Laser monitoring of the temperature profile using an optical fiber as a temperature sensor

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Numerical and experimental estimates of backscattered laser signals for temperature monitoring with the use of optical fiber are considered.

Introduction

Lidar sensing of atmospheric parameters refers to techniques, which are permanently improved both in the methodical sense and in assimilating up-to-date technologies. The optimization of technologies of producing optical elements and lasers bears fruits: the reliability of data obtained with the aid of lidar sensing permanently increases.

However, unfavorable environmental conditions, such as, for example, the limited visibility, background illumination, and others, still significantly restrict the domain of applicability of lidar systems.

Therefore, the need in sophisticated remote monitoring systems becomes increasingly urgent, for example, in pipeline transportation of gas and oil, the state of aggressive fluids in special storage rooms, and others. Most of these problems are solved based on monitoring of the temperature profile over the object of observation, for example, wells, underground mines, atmosphere of an industrial zone.

The quartz optical waveguide being in the thermal balance with the monitored medium can be very useful in such cases as a temperature sensor.

The method of laser monitoring of the temperature profiles with an optical waveguide consists in the measurement of the spontaneous Raman backscattering radiation with the following estimation of the temperature profile of the environment. The sensing pulse crosses a medium with known parameters. This allows a correct solution of the problems of calibration and stability of the measured results.

The radiation propagation in an optical waveguide is mostly restricted by losses in the waveguide material, which are, however, rather low at the current level of commercial production. In addition, to be noted are the capability of optical waveguides to operate in a wide temperature range (–60 to +300°C), their high resistance to the action of aggressive media, and a small bending radius, allowing the optimal configuration of the sensing path and ensuring stability of mechanical and physical parameters.

The correlation between parameters of the waveguide and the radiation, propagating through the optical waveguide, is of interest and requires a special study. In addition, the question on the backscattered Raman radiation intensity as a function of the waveguide length remains still open. Unfortunately, no papers of Russian authors on this subject are available now. The measurements of the waveguide temperature profile in the photon counting mode were not carried out abroad.

This paper presents examples and some results of numerical estimation of backscattered signals, when laser monitoring of temperature with the use of an optical fiber.

1. Basic remarks on propagation of optical radiation in an optical waveguide

The propagation of a radiation pulse in a fused glass in the coordinate system fixed to the group velocity can be represented[2–5] in the following form:

$$\frac{d\Gamma(z)}{dz} = \frac{\omega}{\omega_0}\hat{R}P_0 + \hat{g}_{II}P_0\Gamma(z), \qquad (1)$$

where $\Gamma(z)$ is the optical power per unit angular frequency at the frequency ω; P_0 is the optical power at the frequency ω_0; $\hat{R}$ and $\hat{g}_{II}$ are the scattering coefficient and the gain factor in the fused glass. Hereinafter, the peak radiation power is meant.

Taking into account radiation losses and the correlation between the gain factor g_{II} and the scattering coefficient R in the optical waveguide, we can obtain an important approximation for the radiation propagation in the optical waveguide:

$$\frac{dP}{dz} = -\alpha P + \frac{\hat{g}_{II}}{A_{\text{eff}}}\left[\frac{P}{K} + h(\Omega,T)\frac{\hbar\omega}{2\pi}d\omega\right]P_0, \qquad (2)$$

where P is the power of the optical radiation at a frequency ω, corresponding to the interval $d\omega$;

$$\alpha = \alpha_P + (1-S)\alpha_R + \alpha_S \qquad (3)$$

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is the extinction coefficient; α_P, α_R, and α_S are the absorption, Rayleigh scattering, and Raman scattering coefficients at a frequency ω in the fused glass; S is the fraction of Rayleigh scattering in the optical waveguide in the forward and backward directions determined, for example, for a multimode optical waveguide with the stepwise refractive index as

$$S = 0.38(\mathrm{NA})^2/n; \qquad (4)$$

NA is the numerical aperture of the optical waveguide; n is the refractive index of the optical waveguide core; A_{eff} is the effective area of the optical waveguide; K is the coefficient ranging from 1 to 2 depending on depolarization of the radiation, propagating in the optical waveguide;

$$\Omega = \omega_0 - \omega. \qquad (5)$$

The value of $h(\Omega, T)$ from Eq. (2) can be determined as

$$h(\Omega,T) = \begin{cases} \left(1 - e^{-\frac{\hbar\Omega}{kT}}\right)^{-1} & \text{at } \Omega > 0 \ (\equiv \mathrm{St}(\Omega,T), \\ \left(e^{-\frac{\hbar\Omega}{kT}} - 1\right)^{-1} & \text{at } \Omega < 0 \ (\equiv \mathrm{aSt}(\Omega,T), \end{cases} \qquad (6)$$

where $\hbar$ is Planck's constant; k is the Boltzmann constant; T is temperature; St is the Stokes part of the spectrum, aSt is the anti-Stokes part.

The dependence of the absorption and scattering coefficients, as well as the gain factor for the Raman scattering and the effective waveguide area on the frequency ω can be written in the form

$$\begin{cases} \alpha \propto \omega^4, \\ R \propto \omega^4, \\ \hat{g}_{II} \propto \omega, \\ A_{\mathrm{eff}} \propto \dfrac{1}{\omega^2}, \\ \alpha_P \approx \alpha_R >> \alpha_S. \end{cases} \qquad (7)$$

The system of equations (2) can be solved based on well-known approximations.[6] However, to obtain more accurate qualitative estimates, taking into account the effects like temperature or spectral width of the optical radiation, we should pass on to numerical methods of solution.[1]

It is necessary to refine the physical grounds for compilation of the differential equation for the optical radiation power P_i at the frequency ω_i in the system of equations (2): Raman scattering has the coherent nature, and the radiation of the contribution of this interaction propagates only in the same direction, whereas the contribution of spontaneous Raman scattering is identical for the direct and backward radiation propagation.

The system of equations (2) can be solved by various numerical methods, among which the fourth-order Runge–Kutta Method[7] characterized by a high stability has gained the widest applicability. However, estimates obtained through the solution of the system (2) are computationally expensive. For most applied problems, it is sufficient to use simpler approximations, which allow fast obtaining of the necessary estimates for the scattered radiation power.

It should be noted that the given approximation describes the propagation of pulses with a length of about 1 ns in optical waveguides; the effects of four-photon interaction and intrapulse interaction are neglected.

2. Calculations

The optical waveguide being in the thermal balance with the ambient medium can be considered as an extended temperature sensor. The anti-Stokes part of the Raman scattering spectrum is most sensitive to temperature variations.

The device for temperature laser monitoring using an optical fiber is shown schematically in Fig. 1.

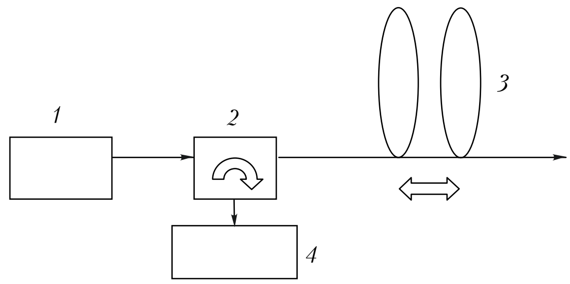

Fig. 1. Measurement of backscattered radiation: laser *1*; optical circulator *2*; optical waveguide *3*; spectral analyzer *4*.

A short laser pulse is injected into the optical waveguide, and the backscattered radiation comes to the spectral analyzer. The optical circulator serves for the efficient matching of the radiation source and detector with the optical waveguide.

In the general case, the sensing pulse has a finite length. This leads to interaction of the backscattered radiation with the radiation propagating in the forward direction. Approximations neglecting this effect typically represent the pulse by a stepwise profile in the form of an additive sum of short pulses.

The calculations are performed for radiation with a wavelength of 1064 nm. The temporal profile of radiation is specified as a Gaussian curve at a width of 10 ns. Then the transition to the stepwise profile, consisting of independent steps with a 1-ns width, is performed. The estimates of the scattered anti-Stokes power of the radiation returning to the optical waveguide entrance are represented as an average photon flow (rate = {rate$_i$}) in 1-m strobes for a frequency shift of 440 cm^{-1} from the fundamental line:

$$\mathrm{rate} = \frac{E_i}{\hbar\omega_i} \ (i = 0, 1, ..., n). \qquad (8)$$

The width of the spectral interval was taken equal to 10 cm^{-1}. The calculations were performed for the optical waveguide of the pure quartz. The waveguide diameter was taken equal to 50 μm. Radiation losses associated with the matching of the radiation sources with the waveguide, as well as the detector with the waveguide, were neglected.

Figure 2 shows the average photon flow in the 1-m strobe from a distance of 1000 m as a function of the peak power of the radiation source for the pure-quartz waveguide.

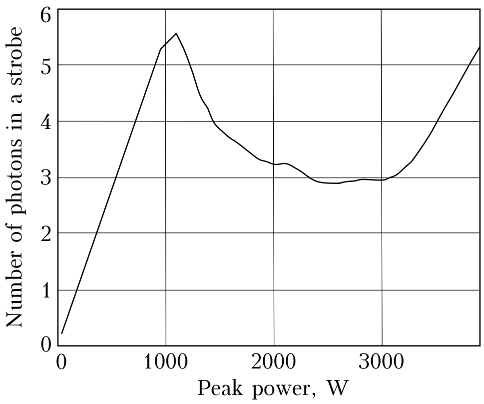

Fig. 2. Average photon flow in a 1-m strobe from the distance of 1000 m in the quartz optical waveguide.

The second peak in the plot corresponds to the influence of the increasing wings in the input radiation pulse. The energy from the pulse center is efficiently transported into higher orders of the Raman scattering spectrum.

3. Experiment

Based on previous model calculations, we have conducted the experiment on the temperature profile reconstruction using a quartz optical waveguide as a temperature sensor. Figure 3 shows the temperature profile reconstructed from the experimental data.

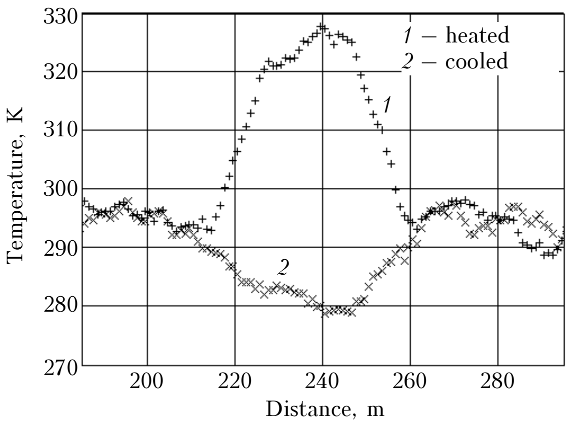

Fig. 3. Reconstructed temperature profile for a waveguide fragment spaced by 250 m from the beginning of the optical waveguide.

A KP L2G-II quartz optical waveguide of 200 μm in diameter and of 525 m in length was used as a temperature sensor. A waveguide fragment of 40 m in length spaced by 250 m from the beginning of the optical waveguide was subjected to cooling and heating during the experiment.

In the experiment, we used the optical setup based on a compact double lens polychromator. The polychromator is constructed by the autocollimation scheme with the optical waveguide coupler on MS Gelios-44 2/58.6 objectives with the use of plane ruled gratings with the parameters: 1200 lines/mm and 30×60 mm. For the optical coupler, a KP L2G-II quartz optical waveguide of 200 μm in diameter was used as entrance and exit slits of the polychromator. The optical waveguides in the polychromator were arranged so that two areas centered relative to the Stokes and anti-Stokes frequency shifts of 440 cm^{-1} in the Raman spectrum stand out in the spectrum of the scattered radiation.

An ILTI-407b laser with a wavelength of 532 nm, a pulse duration of 10 ns, and a pulse repetition frequency of 25 Hz was used as a source of radiation.

The backscattered radiation was recorded in the photon counting mode. The radiation from the output of the double polychromator came to two Hamamatsu PMTs. Then, after amplification and discrimination by level, signals were applied to the input of the photon counter. The PMT time resolution parameters and the photon counter parameters have allowed the measurements to be conducted in the 1-m strobes.

The program control for the photon counter and the data acquisition was performed using a PC-386 computer.

The experimental data were processed in the following order:

(a) measured signals were corrected for miscounts;

(b) signals were corrected for the PMT aftereffect;

(c) the background level was determined and subtracted from signals;

(d) variances of corrected signals were estimated. Estimates, based on the asymptotic property of the signals described by the Poisson statistics, namely, average is equal to variance, were used as initial estimates of the signal variance;

(e) signals were processed using the method of optimal linear regression[8]; then strobe-average signals and errors of reconstruction were found;

(f) the temperature profile was reconstructed from the pre-processed data.

To reconstruct the temperature profile at the waveguide fragment, the following approximation was used:

$$T(i) = \frac{C_1}{C_2 - \ln\left(\dfrac{P_{aSt}(250+i)}{P_{St}(250+i)}\right) - C_3 i} \quad (i = 0, 1, \ldots, 126), \quad (9)$$

where $C_1 = 630$, $C_2 = 0.51$, $C_3 = 0.0021$. Of interest is the last constant, the necessity in the use of which is caused by the presence of variance in the rate of an electromagnetic wave propagation in the waveguide material.

Conclusions

The results of model calculations show that the average photon flow is restricted by the peak power of the radiation source. The data presented suggest that, taking into account the losses for matching and the quantum efficiency of the photodetector, the measurements should be conducted in the photon counting mode.

In the experiment, the following tasks were formulated: to obtain Raman signals upon heating and cooling of a waveguide fragment; to reconstruct the temperature profile along the optical waveguide; to compare the reconstructed parameters with the theoretically predicted ones; to assess the stability of the reconstruction algorithm.

The theoretically predicted value of the parameter $C_1 = 630.96$ from Eq. (9) is in a good agreement with the measured value. In experiment, the value of this parameter was determined through the fitting of the temperature profile obtained in the waveguide to the temperature profiles obtained by an independent method. The accuracy of the fitting was set within one degree.

According to the conditions of the experiment, one part of the waveguide was at the known room temperature in air, while another was in the isolated water volume, whose temperature took two values. The temperature was monitored by a thermometer accurate to 1°.

At the same time, it is seen from the data presented that the temperature profile has smooth transitions upon heating and cooling. This is assumingly connected with the large thickness (0.4–0.5 mm) of the plastic cladding of the optical fiber. Therefore, it is necessary to construct the heat exchange model for the optical fiber in the cladding.

The laser monitoring of the temperature profile using an optical waveguide as a temperature sensor attracts the increasing interest now. Despite the considerable amount of theoretical data on the light propagation in waveguides, this problem calls for further experimental investigations. In addition, experimental investigations in the field of radiation propagation in waveguides in most cases go into either the range of signal amplification or the problem of noise immunity of communication facilities. Thus, the urgency of the problems formulated reflects the current tendency in development of applied lidar methods of the atmospheric monitoring.

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