAD, which is the dark count rate. It corresponds to a false detection, without any incident photon on the detection surface. In our configuration, the noise is equivalent to 0.097 cps.

The Brillouin count rate at 140 km is around 0.14 cps, that leads to an SNR of 1.6 dB at 140 km.

3.2 Hot spot detection in an oven at 100 km

The photon-counting BOTDR (ν-BOTDR) measures the intensity variation of the Brillouin backscattering. The Brillouin intensity dependence is 0.38%/°C. To test our sensor, we place 160 m of optical fiber in an oven heated to 100°C, after 99 km of optical fiber. The ambient temperature of the laboratory is around 20°C.
The temperature measurement is realized with a spatial resolution of 20 m, with a sampling interval of 10 m, for an average of 1 hour.

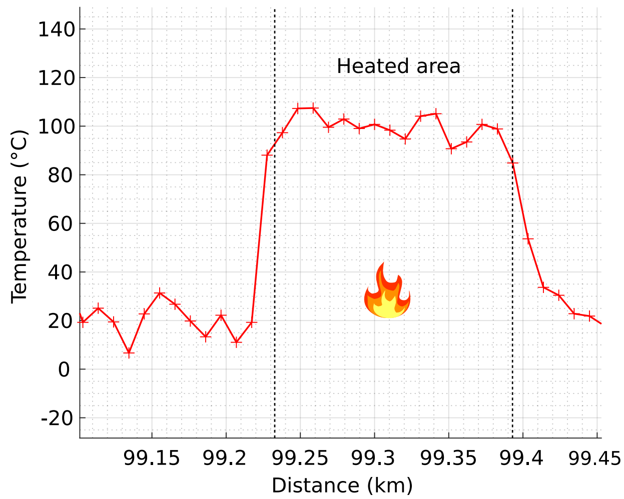

Figure 3. Temperature profile around the oven heated to 100°C. Spatial resolution of 20 m, sampling 10 m, acquisition time 1 hour.

In Fig. 3 we show the temperature profile get around a 160 m fiber loop placed in an oven heated to 100°C. The ambient temperature is around 20°C. The standard deviation on the 14 points located in the oven is 9.7 °C. The standard deviation is lower in the oven compared to the ambient points, due to a higher counting rate of Brillouin scattering at high temperature. The distance between ambient temperature and the heated area is below 20 m and validates the spatial resolution of 20 m.

3.3 Standard deviation on temperature measurements

According to the acquisition time, the temperature accuracy is affected differently. In Fig. 4, we show the standard deviation of the temperature, on 21 physical points as a function of the acquisition time and the distance, for a spatial resolution of 20 m.

In Fig. 4 (left) we see that by increasing the acquisition time of the measurement, we improve the sensitivity of the sensor, by decreasing the standard deviation on measurements.

In Fig. 4 (right) we show the limit of our sensor for different σ, according to the distance and the acquisition time. At 110 km, we are able to realize a measurement in 1 hour, with a standard deviation of 7.5°C. However, to reach a distance of 125 km, with the same σ we need to do an averaging over 190 minutes. With the 3 configurations, we clearly see that a trade-off has to be made, between the sensibility, the range, and the acquisition time.

3.4 Influence of spatial resolution on temperature sensitivity

In order to quantify the sensibility of the fiber sensor, we use the standard deviation (σ), expressed in degrees. In Fig. 5, we show the standard deviation on temperature measurements as a function of the spatial resolution.

In Fig. 5 we clearly see the influence of the spatial resolution on the temperature sensitivity. For long-range measurement, we need to sacrifice spatial resolution in order to improve the sensibility thanks to a higher signal-to-noise ratio. For a 10 m spatial resolution, after 125 km, the measurement starts to be not acceptable, and after

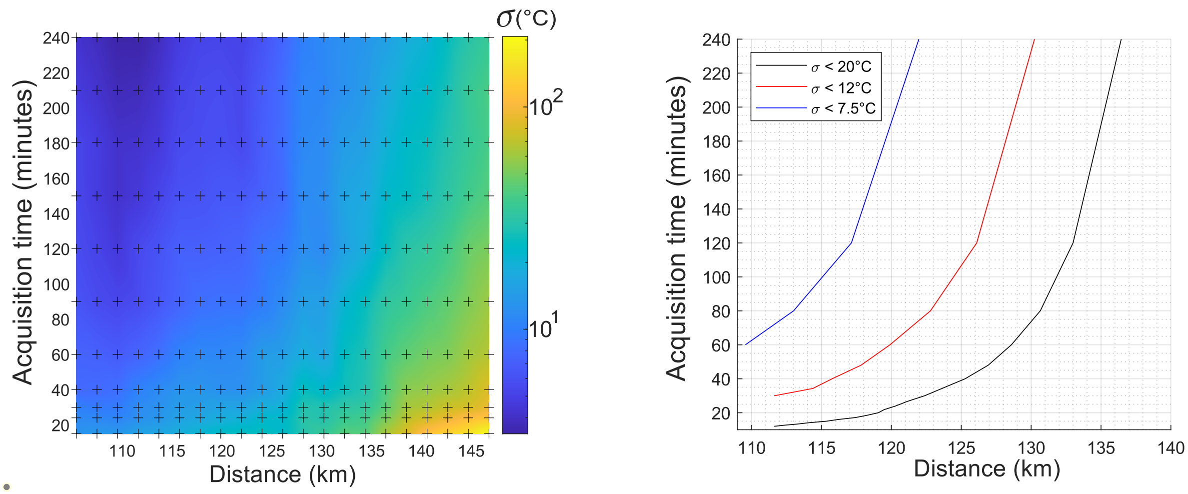

Figure 4. Standard deviation on temperature measurements with a spatial resolution of 20 m. A color map representation is shown on the left. Crosses correspond to a physical measurement of the standard deviation. On the right, we show the limit as a function of the distance and the acquisition time, to reach a measurement below a particular standard deviation (σ).

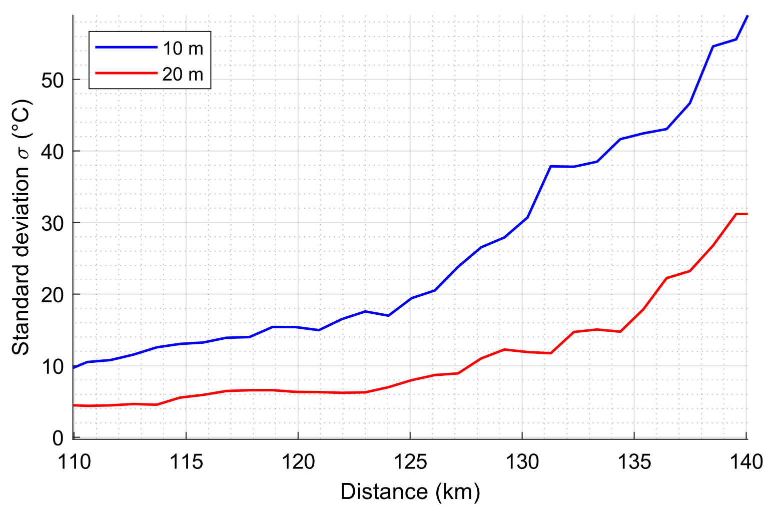

Figure 5. Standard deviation on temperature measurements as a function of the spatial resolution (10 and 20m).

120 km, the measurement is not exploitable, even for hot spot detection. However, for 20 m, the temperature sensibility is better due to a higher SNR. Until 125 km with a spatial resolution of 20 m, the standard deviation is below 10°C, and until 135 km the standard deviation is below 20°C. At 130 km, the standard deviation is around 11°C and 30°C for 20 m and 10 m spatial resolution, respectively. By doing a comparison between the 2 curves, we can observe a gain of around 12 km between the 2 configurations. This is due to larger optical pulses and larger detection gates, with a corresponding gain of 6 dB. As a consequence, the signal detected is larger and the statistic is better.

4. CONCLUSION

In this paper, we have demonstrated a measurement with a BOTDR technique based on photon counting, able to measure Brillouin scattering up to 140 km with a 20 m spatial resolution. We show the influence of the acquisition time and the spatial resolution on temperature sensitivity. According to the application, we show that there is a trade-off between the acquisition time, the range and the sensitivity. When a parameter is the priority, we need to loose on the others.

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