# SNR improvement in a Raman based distributed temperature sensing system using a stimulated Raman scattering filter

Xiaoguang Sun*, Jie Li and Mike Hines
55 Darling Dr. Avon CT 06001

## ABSTRACT

In Raman-based distributed temperature sensing (DTS) systems, the signal to noise ratio (SNR) is often low due to weak backscattered Raman signals. This can limit both sensing distance and temperature resolution. Common methods of increasing the signal, versus noise floor, exist but most have significant limitations. For example, attempting to improve SNR by increasing the launching power is limited by the stimulated Raman scattering (SRS) threshold of the fiber. To overcome this power limitation, we propose a new SRS filtering method that allows more power to be launched into the fiber, beyond the SRS threshold, without causing additional temperature error. With this SRS filtering method we show that 3 dB more power may be launched into the fiber while improving the SNR of the received signals by 1.6 dB.

**Keywords:** distributed sensing, optical fiber, stimulated Raman threshold, Raman, DTS

## 1. INTRODUCTION

Optical fiber sensors have many unique benefits such as light weight, small cross-section, immunity to electromagnetic interference (EMI) and especially their capability to make distributed measurements with fine spatial resolution throughout the length of the entire fiber. Many parameters such as temperature, strain and vibration can be measured over long distance with fine spatial resolution and accuracy. For example, Raman based distributed temperature sensors (RDTS) detect the temperature along the fiber by measuring the backscatter intensities of the spontaneous Raman Stokes and anti-Stokes (AS) signals generated by the input light interacting with the glass on a molecular scale. The RDTS system can achieve high absolute measurement accuracy of 0.1 °C, with low spatial resolution of less than 0.5m [1]. RDTS has found success in broad applications including structural health monitoring, oil and gas pipeline leakage detection, oil recovery optimization and fire detection, and many others.

It will be ideal to create traditional RDTS temperature sensors of very long length, while accurately reporting evenly distributed points of temperature along the entire length, but there are fundamental limits to distance, spatial resolution and measurement accuracy. One of the major limitations is the low backscattered spontaneous Raman signal intensities. For example, the spontaneous Raman scattering capture coefficients of a 50 μm core graded index optical (GI) fiber are $6.63\times10^{-10}$ /m for the Stokes signal and $11.4\times10^{-10}$/m for the AS signal at 1550 nm [2]. With long fiber length, the received scattered spontaneous Raman signal intensity can be below the noise of the optical to electrical (OE) converters, and this low signal to noise ratio (SNR) will result in low temperature resolution of. As a consequence, the range of the RDTS is typically limited to about 40 km with broad 10 m spatial resolution and more than 5 °C temperature resolution at the far end of the fiber.

Several methods have been implemented to increase the SNR, for example averaging the received signal decreases the signal noise. The trade-off, in the case of averaging, is a significant increase in the acquisition time which proves unsuitable for most real-time distributed sensing systems. Using simplex-code [3] is another efficient way to reduce the signal noise but typically requires more complicated electronics and inflated system costs. Increasing the pulse width of the input pulse can increase the received power but results in degraded spatial resolution.

*xgsun@ofsoptics.com; Phone 8606786671; www.ofsoptics.com

Increasing the optical pulse power launched into the sensing fiber can be done with rare-earth doped fiber amplifiers and doesn't increase the acquisition time or the spatial resolution. But the maximum peak power is limited by the SRS threshold of the Stokes signal, and above this threshold the SRS can induce temperature measurement error. The temperature insensitive Stokes signal is needed as a reference to achieve high temperature accuracy. The Anti Stokes signal is temperature sensitive and using only AS signal can measure temperature change, but these measurements include measurement variations and are inaccurate by themselves. The AS reference is essential to remove the measurement variations caused by the intensity fluctuations of the pump light, fiber composition variation and fiber loss, etc. This is especially important for field deployment of the sensing fiber which can experience unknown and time-varying local attenuation.

In this paper we propose a new SRS filter that allows more power to be launched into the fiber, exceeding the SRS threshold, without causing temperature error. The SRS filter is made of wavelength division multiplexers (WDMs) and an optical isolator to block forward propagating SRS signals while allowing the pump and the backscattered Raman signals to pass through. We will first calculate the SRS threshold of the optical fiber in a DTS system with and without a SRS filter. Then the SRS filter is tested in an RDTS system to demonstrate the SNR improvement of the received signal.

## 2. THEORY

### 2.1 The SRS threshold at the Stokes wavelength in optical fiber

Since the Raman gain of the Stokes signal is higher than that of the Anti-Stokes signal at room temperature in optical fiber, the SRS threshold at the Stokes wavelength is lower than that at AS wavelength. In the following analysis we will calculate the SRS threshold of the fiber at the Stokes wavelength.

In a time-domain RDTS system, a short pulse of light (pump) at wavelength $\lambda_p$ is launched into the optical fiber and as the light pulse propagates along the fiber a portion of the light is scattered and a fraction of that scattered light transmits back to the input end and is collected through a dichroic filer device. The received backscattered Raman Stokes signal corresponding to a fiber location z, can be written as [2]:

$$P_S(z) = [P_p(z)\mathrm{K}(T)\Gamma_s v_g \Delta T / 2 + \gamma_s P_{SRS}(z) v_g \Delta T / 2]\exp(-\alpha_S z) \tag{1}$$

Where $P_p$ is the pump power, $\mathrm{K}(T)$ the temperature dependent Bose-Einstein population factor, $\Gamma_s$ the spontaneous Raman Stokes capture coefficient, $v_g$ the group velocity, $\Delta T$ is the pulse width; $\gamma_s$ the Rayleigh scattering capture coefficient at the Stokes wavelength, $P_{SRS}$ the forward propagating stimulated Raman Stokes signal, and $\alpha_S$ the loss at Stokes wavelength. In equation (1) the first term is the spontaneous Raman Stokes signal which is temperature dependent and useful for temperature sensing. The second term is the scattered forward Stokes signal by Rayleigh scattering and can cause error in the temperature. Even though there is no input Stokes power, the forward Stokes signal builds up from amplified spontaneous scattering that occurs along the length of the fiber. $P_{SRS}(z)$ and $P_p(z)$ can be calculated following Ref [4, 5] and then the received spontaneous and stimulated Raman stokes power can be found along the fiber. In Figure 1 we plot simulated result of the received power of the spontaneous signal and the backscattered stimulated signal with different launching power at pump wavelength of 1550 nm. The fiber used in the simulations is a 50 μm core diameter GI optical fiber with an effective area of $1\text{x}10^{-9}$ $\text{m}^2$, Raman gain coefficient of $0.8\text{x}10^{-12}$ W/m, loss of 0.45 dB/km and Rayleigh backscattering capture coefficient of $1.4\text{x}10^{-8}$ /m at 1630 nm.

At an input pump power of 12 W, the intensity of the spontaneous signal is more than 10 dB higher than that of the stimulating signal, so the temperature error can be small. If the pump power is increased to 15 W, the spontaneous Stokes signal also increases 25%, so the SNR will be improved. But at distances over 25 km the stimulated signal increases to more than 50% of the spontaneous signal. This results in a high temperature measurement error. If the pump power is further increased to 20 W, as show in Figure 1, the stimulated signal increases to higher than the spontaneous signal after 15 km. At fiber lengths from 25 km to 32 km, the spontaneous signal at 20 W is lower than that with 15 W pump power since more energy is transferred to the Stokes signal from the pump signal and the pump power becomes lower. Thus, increasing the pump power over the SRS threshold will not extend, rather it reduces the sensing length because of the error caused by SRS and pump depletion.

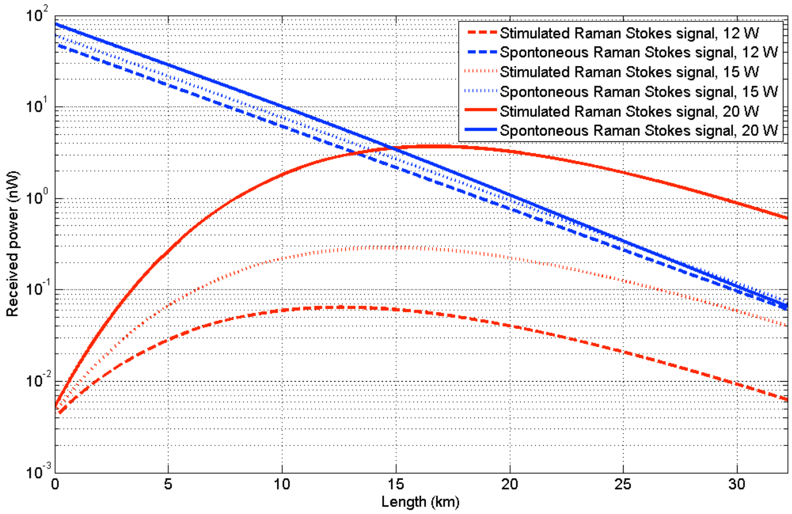


Figure 1. Simulated received spontaneous Raman Stokes signal and the stimulated Raman Stokes signal

If we assume that the stimulated signal needs to be less than 10% that of the spontaneous signal so that temperature error caused by stimulated signal is small, we can calculate the SRS threshold and the SRS threshold vs. fiber length as plotted in Figure-2. For a 32 km long fiber, the threshold is 12W.

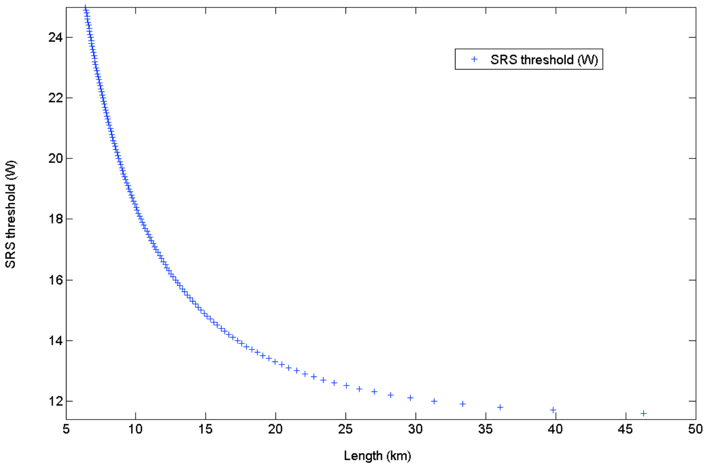


Figure 2. Simulated SRS threshold vs. fiber length

## 2.2 SRS filter

One method to overcome the limit of the SRS threshold is to filter out the forward travelling SRS using the device shown in Figure 3: the first WDM separates the pump and the Stokes signals from the sensing fiber, then the Stokes and AS signals pass an isolator which blocks the forward travelling light but allows the backward propagating light to pass through. The pump and Stokes signals are then recombined by a second WDM back into the sensing fiber. The forward Raman signals have high loss while pump and backward Raman signals have low transmission losses. Thus the forward stimulated Stokes signal can be suppressed and allows us to launch a higher pump power.

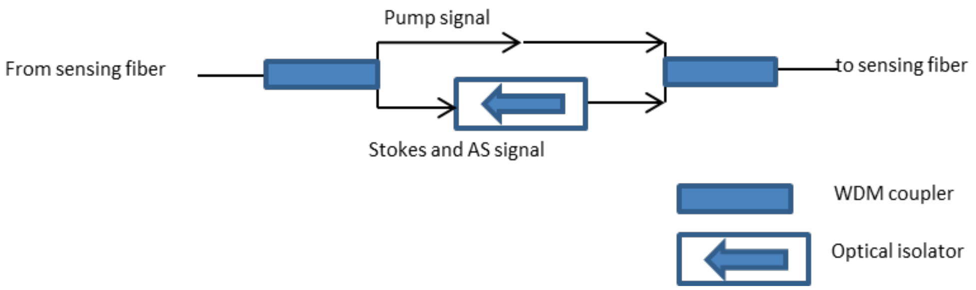


Figure 3. Illustration of the SRS filter

In Figure 4, the simulated Stokes intensities are plotted with and without the SRS filter with an input power of 25 W. The SRS filter is placed at 6 km and the intensity of the stimulated signal is kept below 10% that of the spontaneous signal throughout the entire fiber length. Compared with Figure 1 at 12 W input power, the spontaneous Raman signal increased 3.2 dB. We also can see from Figure-4 that if no SRS filter is used the stimulated signal grows to 10% of the spontaneous signal at 6 km and becomes more than the spontaneous signal after 10 km – this, in turn, make the temperature measurement error too high to be useful. Without the SRS filter, at 25 W input power, the spontaneous signal is actually lower than with 12 W input power after 12km of fiber since portion of the pump power is transferred to the stimulated Stokes.

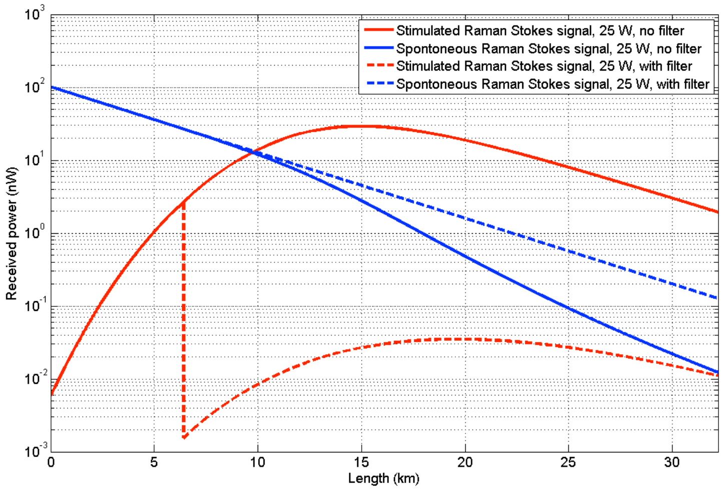


Figure 4. Simulated received spontaneous Raman Stokes signal and the stimulated Raman Stokes signal

## 3. EXPERIMENT

The setup to evaluate the SRS filter in an RDTS system is shown in Figure 5.

The RDTS interrogator is based on Raman optical time domain reflectometer (OTDR). It consists of a diode laser, an Er-doped fiber amplifier, Raman filters and avalanche photodiode (APD) receivers. The wavelength of the laser diode in the setup is 1550 m to match the SRS filter. The output pulse had a pulse-width of 50 ns, a peak power of 50mW and a repetition rate of 2 KHz. The output from the diode was then amplified by an Er-doped fiber amplifier. The amplified light then passed through a bandpass filter with a full width at half maximum (FWHM) of ~6 nm to remove amplified spontaneous emission (ASE) light and was launched into a 50 μm core graded-index (GI) fiber to connect to the sensing fiber. The backscattered Stokes and AS signals from the sensing fiber were separated using a high pass filter and then detected by APD receivers and the electrical signals amplified. The amplified signals were digitized using a 12-bit analog-to-digital converter (ADC) with a 250 MS/s sampling rate corresponding to a spatial sampling resolution of 0.4 m. The sensing fiber consists of 32 km of 50 μm core GI multimode fiber with NA of 0.20. The SRS filter can be inserted at 6 km. The SRS filter was made with three-port bandpass filters with the center wavelength at 1550 nm and 15 nm bandwidth. The isolator had a maximum isolation of 35 dB at 1620 nm. The transmission spectra of the device are shown in Figure 6. In the forward travelling direction, the loss at pump wavelength is ~0.6dB at 1550 nm and the loss is >25dB from 1570 nm to 1700nm. While in backward direction, the loss is less than 0.9dB from 1450 nm to 1700 nm.

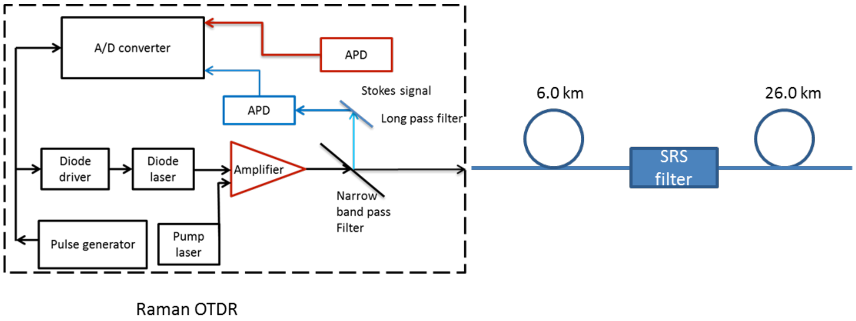


Figure 5. Experiment set up with SRS filter

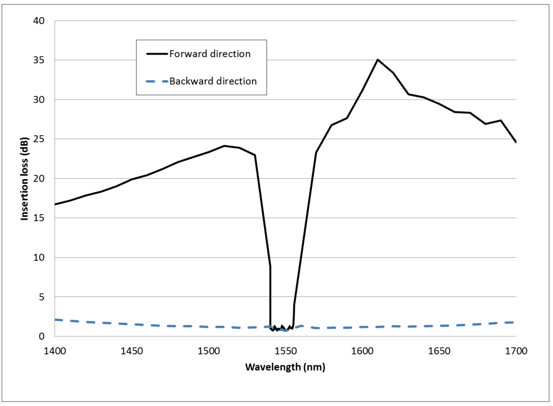


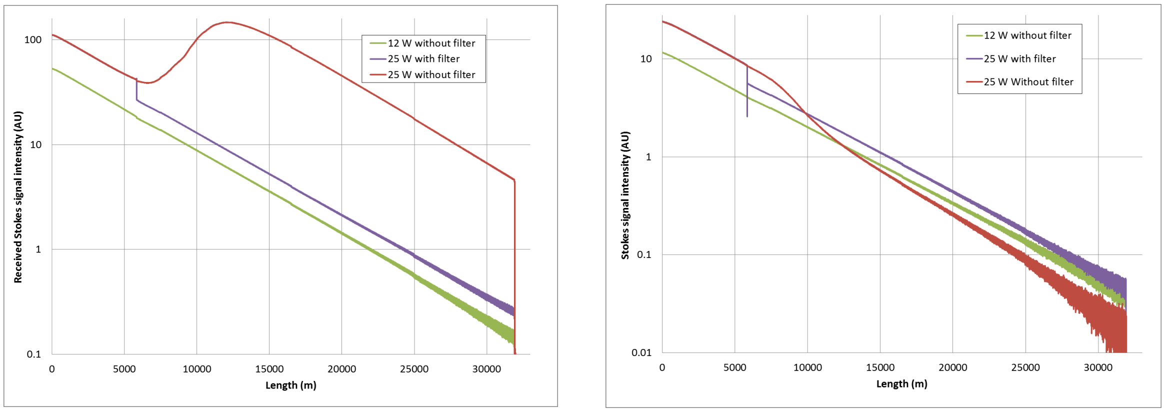
Figure 6. The transmission spectra of the SRS filter of the forward and backward travelling light.

## 4. RESULT AND DISCUSSION

The Raman Stokes and AS signals were first acquired with 12 W and 25 W launching power into the sensing fiber without the filter, then with 25W power and an SRS filter. The sensing fiber was kept at 20°C temperature and the signals were averaged to reduce the noise. The measured Stokes and AS intensities are plotted in Figure 7(a) and (b) respectively. At 12 W launching power which is below the SRS threshold of the 32km fiber, the Stokes and the AS intensity followed the exponential decay, which indicates that the stimulated signal was minimal.

With the launching power of the 32km test system increased to 25 W, the received Stokes intensity was 3.2 dB higher than that with 12W at fiber length less than 6 km. Without the SRS filter, the Stokes signal increased to the maximum level at 12 km, and this indicates that the intensity of stimulated signal is much higher than that of the spontaneous signal in the received Stokes signal. This is similar to the simulation plotted in Figure 4, and the temperature measurement error would be high. For the AS signal, the intensity also increased 3.2 dB at fiber length less than 6 km but dropped below that with 12 W launching power after 13 km. This is caused by the pump light depletion as predicted in Figure 4. We can see that even though the launching power is doubled but at the far end of the fiber the AS signal is actually lower and the SNR worse.

With the SRS filter put at 6 km, the Stokes and AS signals dropped 1.6 dB at 6 km because of the loss associated with the filter, but the Stokes signal followed exponential decay and the stimulated signal was minimal. The Stokes and AS intensities increased 1.6 dB at fiber length from 6 km to 32 km. thus with the SRS filter we could launch more power into the fiber beyond the limitation of the SRS threshold to improve the received SNR. Several filters can be put along the fiber to further improve the SNR to reach a longer sensing distance.



(a) (b)

Figure 7. The received Stokes powers (a) and AS powers (b) with 12 W and 25 W launching power into the sensing fiber

## 5. CONCLUSION

In summary, we have proposed and experimentally demonstrated an SRS filter that allows us to launch higher power into the fiber above the SRS threshold of the fiber. We can launch 3 dB more power above the SRS threshold with one SRS filter and improve the SNR by 1.6dB. The SRS filter is made from passive components and would be suitable for field applications.

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