Single-photon detector-based long-distance Brillouin optical time domain reflectometry

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Abstract. We present a long-range Brillouin optical time domain reflectometer (BOTDR) based on photon counting technology. We demonstrate experimentally the ability to perform a distributed temperature measurement, by detecting a hot spot in a thermal bath at 100 km, and the possibility to achieve measurement until 120 km with a spatial resolution of 10 m. We use the slope of a fiber Bragg grating (FBG) as a frequency discriminator, to convert count rate variation into a frequency shift. A performance study of our distributed sensor as a function of spatial resolution is also presented.

1 Introduction

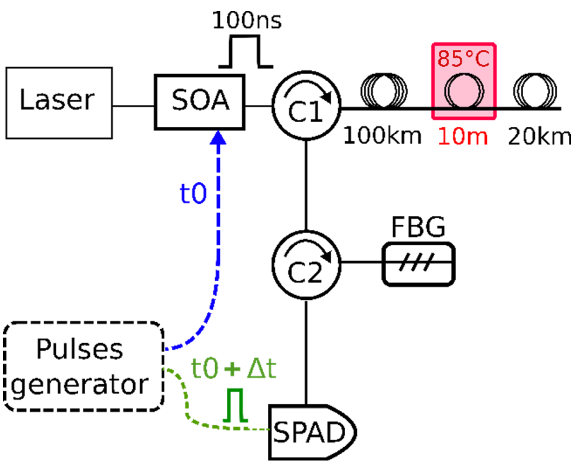
During the last few years, energy transport via the development of offshore wind turbines has experienced strong growth. Monitoring these infrastructures is necessary and requires measuring the temperature along the submarine cables [1]. One solution consists to put an optical fiber along the cables, to monitor the temperature using a distributed fiber sensor based on Brillouin scattering. Here, we present a novel BOTDR (Brillouin optical time domain reflectometer) using a single-photon avalanche diode (SPAD) [2] in gated mode with the ability to measure the Brillouin frequency shift, related to the temperature [1]. In our experiment, a fibre Bragg grating (FBG) slope is used to convert the count rate variation into a frequency shift.

2 Experimental results

2.1 Setup description

A simplified diagram of our ν-BOTDR is shown on Figure 1. A 1547 nm continuous laser is used as the pump, followed by a semiconductor optical amplifier (SOA) to amplify and create optical pulses (100 ns, +15 dBm) with an extinction ratio of 62 dB. The repetition period (T=1.25 ms) of pulses is determined by the optical fiber length (120 km). Optical pulses are sent to the single-mode fiber (G.652.D, attenuation of 0.19 dB/km), and the backscattering light is collected through the circulator C1. We use a Fiber Bragg Grating (FBG) as a filter to reject Rayleigh and Brillouin Stokes scattering to isolate the Brillouin Anti-Stokes signal. Then, the Brillouin scattering is measured with an InGaAs/Inp SPAD, which is used in gated mode with 50 ns gate width (τ) and a dead time of 20 µs. The configuration of the SPAD allows us to reach a low noise level of – 120 dBm. In our case, the dead time has no influence on the photon counting performance, because the gate repetition period is much greater than the dead time. This configuration makes it possible to overcome after-pulsing problems [3]. In order to optimize the SNR and the measurement time, we work at 20% SPAD efficiency [4].

Fig 1. Experimental setup for measuring the distributed Brillouin response. At 100 km, a 10 m spool fibre is placed into a thermal bath heated to 85°C. SOA: Semiconductor Optical Amplifier. SPAD: Single-Photon Avalanche Detector. C: Circulator. FBG: Fiber Bragg grating.



The challenge of using SPADs is to successfully measure the Brillouin frequency. In our system, we convert a number of photons (counts) into a frequency using the slope of a narrow fiber Bragg grating (FBG) which has a

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https://doi.org/10.1051/epjconf/202328709013

full width at half maximum (FWHM) of 2.7 GHz. By positioning the Brillouin Anti-Stokes resonance, 10.86 GHz shifted from the pump in our configuration, on the FBG slope, we are able to retrieve a frequency shift from the count rate variation. The FBG working point can be adapted to optimize the frequency sensitivity. Note that the Brillouin Stokes could be used equally well.

2.2 Brillouin trace

By scanning the optical fiber, we get the Brillouin anti-Stokes trace presented in Figure 2. We obtain a good agreement with linear fiber losses (0.192 dB/km).

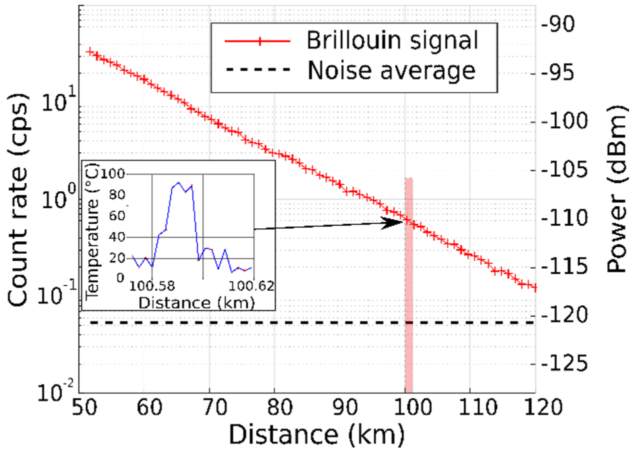

Fig 2. Experimental Brillouin anti-stokes trace (in red) and the SPAD dark noise (in dark). The temperature profile at 100 km around the thermal bath is shown in blue.

3 Influence of spatial resolution on sensor range

One important parameter of fiber sensors is the spatial resolution [5], which is the ability of a distributed temperature sensor to differentiate 2 fiber portions, submitted to different temperatures. Optically, the spatial resolution depends on the optical pulse duration. Our work is based on a 100 ns pulse width, corresponding to 10 m spatial resolution. In Figure 3 we show the influence of spatial resolution on our sensor range.

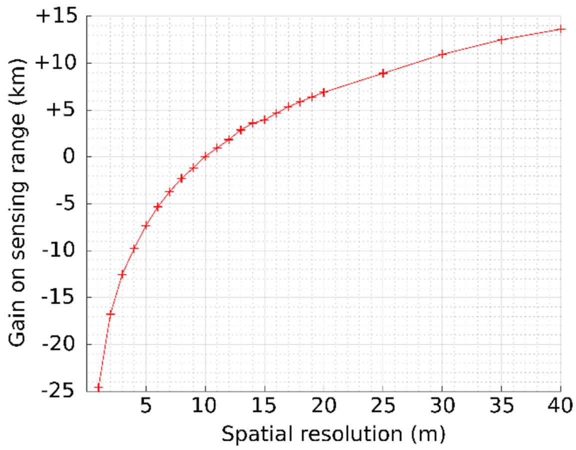

Fig 3. Nu-BOTDR range as a function of the optical pulse width.

Figure 3, quantifies the gain on the sensing range of our sensor, according to the spatial resolution set. We clearly observe that the gain is significant when the optical pulse width is increased by a factor of 2. It is also noted that the gain begins to saturate beyond 30 m spatial resolution.

Conclusion

We have extended the range of distributed Brillouin fiber sensors up to 120 km using a single photon detector while maintaining a spatial resolution of 10 m. The significance of SPAD efficiency in enhancing the sensor's performance has been highlighted, and the minimum acquisition time required for accurate measurements has been determined.

References

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