Physical Limits of Raman Distributed Temperature Sensing - Are We There Yet?

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Abstract: Raman DTS systems provide an accurate measurement of temperature along a sensing fiber. This paper presents fundamental limits of measurement range for a DTS whilst providing a practical temperature and spatial resolution for most applications. Advances towards those limits are presented along with DTS measurements at a range of 70 km of fiber.

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1. Introduction

Since the first demonstration, in 1984 [1], DTS systems have become a standard tool in several applications like fire detection, power cable monitoring, pipeline or dam leak detection, oil and gas downhole production optimization, and process monitoring [2]. In some of these applications the required distance to be monitored can be up to hundreds of kilometers, for example in pipeline or subsea power cable monitoring, which stretch across continents and oceans. These applications are also required to cover very remote areas with potentially no infrastructure, it is favorable to use as few instruments as possible to reduce the cost. For the example of subsea power cables it is generally not possible to install interrogators except at the shore ends of the power transmission line. In these cases the measurement range of the monitoring instruments should be as long as possible but fulfilling the required performance.
Raman-DTS is a favorable temperature measurement compared to Brillouin-DTS in applications where absolute temperatures and reliable, strain insensitive measurements are required. These applications include real time thermal rating, umbilical and riser monitoring, process monitoring, and leak detection.
For long-range measurements a fiber loss as low as possible is desired, thus DTS targeting long-range measurements are mostly utilising a probe wavelength at the spectral attenuation minimum of standard telecom fiber at 1550 nm. In this wavelength range, Raman backscatter is about 90 dB below the incident light power, for a typical pulse width of 20 ns. Therefore for long range applications the signal, after a few tens of km, reaches a regime where for each probe pulse only a few photons reach the detector. Due to the shot noise of photon detection the DTS performance is fundamentally limited. To achieve a useful measurement it is essential to accumulate the signals from multiple pulses (shots). A more detailed description is given in section 2.
In this paper we provide an estimation of the fundamental shot noise limit in section 2. In section 3 we show how we generate well shaped fiber-amplified high power Golay code sequences. This is followed in section 4 by results of measurements using this method to achieve a world leading 70km range using Raman DTS. This was achieved with reasonable measurement time, temperature- and spatial resolution and without the need for additional measures like optical amplifiers along the measurement fiber.

2. Fundamental perfomance limit

Assuming an ideal detector with 100% photon detection efficiency and no dead-time, the fundamental physical limit of a Raman DTS is given by Poisson statistics of the photons scattered from the fiber and reaching the detector. For further simplification a DTS using only Anti-Stokes backscatter is considered. These assumptions allow a basic estimation of the limit of the performance of Raman-DTS. Single pulses and no coding are used as this ideal instrument would be shot-noise-limited, see also section 3. The number of photons N_{ph} is proportional to the received power of the Anti-Stokes back-scatter $P_{AS,x}$ from a certain location x

$$P_{AS,x} = P_{AS,0} \cdot 10^{-\frac{1}{10}\int_0^x (\alpha_p(z)+\alpha_{AS}(z))dz} \quad \text{with} \quad P_{AS,0} = k_{fiber} \cdot t_{pulse} \cdot P_{in} \quad . \tag{1}$$

Where k_{fiber} represents the fiber back-scatter coefficient relating the backscatter to the pulse energy given by the product of pulse duration t_{pulse} and the peak power P_{in}. The product of all three gives $P_{AS,0}$, the received Anti-Stokes power from the beginning of the fiber. The fiber attenuation of the probe α_p and Anti-Stokes wavelength α_{AS} is here given in dB/km. The number of photons N_{ph} expected during the acquisition interval t_{gate} is given by the ratio of the acquired energy E_{acq} and the photon energy E_{ph}. It is reasonable to set t_{gate} to half of t_{pulse} to maintain spatial resolution after sampling.

$$N_{ph} = \frac{E_{acq}}{E_{ph}} = \frac{t_{gate} \cdot P_{AS,x}}{hc/\lambda_{AS}} \tag{2}$$

The variation of photon number with distance for both single-mode (SM) and multi-mode (MM) fiber is shown in Figure 2(a). The parameters used in this example are: Anti-Stokes wavelength $\lambda_{AS} = 1450\,\mathrm{nm}$, $t_{pulse} = 2 \cdot t_{gate} = 20\,\mathrm{ns}$, $\alpha_{p,SM} = 0.19\,\mathrm{dB/km}$, $\alpha_{AS,SM} = 0.25\,\mathrm{dB/km}$, $\alpha_{p,MM} = 0.28\,\mathrm{dB/km}$, $\alpha_{AS,MM} = 0.4\,\mathrm{dB/km}$, $k_{fiber,MM} = 0.0414\,\mathrm{W/J}$, $k_{fiber,SM} = 0.0075\,\mathrm{W/J}$ [2].

Collecting individual photons occurs after about 30 to 40 km resulting in poor signal-to-noise ratio (SNR) values.

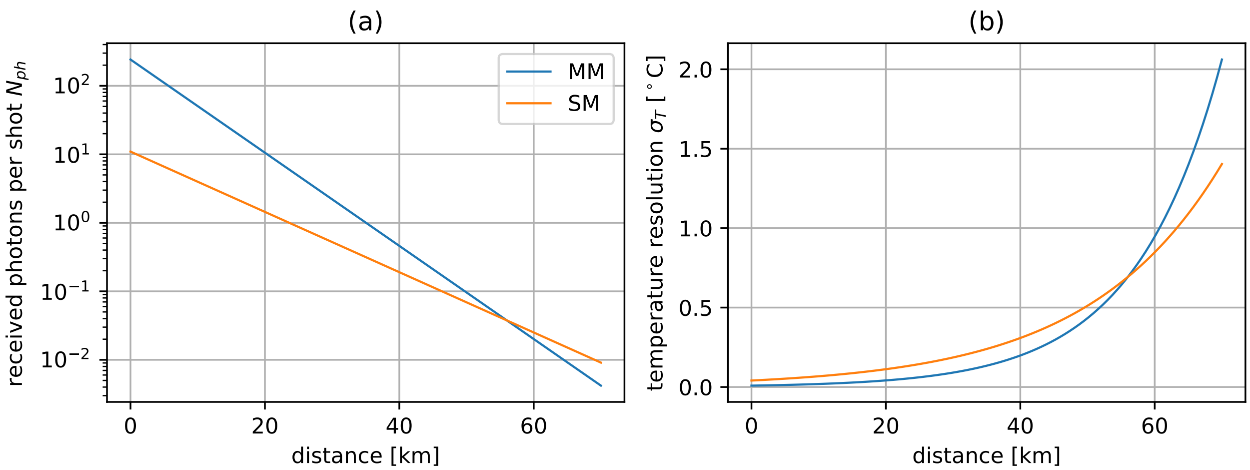

Fig. 1. (a) Expected number of photons per shot at the receiver, (b) Fundamental limit for temperature resolution over distance for an ideal detector on a 70 km fiber

Accumulating the photons $N_{ph,acc}$ from multiple shots makes it possible to achieve a sufficient SNR and calculate the temperature with a useful temperature resolution

$$\sigma_T = \frac{\gamma_T}{\sqrt{N_{ph,acc}}} = \frac{\gamma_T}{\sqrt{t_{meas} r_{pulse} N_{ph}}} \quad \text{with pulse rate} \quad r_{pulse} = \frac{c}{2nL_{fiber}} \quad . \tag{3}$$

For typical acquisition times of $t_{meas} = 600\,\mathrm{s}$, illustrative results of equation 3 are shown in Figure 2(b), using temperature sensitivity of Raman backscatter at room temperature $\gamma_T = 0.8\,\%/\mathrm{K}$, speed of light $c = 2.99 \cdot 10^8$ m/s, fiber refractive index $n = 1.48$, and fiber length $L_{fiber} = 70\,\mathrm{km}$.

3. Improvements by coding

An approach used to improve perfomance of DTS instruments is sending codewords instead of single pulses, namely Golay codes [3,4] and Cyclic codes [5,6]. These techniques have the advantage of increasing the signal proportionally with code length whilst the uncorrelated noise increases proportional to square-root of code length. This results in a coding gain proportional to the square-root of the code length L. For long codewords ($L \gtrsim 64$) both techniques approach an SNR-gain of $G_{code} = \sqrt{L}/2$ [2, 6]. However, as shot noise also scales with the square-root of the signal intensity, coding only benefits when the detector and electronic noise are dominating. This is usually the case for long distances where a low number of photons are received. If the main contributor of the noise is shot noise, there is no benefit in coding. For a perfect detector as assumed in section 2, shot noise is the only contributor and coding will not improve SNR. In the limit of infinite code length and regardless of the detection or coding scheme, a fundamental limit for temperature resolution is reached and is provided by equation 3 and shown in figure 2(b).

3.1. Amplification of Golay code sequences

Direct modulation of diode lasers is a cost efficient way to generate a desired code sequence. However, to achieve the best possible performance it is necessary to send more power into the sensor fiber than typically possible with this method. By direct modulation typically several hundreds of mW peak power can be generated. But the limit for nonlinear effects like stimulated forward Raman scattering allows several Watts. To close this gap an erbium doped fiber amplifier (EDFA) within the instrument is used to increase the power of the generated code sequence.
Amplification of code sequences poses challenges when using fiber amplifiers as the inversion of the dopants is depleted during amplification of the code due to the pump processing happening on time scales significantly larger (ms) than the code duration (μs). For a constant input power, this results in a reduction of gain (droop) and therefore output power during the code word (see Figure 2(a)). Using the backscattered signal of these codes for a decorrelation with the original Golay codes would cause unwanted artifacts at all spatial temperature features. To mitigate this issue, an iterative loop was implemented to pre-emphasize the droop and ramp up the seed laser drive current for each launched sequence. In Figure 2(b) the result after implementation of the iterative loop is shown. The results show that except for noise in the monitor path and current source, the droop of the amplifier is well compensated.

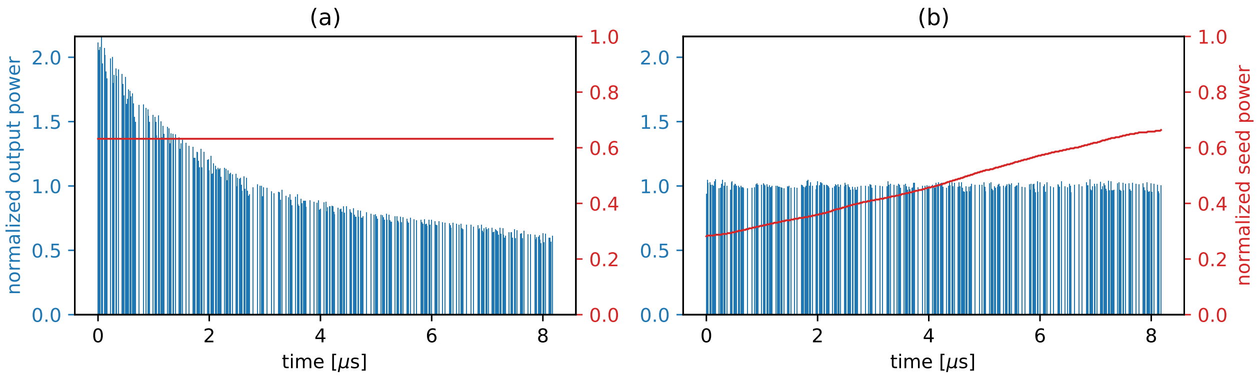

Fig. 2. (a) code containing target energy but no droop compensation; (b) corrected code, input envelope; (both figures) blue bars, left scale: result of outgoing pulse monitor, output power is normalized to the target pulse peak power; red line, right scale: envelope of seed laser power, calculated from driving current, normalized to maximum possible output power

4. Ultra-long range measurement

AP Sensing N45xx series instruments are designed for long-range operation on either singlemode or multimode fiber, the temperature resolution of the instrument for each fiber type is shown in figure 3. In addition to the droop compensation method as described in section 3.1, the system takes advantage of Golay coding with code durations of $8.2\,\mu s$ and 512 bits. This coding enhances the average optical power launched into the fiber and provides a coding gain of 13.5 dB compared to single pulse operation. The system also uses a single avalanche photo diode with a band switch for detection to avoid calibration issues, improve reliability and to reduce cost. The current temperature resolution at 50 km using a measurement time of 10 min is 2°C using MM fiber (scaled to a probe attenuation of 0.28 dB/km) and 3.1°C using SM fiber (probe attenuation: 0.19 dB/km). This corresponds to a dynamic range of more than 28 dB for MM and 19 dB for SM respectively.
To extend the measurement range further a compromise in measurement time and spatial resolution is necessary. In some applications where measurement time and spatial resolution can be relaxed. A practical temperature resolution can be achieved with a system configuration with an increase in measurement time of a factor of 6 and an increase in spatial resolution of a factor of 4. With these conditions a temperature resolution at 70 km distance of 2.3°C using MM fiber and 1.5°C with SM fiber can be achieved. The dynamic range increases to 39.2 dB in the multi-mode case and 26.6 dB for single-mode. Although the measurement time had to be increased significantly, in applications where slow temperature changes are observed like in buried power cables, this is still a very useful measurement. The instruments also offer a temporal sliding average mode, where a high update rate can be combined with a high signal quality, e.g. averaging for 1 h but updating the result every minute.
The model of the temperature resolution in section 2 matches well with the shape of the results, but it also shows that

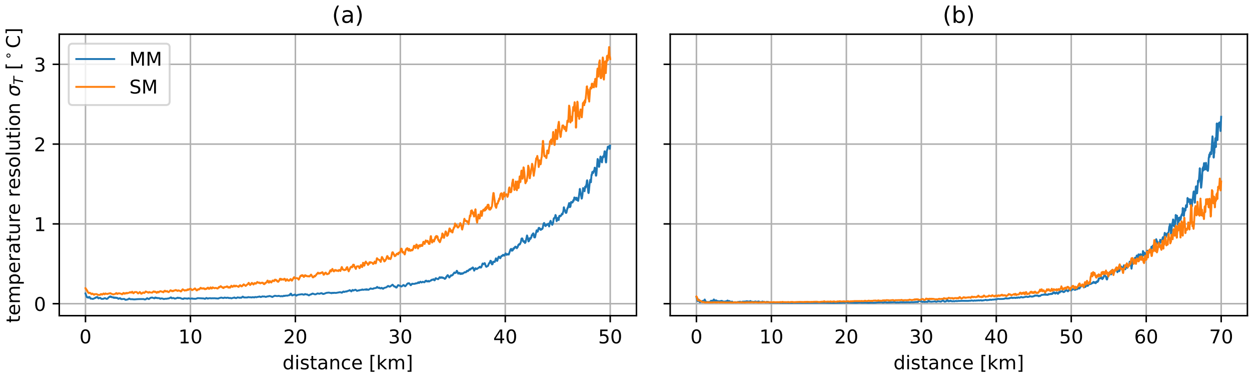

Fig. 3. Current temperature resolution of AP Sensing long-range Raman instruments (MM: N4516A; SM: N4526A), (a) up to 50 km , (b) up to 70 km (same temperature scaling, longer measurement time and wider spatial resolution)

up to an order of magnitude is available for improvement. As expected from the estimation, MM performs better than SM in the range up to 50 km. The temperature resolution of MM is about 35% better. The cross-over location, where performance is equal, is around 55 to 60 km. As displayed in figure 3(b) at the range of 70 km the ratio inverts and the SM setup outperforms the MM setup by about 35%. It is advantageous to use SM instruments and fiber for such ranges and beyond.

5. Conclusion

In this paper we present a Raman DTS system with what we believe to be the first demonstration of a temperature measurement at 70km range on both multimode and singlemode fibers. The results match the model with singlemode fiber providing improved performance at long range over multimode fiber. The crossover range for single mode and multimode was experimentally confirmed to be between 55 and 60 km. At 50 km the commercially available instrument offers comparable or better performance to previous reported results ([7], [5]), with the additional advantage of using only a single avalanche photon detector offering improved reliability and lower cost. At 70 km this is the first reported demonstration of a Raman based DTS. As the modeling shows that there is capacity for further improvement, we consider future work to involve the optimization of the performance of Raman DTS, e.g. by improving optics and electronics, using photon counting or further enhanced coding schemes.

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