

Design of distributed Raman temperature sensing system based on single-mode optical fiber

Ziheng XU, Deming LIU, Hairong LIU (✉), Qizhen SUN, Zhifeng SUN, Xu ZHANG, Wengang WANG

College of Optoelectronic Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

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Abstract The distributed optical fiber temperature sensor system based on Raman scattering has developed rapidly since it was invented in 1970s. The optical wavelengths used in most of the distributed temperature optical fiber sensor system based on the Raman scattering are around from 840 to 1330 nm, and the system operates with multimode optical fibers. However, this wavelength range is not suitable for long-distance transmission due to the high attenuation and dispersion of the transmission optical fiber. A novel distributed optical fiber Raman temperature sensor system based on standard single-mode optical fiber is proposed. The system employs the wavelength of 1550 nm as the probe light and the standard communication optical fiber as the sensing medium to increase the sensing distance. This system mainly includes three modules: the probe light transmitting module, the light magnifying and transmission module, and the signal acquisition module.

Keywords optical fiber, distributed temperature sensor, Raman scattering, field-programmable gate array (FPGA)

1 Introduction

As the theories and the technology, novel devices has been invented continuously to substitute the traditional devices, including the kinds of optical fiber, optical fiber devices, light source, and detectors, such as microfiber, special doped fiber, fiber Bragg grating, broadband low-noise light source, high-precision wide-spectrum detector [1]. In another aspect, the performance of the mature sensing systems have been thoroughly optimized, which includes improving the precision and distance, increasing the kinds and number of parameters, and realizing the networking and distributed sensing while decreasing the cost and narrowing the shape of the system.

When light goes through the medium, the interaction between the input light and molecular vibration causes the Raman scattering. Raman scattering is a kind of nonlinear effect in the optical fiber, including two backward scatterings, the Stokes light (1665 nm) and the anti-Stokes light (1465 nm), as shown in Fig. 1. Rayleigh scattering is the noise of the system, and it should be filtered during the transmission.

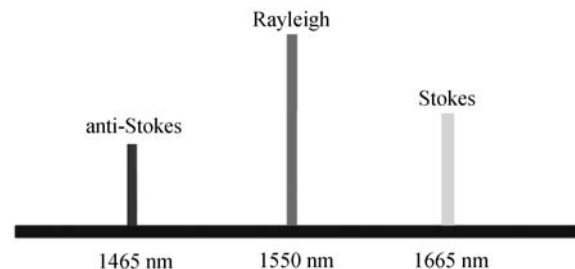


Fig. 1 Spectrum of Raman and Rayleigh scatterings

The temperature and the power of the Stokes and the anti-Stokes light are described as the following equation[2]:

$$\frac{I_{as}}{I_s} = \left(\frac{\nu - \nu_i}{\nu + \nu_i} \right)^4 e^{-\frac{h\nu}{kT}}, \quad (1)$$

where I_{as} means the power of the anti-Stokes light, I_s means the power of the Stokes light, ν is the frequency of the probe light, ν_i is the frequency of the molecular vibration, h is the Planck constant, k is the Boltzmann constant, and T is the absolute temperature. Only I_{as} changes with T . In this equation, ν , ν_i , h and k are already known, so if we detected the power of Stokes and anti-Stokes light, we can obtain the temperature T .

2 Operation principle

The construction of the system is shown in Fig. 2. We can divide the system into three parts: signal-producing

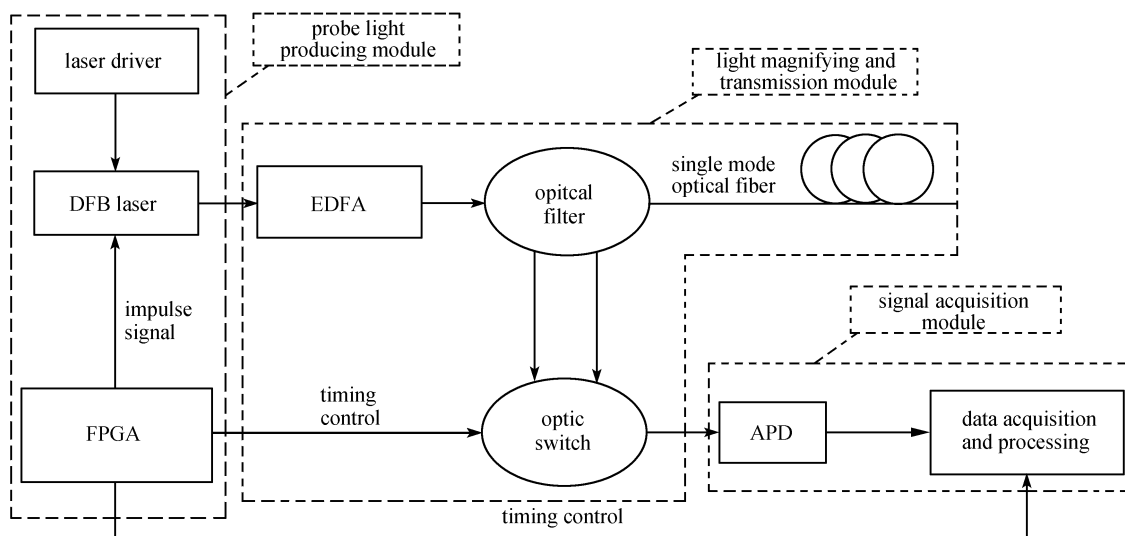


Fig. 2 System construction

module, light magnifying and transmission module, and signal acquisition module. From the picture, we can see the signal-producing module including field-programmable gate array (FPGA), distributed feed back (DFB) laser, and the laser driver; the light magnifying and transmission module including erbium-doped optical fiber amplifier (EDFA), optical filter, single-mode optical fiber and optic switch; and the signal acquisition and processing module including avalanche photo diode (APD) and data acquisition and processing.

FPGA can be compared as the brain of the system. It sets the electric impulse signal, with the frequency of 20 MHz and the specific repeat frequency, to DFB laser. The parameter of the impulse signal is based on the space resolution and sensing distance. The resolution and distance are described by the following equations [3]:

$$\delta_1 = \Delta T \frac{c}{2}, \quad (2)$$

$$L = \frac{cf}{2}, \quad (3)$$

where c is the speed of light in the optical fiber, ΔT means the width of the impulse, and f is the repeat frequency. FPGA also produces the timing control signal for optic switch and data acquisition board.

Although the loss of optical fiber on long-wavelength range is smaller than that on short-wavelength range, the signal of scattering photon flux on the long-wavelength range is weaker than that on the short-wavelength range. To increase the power of the scattering light, an EDFA is utilized to magnify the power of the probe light to 300 mW before the light being coupled into the optical fiber. EDFA has two pumping lasers supplying the pumping power forward and backward, respectively.

Optical filter is used to filter the Rayleigh scattering and separate Stokes and anti-Stokes light. Figure 3 shows the construction of the filter. There are two filters in this filter module, both of which are transparent for the probe light; thus, the probe light can go through the filters into the optical fiber. The backward scattering lights come back into the optical filter. Filter 2 is transparent for the Stokes light at 1665 nm and reflects the other scattering lights. Filter 1 is transparent for Rayleigh scattering and reflects the anti-Stokes light. So, by using the optical filter, we filter the Rayleigh scattering and separate the Stokes and the anti-Stokes light.

To reduce the cost of the system, there is only one detector in this system to receive the Stokes and the anti-Stokes light time-sharingly. Optic switch is used to switch the Stokes light and the anti-Stokes light detected by one detector time-sharingly. The optic switch has low insertion loss and high isolation degree. Because the power of the scattering light is very small, we use an avalanche photodiode to be the detector, which has high sensitivity (< -50 dBm) and response rate (> 50 MHz). Finally, a high-speed data acquisition board is used to receive and process the data. The data acquisition board and optic switch are both controlled by FPGA.

The signal received by the APD mixed much noise, and the power of the signal is very small, so we average the data many times to extract the temperature signal from the noise. The signal of the anti-Stokes light is collected ten thousand times compared with the Stokes light, and the work is repeated. That means that we collect one time Stokes light per ten thousand time anti-Stokes lights, and the ten thousand acquisition of anti-Stokes light is averaged for one temperature curve. Through this processing, the noise is filtered. Likely, however, measurement error is produced during the synchronization between the

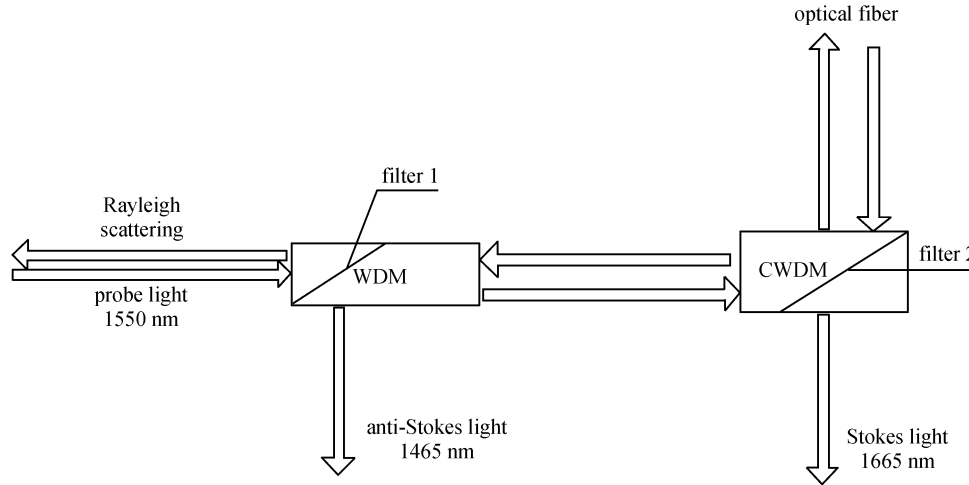


Fig. 3 Construction of optical filter

signal setting and the data acquisition board. In this system, we use FPGA to synchronize the data acquisition board to decrease the measurement error.

3 Experimental results and discussion

Figure 4 shows the spectrum curve of the Raman light and the Rayleigh light. The pulse, in the center of the graph, is the spectrum of the Rayleigh light, the top of which cannot be seen. The spectrum of the Stokes light is in the right, which is about -47 dBm. The spectrum of the anti-Stokes light is in the left, which is about -56 dBm at 1465 nm.

The spectrum of the Stokes and the anti-Stokes light are shown in Figs. 5 and 6, respectively. In Fig. 5, it can be seen that the Rayleigh and the anti-Stokes spectrum have been filtered, and the spectrum of the Stokes light is

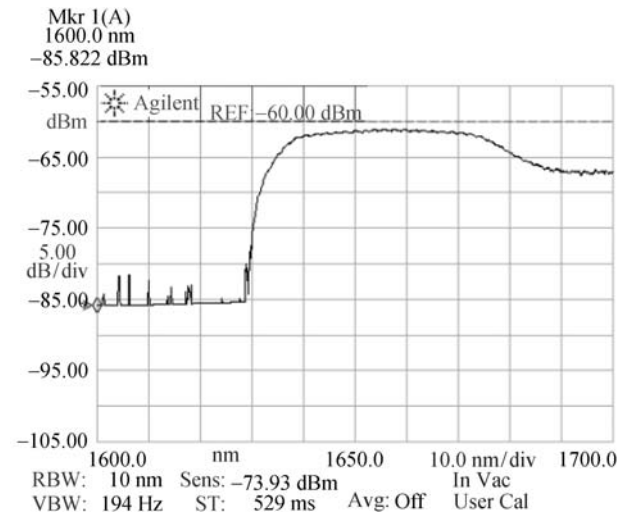


Fig. 5 Spectrum curve of Stokes light

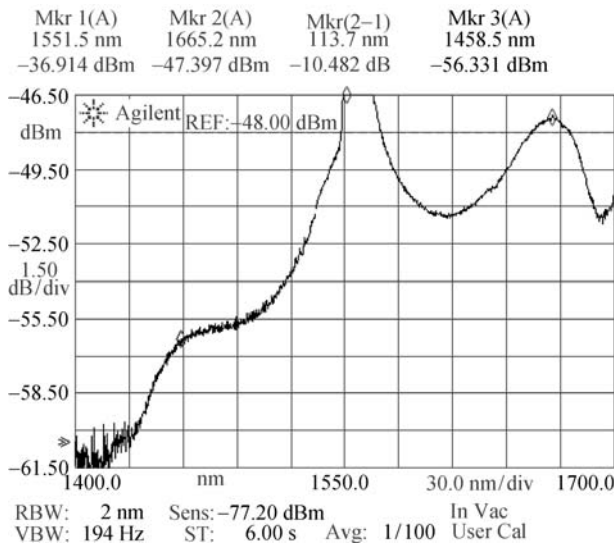


Fig. 4 Spectrum curve of Raman light and Rayleigh light

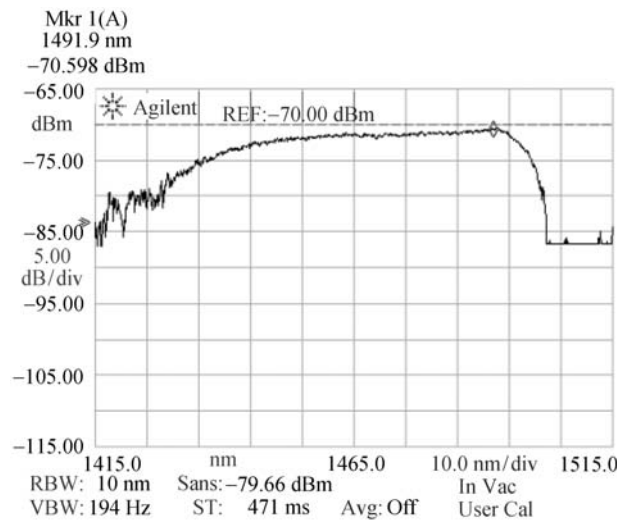


Fig. 6 Spectrum curve of anti-Stokes light

smooth. Similarly, in Fig. 6, only the spectrum of the anti-Stokes light exists, the other spectrums have been filtered. However, the power of the Raman scattering is very weak as can be seen in the two figures.

4 Conclusion

A novel scheme has been proposed in this paper: using single-mode communication optical fiber and long wavelength as the transmission medium and probe light to realize long-distance temperature sensing. Compared with the other existing temperature sensing systems, this system has been considered on performance, stability, and cost. Only one high-performance APD is utilized in this system to detect the power of the Stokes and the anti-Stokes light time-sharingly to decrease the cost. Mature theory and

common devices have improved the stability and reduced the price of the system; at the same time, the performance is still superior. This improvement will expend the application of the Raman temperature sensing in long-distance conditions.

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