High-sensitive spectrometer with high-*Q* cavity within 0.9 μm range

L.N. Sinitsa and A.M. Solodov

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk

Received April 16, 2007

A spectrometer with outer high-*Q* optical cavity and non-coherent radiation source in the range 0.9 μm and spectral resolution of 0.08 cm^{-1} is designed. A halogen lamp of 100 W was used as the radiation source. Absorption spectra of atmospheric air and ethanol near 0.9 μm were recorded with the spectrometer. The signal contrast coefficient of the spectrometer turned out to be 65 comparative to standard spectrophotometric method all other parameters equal.

Spectrometers, in which the light is put into the optical cavity mode, have been proposed and have made a significant progress during the last years. Such spectrometers are characterized by a very high threshold sensitivity to the $10^{-7} - 10^{-9}$ cm^{-1} absorption. The method of radiation attenuation in a cavity is the first, in which a short narrow-band laser radiation pulse (the laser pulse time t_p is less or comparable with the cavity round trip time) is directed into the optical cavity with the mirror reflectivity coefficient $R = 0.9999$; and the absorption coefficient of the medium between cavity's mirrors is determined from the time of optical radiation attenuation at the cavity output.[1]

In the cavity-enhanced absorption method (CEA) a narrow-band radiation of a continuously tuned laser is put in the cavity in case of a random coincidence of laser frequency with the frequency of one of the cavity modes. The information on the absorption is obtained from the recorded time scan of intensity of the laser radiation, outgoing from the cavity.[2]

The use in CEA-spectroscopy of high-luminosity lamps as a source of non-coherent optical radiation allows one to cover the whole spectral range from the UV to the far IR.[3] In this case the optical radiation of the source has a continuous frequency set, a part of which coincides with cavity own frequencies and is efficiently input in it. In this article, a broad-band high-sensitive spectrometer with high-*Q* cavity within 0.9 μm is described.

Experiment

In our experiment, a 100-W xenon lamp (Fig. 1) was used as the radiation source. Trough selection of absorption light-filters we defined a spectral region best corresponding to the maximal reflectivity of dielectric mirrors, which formed the optical stable cavity. The Fabri–Perot interferometer with spherical mirrors was used as a high-sensitive cavity. The optical cavity has a length of 44 cm, a mirror curvature radius of 1.5 m and the mirror transmission coefficient $\Theta = 0.007$.

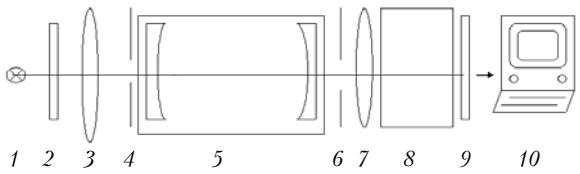

Fig. 1. Spectrometer schematic view: halogen lamp (*1*); optical filter KS-19 (*2*); lens (*3*, *7*); iris diaphragm (*4*, *6*); high-Q spherical cavity (*5*); monochromator (*8*); photodiode array (*9*); computer (*10*).

The filter also cut off the radiation lower than 0.45 μm, which corresponded to the radiation reflected in second and third orders of the diffraction grating. The interferometer-emitted radiation was directed to the polychromator with objective's focal length of 1200 mm. The use of 600 grooves per millimeter in the diffraction grading of third order provided a spectral resolution of ~0.1 cm^{-1}. To calibrate the wavelength, the radiation of He–Ne laser and a neon lamp were used, which was input in the polychromator at the same angle as the basic radiation from the cavity. Due to losses caused by the reflection from mirrors, the radiation intensity was reduced by a factor of $0.5(1 - R)$ after the cavity and further lowered at the cost of the light passed through the polychromator down to $10^{-5} I_0$. Therefore, a low-noise photodiode array with a high sensitivity was used at the output, the signal from which was directed to the computer. A more detailed description of the photo-recorder based on the photodiode array can be found in Ref. 4. After accumulation and averaging the radiation, passed through the cavity, the absorption spectrum of the matter was obtained. Figure 2 presents a 44 cm spectrum fragment of atmospheric air transmission at a single-pass measurement mode (*1*) and with the use of a high-*Q* optical cavity (*2*). The coefficient of the signal contrast enhancement with given mirrors, as compared to the measurements by the classic spectroscopic method with a cell of the same length, is 65.

0235-6880/08/04 306-03 $02.00

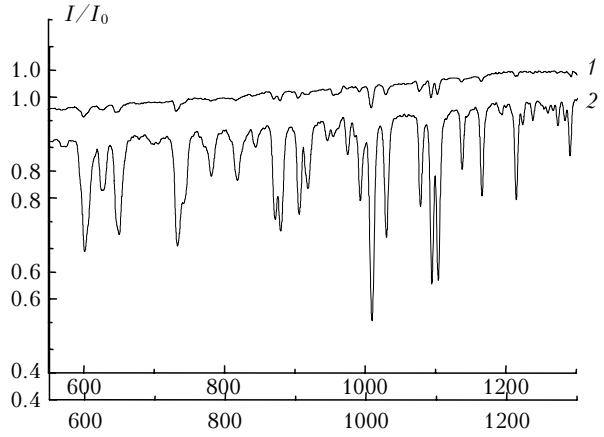

Fig. 2. Normalized atmospheric air transmission spectrum in 0.9 μm region, detected without (*1*) and with (*2*) the 44 cm optical cavity, which increases the sensitivity by 65 times. *X* axis points the cell numbers of the diode array.

Spectrometer sensitivity

Let us consider formation of a gap in the broad-band non-coherent light spectrum in the high-sensitivity optical cavity, basing on principles formulated in Ref. 5. It is assumed that nonlinear effects are negligible and the bandwidth $\Delta\nu$ is much wider than the cavity free interval width $\delta\nu$ for the intensity variations, caused by the cavity mode structure, cannot be detected.

Under consideration is an optically stable cavity of the length d, formed by two mirrors with the reflectivity R, transmission coefficient Θ, and loss coefficient α ($R + \Theta + \alpha = 1$) (back mirror surfaces are antireflecting). The cavity is continuously exposed to incoherent light of the intensity I_0.

The intensity of the light, passed through high-Q cavity at $\alpha = 0$, is described as

$$I = \frac{t\Theta^2}{(1-Rt)^2 + 4Rt\sin^2\left(\frac{\Phi}{2}\right)} I_0, \qquad (1)$$

where t is the transmittance of the medium in the cavity; $\Phi = 2nd\cos\varphi$ is the phase difference between neighboring interfering rays; n is the index of refraction of a medium; φ is the angle between the ray propagation in the cavity and the cavity axis.

For an empty cavity with $t = 1$, the intensity of radiation passed through the cavity in the interference maxima ($\Phi = 2k\pi$) is equal to the incident radiation intensity

$$I = I_0. \qquad (2)$$

In the presence of absorbing medium in the cavity it becomes

$$I = \frac{t(1-R)^2}{(1-Rt)^2} I_0. \qquad (3)$$

Note that no approximation was made for t and R, therefore, equation (3) is true both for strong absorption and for low reflectivity R of mirrors.

Figure 3 shows the dependence of the gap depth $1 - I/I_0$ in the cavity transmission spectrum as a function of absorption $(1 - t)$ of the medium under study. It is seen that for small absorption coefficients (the transmittance is close to 1), when the gap does not exceed 20%, the gap depth is connected linearly with the transmittance. At larger values of $1 - t$ the linearity is violated.

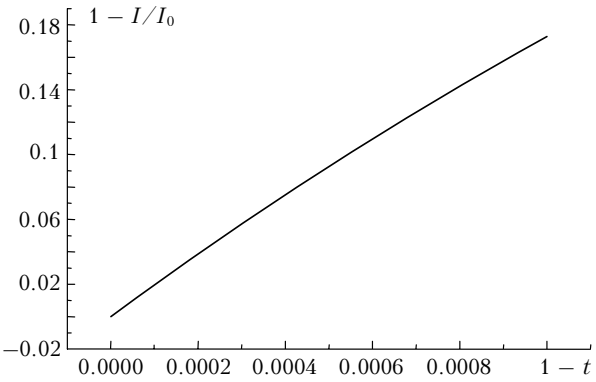

Fig. 3. The dependence of the gap depth $1 - I/I_0$ in the radiation spectrum from $1 - t$ for mirror reflectivity coefficient $R = 0.99$.

Let us compare the contrast enhancement coefficient β of the new method relative to single-pass spectroscopy. This coefficient is a ratio of the gap depth $(1 - I/I_0)$ in the cavity transmission spectrum to the gap depth in the single-pass case $(1 - t)$:

$$\beta = (1 - I/I_0)/(1 - t).$$

Figure 4 presents the dependence of β on different values of the mirror reflectivity coefficient R. At $R = 0.9999$, β reaches 10^4 and then, as R decreases, rapidly decreases following the exponential law, reaching 98 at $R = 0.98$ and 19 at $R = 0.9$.

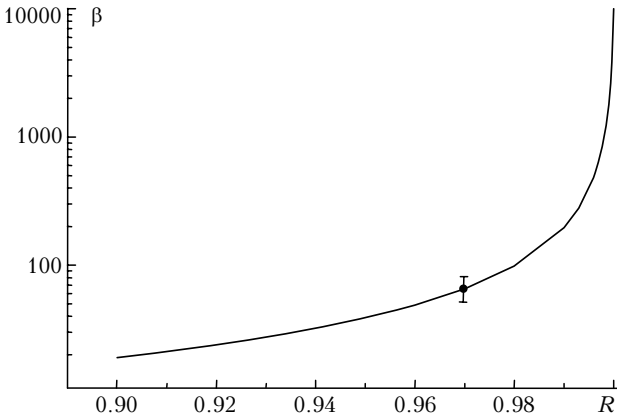

Fig. 4. Contrast enhancement β in high-Q cavity as a function of mirror reflectivity coefficient R.

Thus, even using standard dielectric mirrors with a reflectivity coefficient of 0.9…0.99, a significant contrast enhancement by 20…100 times can be obtained. A 1000-fold and higher contrast enhancement occurs at a mirror reflectivity coefficient higher than 0.999. In our case, a 65-fold contrast enhancement has been yielded, which corresponds to a mirror reflectivity coefficient of 0.97 and points to the fact that the given mirrors have significant losses in α, reaching 0.027. The confidence interval for the measured value of β in Fig. 4 corresponds to measurements performed for several spectral lines.

The obtained contrast enhancement, even with low-quality mirrors, is comparable to that, obtained with multi-pass cells, which usually amounts to 100. Thus, the use of optical resonators instead of multi-pass cells allows constructing a simple and efficient high-sensitive spectrometer, even with low reflectivity mirrors. This fact makes the method of resonant absorption enhancement effective for designing gas-analyzers.

Acknowledgements

L.N. Sinitsa is grateful to Yu.A. Poplavskii and A.P. Sherbakov for putting in his disposal of the photorecorder with CCD array and the software for processing measurement results.

This work was performed under financial support of Russian Foundation for Basic Research (Grants Nos. 06-02-08073 and 05-03-32782).

References

1. A. O'Keefe and D.A.G. Deacon, Rev. Sci. Instrum. **59**, No. 12, 2544–2551 (1988).
2. R. Engeln, G. Berden, R. Peeters, and G. Meijer, Rev. Sci. Instrum. **69**, No. 11, 3763–3769 (1998).
3. S.E. Fiedler, A. Hese, and A.A. Ruth, Chem. Phys. Lett., No. 371, 284–294 (2003).
4. Yu.A. Poplavskii, V.I. Serdyukov, L.N. Sinitsa, A.P. Sherbakov, and Yu.A. Matul'yan, Nauka – Proizvodstvu **65**, No. 9, 28–29 (2003).
5. G.S. Lansberg, *Science* (Nauka, Moscow, 1976), 926 pp.