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Fibreoptic distributed temperature sensor with spectral filtration by directional fibre couplers

A.G. Kuznetsov, S.A. Babin, I.S. Shelemba

***Abstract*. We demonstrate a Raman-based all-fibre temperature sensor utilising a pulsed erbium fibre laser. The sensor is made of a standard single-mode telecom fibre, SMF-28, and includes a number of directional couplers as band-pass filters. The temperature profile along a 7-km fibreoptic line is measured with an accuracy of 2 °C and a spatial resolution of 10 m. In data processing, we take into account the difference in attenuation between the spectral components of the backscatter signal.**

Keywords: *distributed temperature sensor, Raman scattering, directional fibre coupler, pulsed fibre laser.*

1. Introduction

In recent years, fibreoptic sensing systems have found many applications in science and technology (see, e.g., Refs [1, 2]) primarily because such systems enable temperature, pressure, stress, and other measurements without connecting the sensor to a power line. This is of particular importance in industries where flammable and explosive substances are used, e.g., in coal, petroleum, and gas production. In addition, fibreoptic sensors are sufficiently compact, require no systematic maintenance and have high chemical stability. Fibreoptic temperature sensors can also be used in fire detection systems for various building types.

This work examines a Raman-based fibreoptic distributed temperature sensor. Light conversion through Raman scattering is usually accompanied by a transition of the scattering molecules to other vibrational and rotational energy levels, and the frequencies of the new spectral lines are combinations of the incident light frequency and rovibrational frequencies of the scattering molecules. If a molecule is excited from its ground state to a higher energy state, its Raman spectrum shows lines at considerably longer wavelengths (Stokes components). Also possible is a reverse process: as a result of Raman scattering, the molecule passes from an excited state to its ground state, giving rise to anti-Stokes lines. Clearly, since the excited-state population depends directly on the temperature of the substance, the anti-Stokes intensity is also temperature-dependent. Therefore, measuring the anti-Stokes intensity with the sensor in question, one can determine the temperature along the entire length of the fibre.

The response and spatial resolution of Raman sensors depend directly on the characteristics of the laser source that is used to probe the fibreoptic line. Therefore, the probe laser pulse parameters are of special importance in sensing systems. The principal difficulty in designing Raman-based temperature sensors is the low backscattered light intensity. Figure 1 shows the Raman backscatter spectrum of the optical fibre. The central line at 1529 nm is due to Rayleigh scattering, and the two symmetrically located features at ~ 1430 and ~ 1630 nm are the anti-Stokes and Stokes components, respectively. Since glass is an amorphous material, the spectral lines due to vibrational excitation are broadened and overlap with one another. As seen in Fig. 1, the anti-Stokes backscatter signal, carrying information about the temperature of the fibre, is 30 dB weaker than the Rayleigh signal.

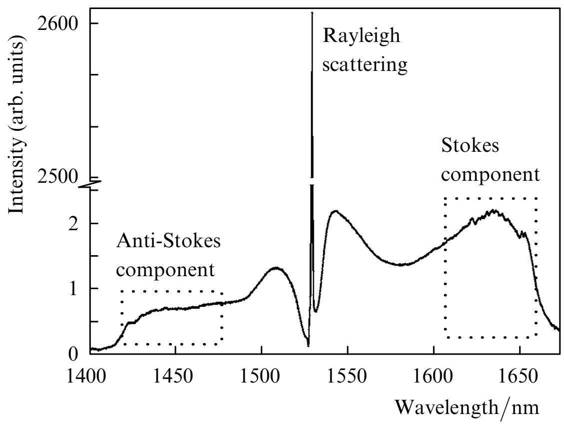

Figure 1. Raman spectrum of SMF-28 fibre.

The probe beam power level is limited by nonlinear effects such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). To achieve high accuracy in temperature measurements under such conditions, one must optimise the wanted-signal detection and filtration technique in order to minimise information losses. Typical filters are fibre Bragg gratings, separating narrow-band Stokes and anti-Stokes signals [3], which are then fed to

A.G. Kuznetsov, S.A. Babin, I.S. Shelemba Institute of Automation and Electrometry, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Koptyuga 1, 630090 Novosibirsk, Russia; Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia;
e-mail: babin@iae.nsk.su, shelemba@iae.nsk.su

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different measuring channels. This approach, however, places stringent requirements on the quality of the gratings, in particular on their spectral width (which should be as large as possible), reflectance, and losses. Unfortunately, even under optimal conditions a significant part of the wanted signal is lost upon filtration. To raise the intensity of the backscatter signal, use is often made of multimode sensing fibres [4], which allows the SRS and SBS thresholds to be raised and, hence, offers the possibility of raising the source power. Multimode-fibre sensors, however, require nonstandard, expensive components.

In this paper, we report an all-fibre temperature sensor with a single-mode fibre sensing element and a directional coupler filter, which makes it possible to raise the wanted-signal strength owing to the larger filter bandwidth, to simplify the filtration technique, and to reduce the price of the temperature sensor.

2. Model

Raman scattering is inelastic scattering of a photon accompanied by absorption or emission of a vibrational quantum of energy. If a laser pulse of frequency ν_0 is launched into a fibre, the backscatter spectrum will show a central peak at ν_0 and two extra signals shifted by frequency ν: the Stokes line at $\nu_s = \nu_0 - \nu$ and the anti-Stokes line at $\nu_{as} = \nu_0 + \nu$. The Raman components of silica fibre are located approximately 440 cm^{-1} from the central component. To rule out nonthermal effects (such as bending or splice losses) that may change the anti-Stokes intensity, it should be normalised to the Stokes intensity. We obtain then the well-known formula for the temperature dependence of the two intensities [5]:

$$\frac{I_{as}(T)}{I_s(T)} = \left(\frac{\nu_{as}}{\nu_s}\right)^4 \exp\left(-\frac{h\nu}{k_B T}\right), \quad (1)$$

where k_B is the Boltzmann constant; h is the Planck constant; and T is the absolute temperature.

Relation (1) does not take into account the difference between the attenuation coefficients of the two components, which is rather significant at long probe wavelengths, when the Stokes and anti-Stokes components are far apart. Generally, the backscattered light intensity is an exponential function of the distance along the fibre, with the corresponding attenuation coefficients [6]:

$$I'_s(z,T) = I_s(T) f(z) \exp(-\alpha_s z) + A,$$
$$I'_{as}(z,T) = I_{as}(T) f(z) \exp(-\alpha_{as} z) + B, \quad (2)$$

where A and B are constants (dark noise); α_s and α_{as} are the attenuation coefficients of the Stokes and anti-Stokes components; and $f(z)$ represents different processes unrelated to temperature changes (losses due to bending, splices, tensions, and other distortions of the fibre). In effect, both α coefficients slightly depend on temperature, but a more complex approach to signal correction is needed to take into account this dependence. In what follows, the attenuation coefficients α are assumed to be temperature-independent and to differ between the Stokes and anti-Stokes components.

3. Experimental

Figure 2 shows a schematic of the fibre laser. We used a ring cavity geometry with an about 2-m-long erbium-doped fibre and a JDSU OC-192 Mach–Zehnder electro-optic modulator as a Q-switch. The laser was pumped by a 980-nm laser diode with an $\sim$ 80-mW output power. The pump beam was coupled into the cavity by a WDM directional coupler. The lasing linewidth was determined by a 1529-nm fibre Bragg grating with 0.5-nm bandwidth (full width at half maximum). To extract 70 % of the beam power from the cavity, we used a 30/70 fibre coupler. Figure 3 shows the output laser pulse $\sim$ 60 ns in duration and its spectrum. The laser output was amplified by a 18 dB gain erbium-doped fibre amplifier. The peak power at the amplifier output exceeded 5 W.

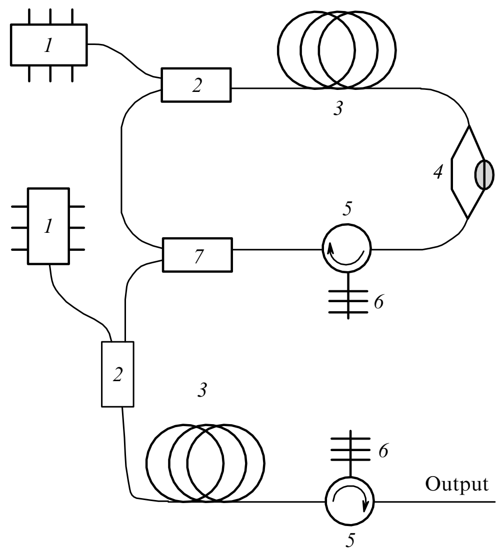

Figure 2. Schematic of the pulsed fibre laser: (*1*) 980-nm pump laser diode; (*2*) directional coupler; (*3*) erbium-doped fibre; (*4*) electro-optic Q-switch; (*5*) circulator; (*6*) Bragg grating; (*7*) fibre coupler.

The Raman measurement circuit is shown schematically in Fig. 4. Laser pulses with a repetition rate of 1.2 kHz were launched into a 7-km fibreoptic line (Corning SMF-28) consisting of two 3.5-km coils. A 250-m-long section of the fibre between the coils was heated to $\sim$ 100 °C. The Raman backscatter signal was separated by a wavelength-selective filter into the Stokes and anti-Stokes components, which were then directed to two photodiodes with 10-MHz bandwidth. The analogue signal from the photodiodes was fed to an ADC and then processed on a computer to determine the fibre temperature by formula (1) with premeasured corrections in (2).

The filter consisted of series-connected directional fibre couplers. To minimise the Rayleigh signal, several wavelength-selective directional couplers were needed. They cut off the central part of the spectrum around 1529 nm and transmitted the anti-Stokes and Stokes signals at 1430 and 1630 nm, respectively, with a bandwidth of 30 to 50 nm, depending on the number of directional couplers (Fig. 5). To further suppress the Rayleigh signal, we used fibre Bragg gratings with $\sim$ 0.5-nm bandwidth, which allowed us to minimise the Rayleigh noise. After filtration, the Raman

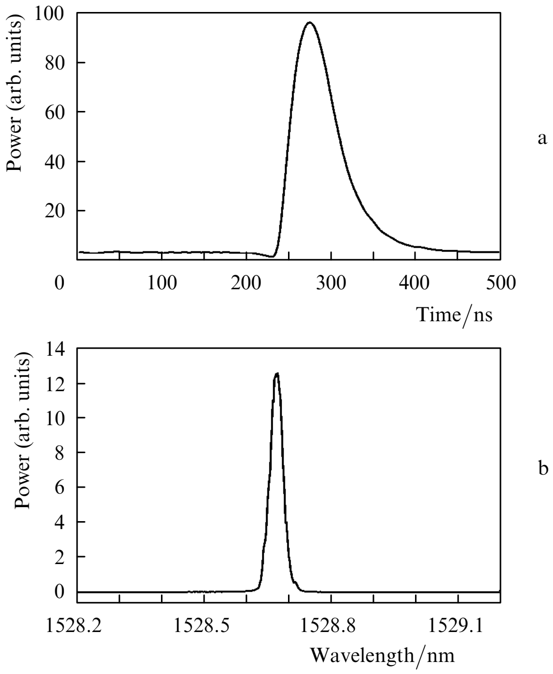

Figure 3. (a) Shape and (b) emission spectrum of the fibre laser pulse.

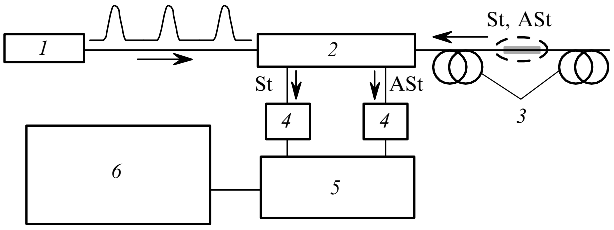

Figure 4. Schematic of Raman measurements: (*1*) pulsed fibre laser; (*2*) signal filtration system; (*3*) 7-km-long sensing fibre; (*4*) photodiodes detecting the backscatter signals; (*5*) ADC; (*6*) computer-based signal processing/temperature evaluation system; St: Stokes component, ASt: anti-Stokes component.

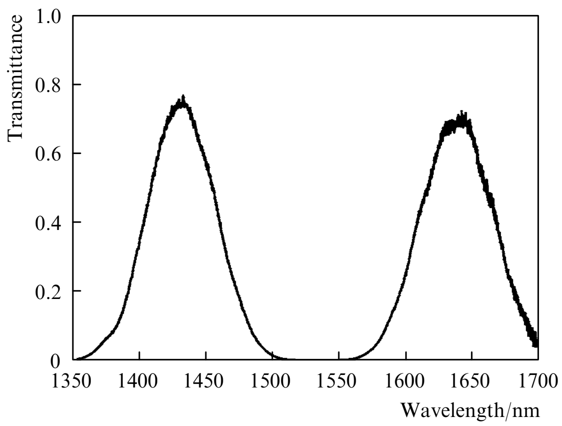

Figure 5. Transmission spectrum of the filter.

components were separated by directional couplers with appropriate wavelengths and detected by PIN photodiodes.

In this way, using directional couplers as Raman signal filters, we were able to suppress the strong central line due to Rayleigh scattering and to ensure Raman signal transmission in a wide spectral range, which enabled Raman signal detection without high-sensitivity avalanche photodiodes.

4. Results and discussion

Figures 6a and 6b show the time-dependent intensities of the Stokes and anti-Stokes components. To minimise the noise, the signal was averaged a hundred times. The anti-Stokes component is seen to have a distinct peak where the fibre was heated.

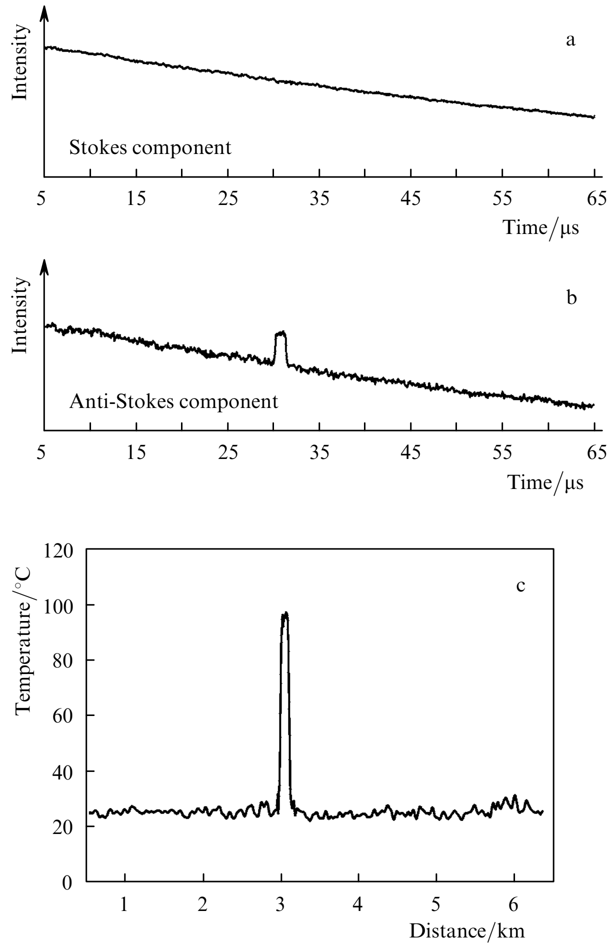

Figure 6. Intensity as a function of time for the Stokes (a) and anti-Stokes (b) components and the calculated temperature profile along the fibre (c).

From these data, we assessed the temperature profile along the length of the fibre (Fig. 6c) using formula (1) and calibration (2). The temperature resolution was 2 °C (rms deviation), and the spatial resolution, determined by the pulse duration and the speed of the photodiodes (10 MHz), was ~ 10 m. To determine the response of the fibreoptic sensor as a function of the real temperature, the test fibre temperature was varied from 7 to 100 °C and monitored with a thermocouple. Figure 7 plots the temperature measured by the fibreoptic sensor against that measured by the thermocouple (averaged over 500 measurements). As expected, the sensor has a linear temperature response, with deviations corresponding to the estimated measurement accuracy.

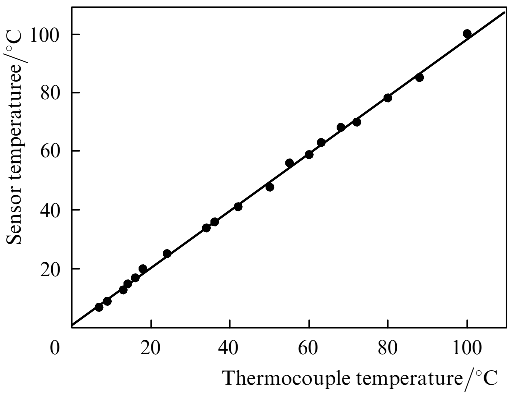

Figure 7. Temperature measured by the fibreoptic sensor against that measured by the reference thermocouple.

5. Conclusions

We demonstrated a Raman-based temperature sensing system utilising a single-mode fibre. A distinctive feature of the sensor is the all-fibre design, which incorporates a *Q*-switched erbium fibre laser probe source, an amplifier and a wavelength-selective filter based on WDM directional fibre couplers. Owing to the Raman signal transmission in a wide spectral range, we were able to measure the spatial intensity profile of the anti-Stokes component along a 7-km-long fibre using standard PIN photodiodes.

The spatial resolution of the sensor, limited by the response time of the photodiodes, is 10 m. The temperature resolution is 2 °C and can be improved by using high gain avalanche photodiodes (noise reduction at the same testing time) and by optimising the filter configuration in order to minimise the Rayleigh noise. To check the accuracy in the measured temperature, the sensor signal was compared to the real temperature of the test fibre. The linear temperature response obtained coincides with the absolute temperature to within 2 °C, which suggests that the described fibreoptic temperature sensor is potentially attractive for monitoring the temperature profile of extended objects.

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