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

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ABSTRACT

A wavelength-division-multiplexer (WDM) was used to extract the Ramam 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 4km. The temperature accuracy and the distance resolution reached to ±1℃ and ±1m, respectively. The system is stable and adequate for commercial usage, such as the power industry, the underground tunnel, the subway, 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 (62.5μm / 0.275 NA), is not only an excellent communication transmission media, but also a good sensitive device in 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 is given. The design of the special wavelength-division-multiplexer 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.

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2. SPECTRUM OF THE RAMAN SCATTERING IN A 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:

1) the intensity of the scattering is directly proportional to the induced light intensity, and in the magnitude the former is only about 10^{-8}/m~10^{-10}/m of the latter;
2) the scattering light is random in the propagation direction;
3) the Raman frequency has a broad spectrum and a "Raman shift" corresponding to the central frequency of the induced light;
4) 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 equation:

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

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

in which, 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 400cm^{-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 nm and 832 nm, respectively.

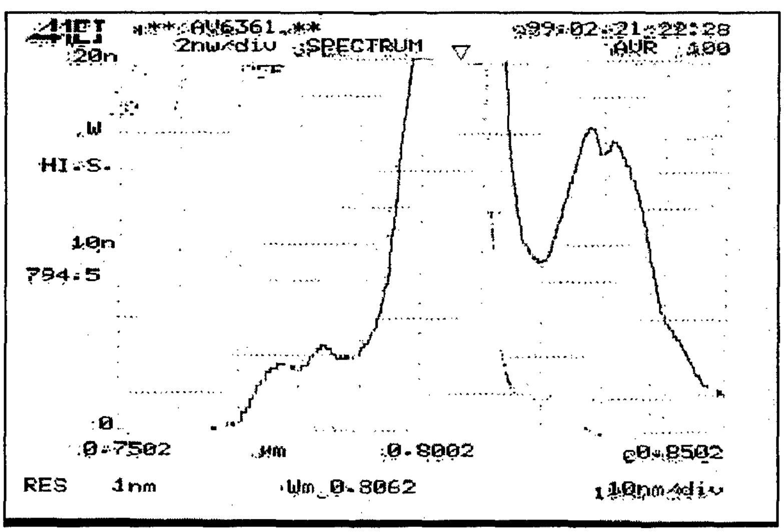

Fig.1 Back-scattering spectrum of the data fiber

Fig.1 shows the back-scattering spectrum of the data fiber. It could be seen that there exist three peaks in the back-scattering 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.

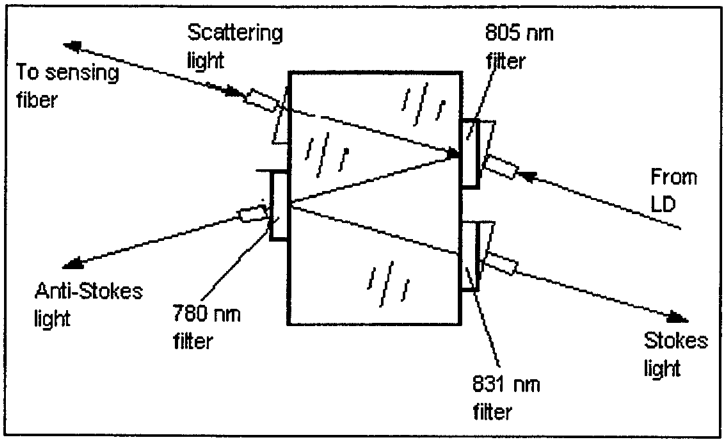

Fig. 2 Curve of ratio of anti-Stokes intensity to Stokes intensity vs. temperature

A specially designed (WDM) was used as the splitter of the three kind of scattering light. Fig. 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 805nm and is coupled into the sensing fiber. The back-scattering light from the sensing fiber comes back again to the 805nm filter, in which the Stokes and anti-Stokes components are reflected and the Rayleigh component is lost. Thereafter a 780nm filter and a 831nm filter are used to extract the anti-Stoke component and the Stokes component, 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. Fig.3 shows the Band-transmission performance of the WDM device.

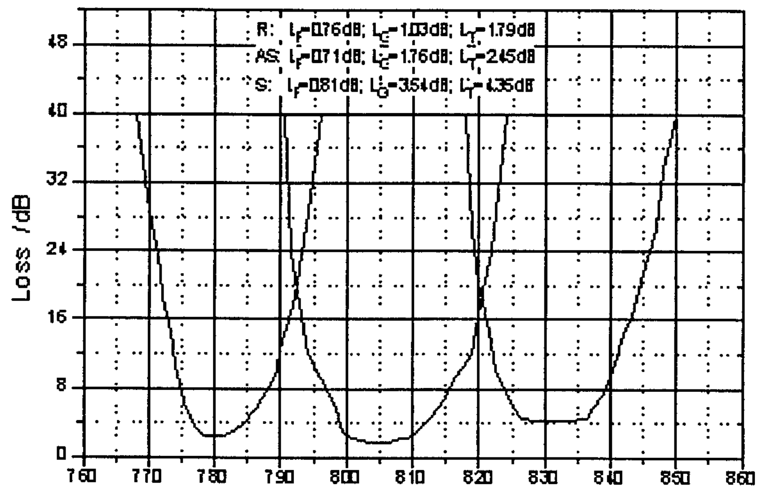

Fig.3 Band-transmission performance of the WDM device

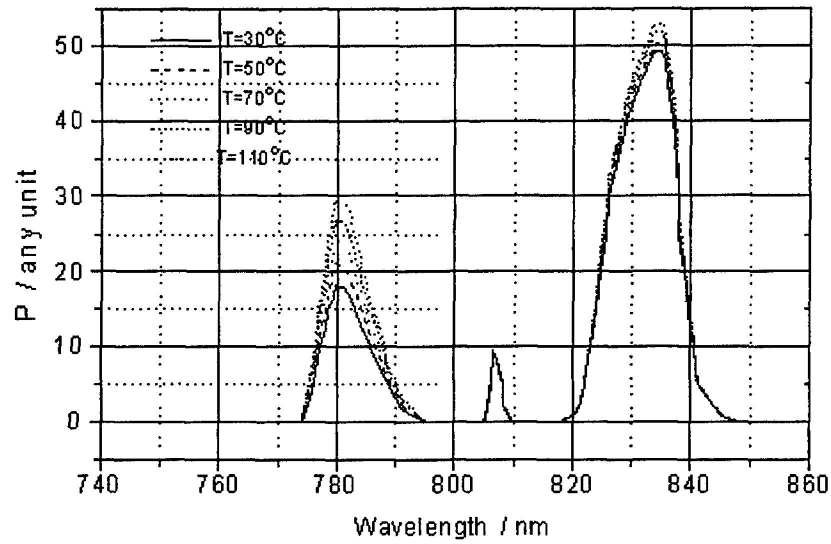

Fig. 4 Temperature response of the back-scattering spectrum of the data fiber

Fig.4 is the measured spectra back-scattering 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-sensitive response. Rayleight light is however almost insensitive to the temperature, which could be consider 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, a LD is modulated by a short pulse of 30 ns and exports an optical pulse. The LD is temperature-controlled to keep 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 wavelength division multiplexer (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 in to the signal process module together with a synchro-signal. The distance is calculated based on the theory of optical time domain reflectometry (OTDR). The light transmission velocity in data fiber is about 0.2m/ns, i.e. every 10 ns of the time from the injection of the optical pulse to the arrival of the back scattering light can be converted into 1m in fiber length. The ratio of anti-Stokes intensity and Stokes intensity under given temperature environment is measured and calculated, and converted into a temperature value. Accordingly the distribution of the temperature along the sensing fiber could be depicted.

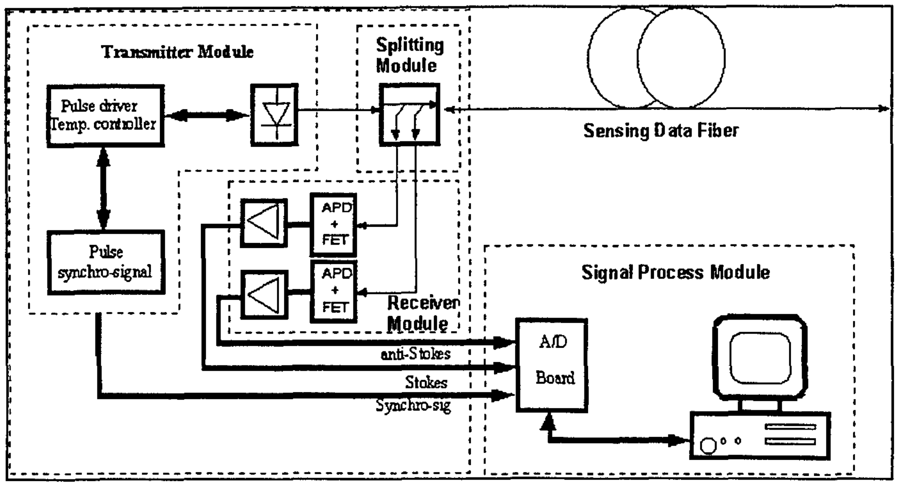

Fig. 5 Schematic of the DFTS experimental system

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 M sampling speed, the multiple data process, real-time temperature calibration, seeking for the abnormal points, as well as alarming the fire and storing the data.

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

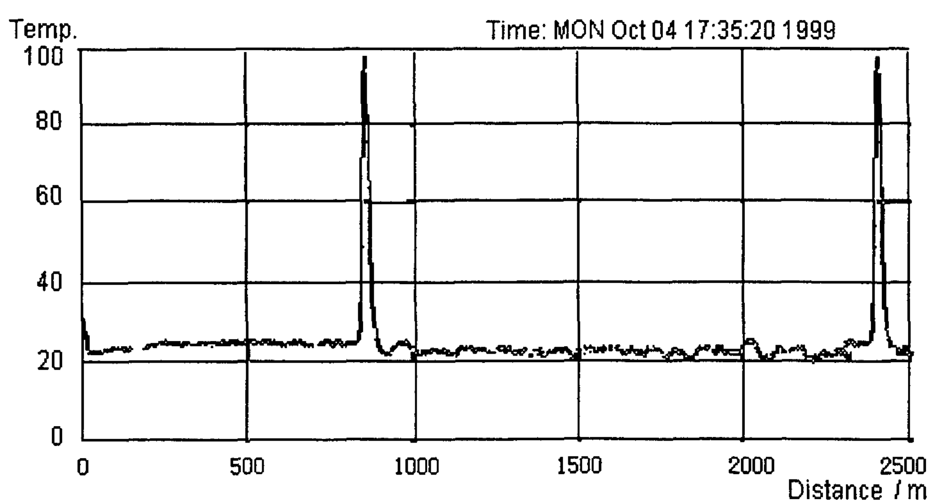

Fig. 6 Measured temperature distribution

Table 1 Specifications of the fiber distributed temperature-sensing system

Technol. Parameter	Specification
Optical fiber	62.5/125 μm GI-data fiber
Temperature accuracy	± 2°C
Measured temperature range	-40 ~ +140 °C
Distance resolution	± 2 m
Measured distance range	4 km

4. Conclusion

The spectra of the back-scattering 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 back-scattering 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.

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