

Temperature performance of Raman scattering in data fiber and its application in distributed temperature fiber-optic sensor

Deming LIU (✉), Shuang LIU, Hairong LIU

Wuhan National Laboratory for Optoelectronics, College of Optoelectronic Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

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Abstract A wavelength division multiplexer (WDM) was used to extract the Raman scattering signal from a data fiber. The temperature performance of Raman scattering spectrum was studied theoretically and experimentally. On the base of this study, a distributed fiber-optic temperature sensor (DFTS) system was developed. The sensing distance was 4 km. The temperature accuracy and the distance resolution reached to $\pm 1^\circ\text{C}$ and $\pm 1\text{ m}$, respectively. The system is stable and adequate for commercial usage, such as the power industry, the underground tunnel, the subway, and the pipe laying, and also for the mission applications, such as the warship and the airplane.

Keywords fiber-optic sensor, distributed temperature sensor, data fiber, Raman scattering

1 Introduction

The distributed fiber-optic sensors are attracting more and more attention recently. Many sensor schemes based on a number of physical parameters, such as fiber attenuation, temperature, and strain of the optical fiber, have been developed. Optical time-domain reflectometry (OTDR) is one of the powerful tools to fulfill the distributed measurement in the fiber. The spontaneous Raman scattering in optical fibers can be used to measure distributed temperature along the sensor fiber [1–4]. Here, a laser pulse is injected into the sensing fiber and transmitted along the fiber. The backscattered Raman light due to the interaction between photons and phonons will contain information about loss and temperature along the fiber. This backscattered Raman light is detected with high

temporal resolution and then transformed to a temperature distribution diagram along the fiber.

The data fiber, with a large core diameter and numerical aperture (62.5 μm and 0.27), is not only an excellent communication transmission media but also a good sensitive device in distributed fiber-optic temperature sensor (DFTS) system because of its larger Raman scattering efficiency and ascendant temperature sensitivity. In this paper, we describe a recently developed DFTS system using the data fiber. The detail analyses for the performance of the system are given. The design of the special wavelength division multiplexer (WDM) is introduced. The temperature-response performance of the Raman scattering and the influence of the system working condition on central wavelength and peak power of Stokes and anti-Stokes lights are analyzed theoretically and experimentally.

2 Spectrum of Raman scattering in data fiber

The data fiber is a high Ge-doped quartz fiber to increase its numerical aperture and effective area. This kind of fiber is especially suitable to the distributed fiber-optical temperature sensors based on Raman scattering due to the high Raman scattering coefficient of the Ge molecules. The spontaneous Raman scattering in a data fiber has the following characteristics:

- a) the intensity of the scattering is directly proportional to the induced light intensity, and in the magnitude, the former is only about 10^{-8} – 10^{-1} m^{-1} of the latter;
- b) the scattering light is random in the propagation direction;
- c) the Raman frequency has a broad spectrum and a “Raman shift” corresponding to the central frequency of the induced light;

d) the Raman scattering has an exact relationship with the temperature.

The central wavelengths of the Stokes and anti-Stokes spectrum of Raman scattering, λ_{as} and λ_s , could be given by the following equations:

$$\frac{1}{\lambda_{as}} = \frac{1}{\lambda_0} + \nu, \quad (1)$$

$$\frac{1}{\lambda_s} = \frac{1}{\lambda_0} - \nu, \quad (2)$$

where λ_0 is the wavelength of the input light, ν is the wave number of the Raman frequency-shift decided by the material content of the fiber. For high Ge-doped data fiber, ν is about 400 cm^{-1} . If the wavelength of the input light is 805 nm, the wavelengths of the anti-Stokes and Stokes spectrum of the Raman scattering, λ_{as} and λ_s , will be 780 and 832 nm, respectively.

Figure 1 shows the backscattering spectrum of the data fiber. It could be seen that there exist three peaks in the backscattering spectrum, which are Rayleigh, Stokes, and anti-Stokes, respectively. The Rayleigh peak is much larger than Stokes and anti-Stokes peaks. The anti-Stokes light is the most sensitive to the temperature but the smallest in the three scattering components. How to effectively extract the anti-Stokes signal is the key of the distributed temperature fiber-optic sensor.

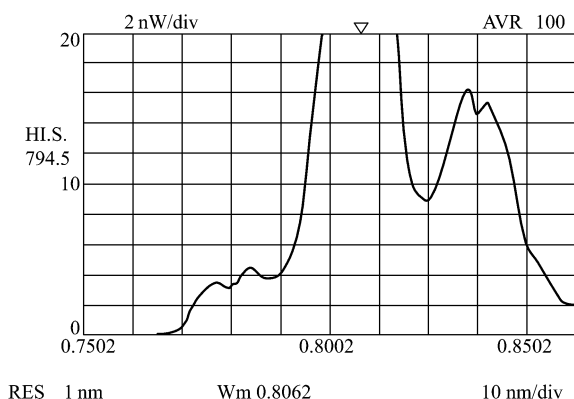


Fig. 1 Backscattering spectrum of data fiber

A specially designed WDM was used as the splitter of the three kinds of scattering light. Figure 2 shows the configuration of the WDM device. The input light from a laser diode (LD) is transmitted through a dielectric film filter of central wavelength 805 nm and is coupled into the sensing fiber. The backscattering light from the sensing fiber comes back again to the 805 nm filter, in which the Stokes and anti-Stokes components are reflected, and the Rayleigh component is lost. Thereafter, a 780-nm filter and an 831-nm filter are used to extract the anti-Stokes and the Stokes components, respectively. All the optical parts are glued to a glass block and form a compact and stable

device. The filters are designed so that the Rayleigh scattering is suppressed at the maximum extent, and the loss for the anti-Stokes component is smallest. Figure 3 shows the band-transmission performance of the three wavelength-channels of the WDM device, in which AS (anti-Stokes), R (Rayleigh), and S (Stokes) are corresponding to the left, middle and right curves.

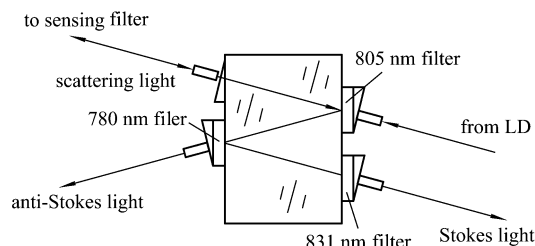


Fig. 2 Configuration of WDM device

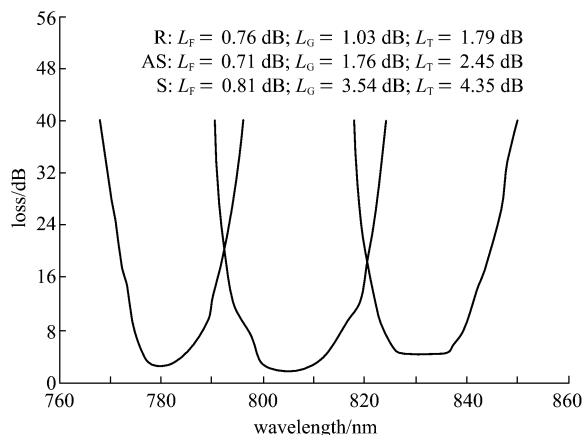


Fig. 3 Band transmission performance of WDM device

Figure 4 is the measured backscattering spectrum of the data fiber using the WDM under different temperatures. It could be seen that the anti-Stokes light is the most sensitive to the temperature and of excellent linear temperature-

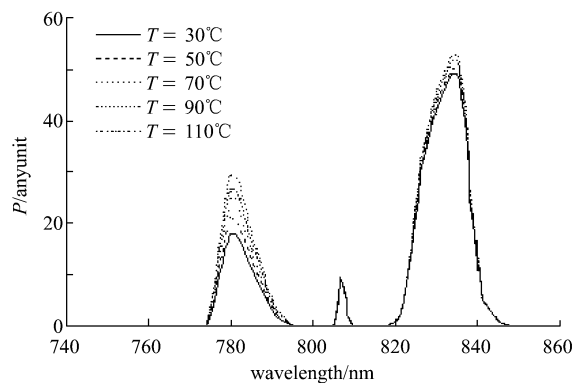


Fig. 4 Temperature response of backscattering spectrum of data fiber

sensitive response. Rayleigh light is, however, almost insensitive to the temperature, which could be considered a background for the temperature sensing and should be reduced to the lowest so as to increase the sensitivity of the system.

3 Experimental system

The newly developed experimental system consists of optical transmitter module, optical splitting module, sensing data fiber, optical receiver module, and signal process module, as shown in Fig. 5. In the optical transmitter module, an LD is modulated by a short pulse of 30 ns and exports an optical pulse. The LD is temperature controlled to keep a stable optical performance. The light signal is sent to the optical splitting module, where the forward pump light signal is coupled to the sensing data fiber, and the backward Stokes and anti-Stokes light signals from the fiber are split and exported to the optical receiver module. A specially designed WDM is used to realize the low loss splitting of the pump laser, Stokes light, and anti-Stokes light. The total coupling loss is reduced successfully to 1.7 dB for anti-Stokes light, which is very helpful for increasing the signal-to-noise ratio of the system. In the optical receiver module, the light signals are transmitted into electrical signals and sent into the signal process module together with a synchro signal. The distance is calculated based on the theory of OTDR. The light transmission velocity in data fiber is about 0.2 m/ns, i.e., every 10 ns of the time from the injection of the optical pulse to the arrival of the backscattering light

can be converted into 1 m in fiber length. The ratio of anti-Stokes and Stokes intensities under given temperature environment is measured, calculated, and converted into a temperature value. Accordingly, the distribution of the temperature along the sensing fiber could be depicted.

A practical fiber-optic distributed temperature sensing and fire-alarming system with complete functional software and excellent performances has been developed. The main functions for this system include the access, the signals of the multiple channels with 100 MHz sampling frequency, the multiple data process, real-time temperature calibration, seeking for the abnormal points, as well as alarming the fire and storing the data.

Figure 6 shows the measured temperature distribution. The heaves occur in the high temperature districts, which indicate that the Raman scattering intensity increases with the temperature. Table 1 lists main technological parameters of this system.

4 Conclusion

The spectra of the backscattering of the data fiber and their temperature performance were analyzed. A WDM with excellent technological quotation was designed and fabricated and used to extract the weak temperature signal from the backscattering of the data fiber. A perfect DFTS system based on Raman scattering has been demonstrated. The whole system is credible for long-term operation and has been applied into the fire-alarming field, in which it has more advantages than the fiber Bragg grating (FBG) sensing systems [5,6].

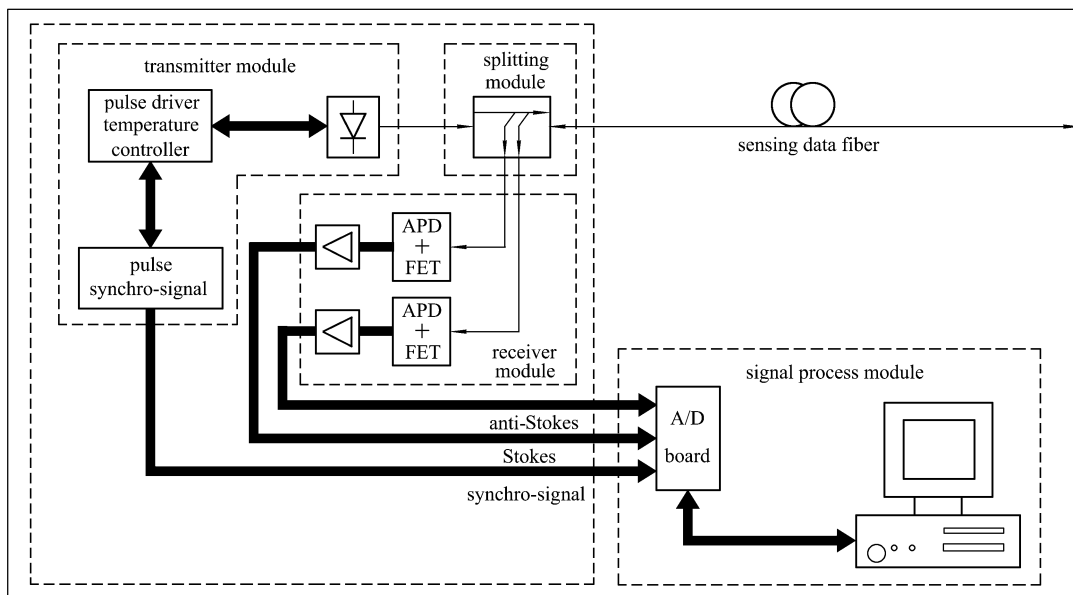


Fig. 5 Schematic of DFTS experimental system

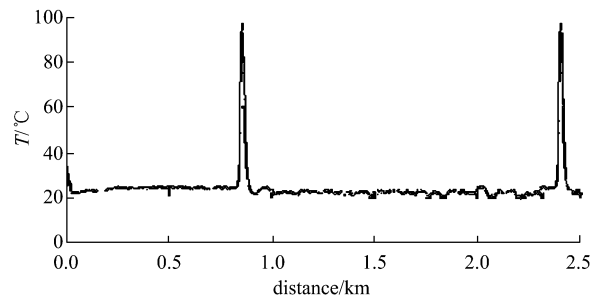


Fig. 6 Measured temperature distribution

Table 1 Specifications of fiber distributed temperature-sensing system

optical fiber	temperature accuracy	measured temperature range	distance resolution	measured distance range
62.5/125 μm graded index-data fiber	$\pm 2^{\circ}\text{C}$	-40°C – 140°C	$\pm 2\text{ m}$	4 km

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