ENHANCEMENT OF THE POTENTIALITIES FOR COHERENT DETECTION BY THE METHOD OF INTRACAVITY LASER DETECTION

S.V. Lasarev

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
Received February 1, 1993

Possible ways of increasing the sensitivity of coherent detection of optical signals by the method of intracavity laser detection based on a decrease in the relative level of pumping by changing the intracavity losses and decreasing the pump power are studied. An eightfold increase of the detection sensitivity has been experimentally reached. Another way of increasing the detection sensitivity is to adjust the operating point of a laser to the point of the steepest slope in the amplification curve. These mechanisms of the sensitivity increase are studied experimentally. As a result, we have obtained a 30–fold increase in the detection sensitivity. Possible ways of its further increasing are discussed.

Coherent lidars are the main means of remote laser sounding of the wind velocity vector fields in the atmosphere.[1–3] Having all the merits of the method of coherent detection of optical signals, first of all, high sensitivity and considerable magnitude of the Doppler shift, they also have the demerits peculiar to this method. Wavefront distortion in the process of propagating of laser radiation through the atmosphere and its scattering by the atmospheric aerosol is the main problem.

Attention paid to these systems is well explicable by all merits of the coherent lidars used for the remote sounding of wind as well as by the fact that IR lasers used in such lidars enable one to perform simultaneously gas analysis of the atmosphere.

A great deal of effort is going not only into the improvement of coherent lidar technology, but also into the development of new techniques aimed at enhancement of the potentialities for coherent detection. One of these techniques is the intracavity laser detection method borrowed from laser spectroscopy.[4–5] The essence of laser detection is the use of a transmitting laser as a highly selective optical receiving amplifier. The laser radiation scattered by atmospheric aerosol or topographic object is directed into a laser cavity. The laser turns out to be very sensitive to the emitted radiation.

Let us examine the transceiving laser operation when low–power optical radiation is injected into the laser cavity. We assume that wave and energy parameters of the injected radiation match the radiation inside the cavity.

We use the system of balance equations for the photon number density $J(\omega, t)$ and the inverse population density $N(\omega, t)$ to analyze the lasing dynamics

$$\frac{dJ}{dt} = \nu\, J(\omega, t) \left\{ \kappa(\omega, t) - \beta - [2l \ln(r_1 r_2)]^{-1} + \frac{1}{2l} \ln\left[1 + r_{\text{eff}} + 2B_c \sqrt{r_{\text{eff}}}\right] \right\},$$

$$\frac{dN}{dt} = n_0\, w_{\text{p}} - [\, w_{\text{p}} + \nu\, \sigma\, J(\omega, t) + \tau^{-1}]\, N(\omega, t), \qquad (1)$$

where $\kappa(\omega, t) = \sigma N(t)$ is the gain, β is the total loss coefficient, r_1 and r_2 are the reflectances of the mirrors of the laser cavity of length l, and B_c is the coherence function. In the case of diffuse reflection (scattering) from an external reflector with the scattering phase function $r_3(\theta)$

$$r_{\text{eff}}(\omega) \simeq \left(\frac{R_0}{2L}\right)^2 (1 - r_2)^2 \frac{r_3(\theta)}{r_2} \exp\left[-2L\, \alpha_g(\omega)\right],$$

where R_0 is the receiving aperture radius. In the second equation of system (1) w_{p} is the probability of stimulated transition due to pumping, τ^{-1} is the probability of spontaneous transitions in the pumping channel, and n_0 is the total number of active centers in a unit volume.

An approximate solution of system (1) in the case of small deviations from the stationary values of $N(t)$ and $J(t)$ for the amplitude of a variable component of laser response to periodic external action has the form

$$\Delta J = \frac{J_0\, r_{\text{eff}}}{[\kappa - \beta - (2l)^{-1} \ln(1 + r_{\text{eff}} + 2B_c \sqrt{r_{\text{eff}}})]\,(g - 1)}. \qquad (2)$$

Here J_0 is the stationary value of the photon number density and g is the relative excess of pumping energy level above threshold one which allows for not only the pump power but also the intracavity losses. As the pump energy level approaches the threshold one, the amplitude of laser response ΔJ increases. This fact is widely used in intracavity laser spectroscopy in order to increase its sensitivity. However, as $g \to 1$ the lasing noise sharply increases.

Dependence of the minimum detectable reflectance R on the angle of rotation of a plane–parallel BaF_2 plate inserted in the cavity of a CW gas–discharge CO_2–laser is shown in Fig. 1*a*. The laser was equipped with a lasing frequency stabilization system and a noiseless stabilized power supply. The plate was oriented perpendicular to the cavity optical axis, and the angle was changed from 90 to

0235-6880/93/09 641-04 $02.00

54.5° (Brewster's angle). One more possible use of Eq. (2) is to change the discharge current (Fig. 1*b*), which determines the value of g as well. The maximum signal level was observed for a discharge current of 22 mA. Further decrease of the current amplitude results in a lasing breakdown. In this case an eightfold increase of sensitivity was observed. Due to efficient system of lasing frequency stabilization and low–noise power supply, the expected amplification of the laser radiation fluctuations did not occur.

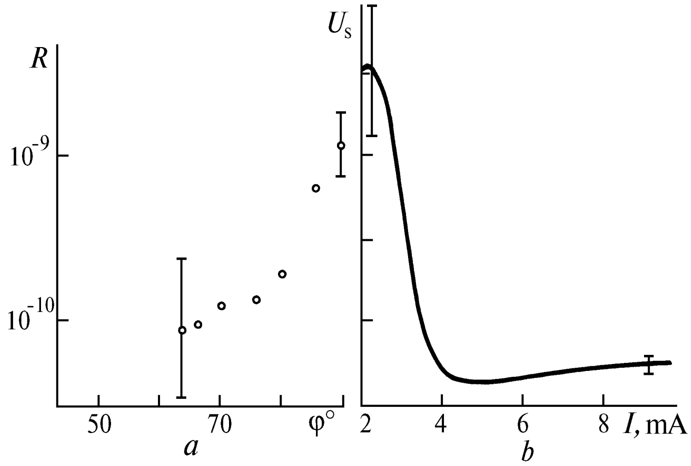

Fig. 1. Dependence of the minimum detectable reflectance on the intracavity losses (a) and variation of the photodetector signal level U_s vs. pump level determined by the discharge current I (b).

Description of the stabilization system and power supply will be presented in Ref. 7.

Joint action of the intracavity absorber and discharge current variations gave no noticeable results. An increase of intracavity losses was followed by an increase of the threshold discharge current amplitude and *vice versa*. The sensitivity remained at the achieved level.

An increase of the coherent detection efficiency can be reached by adjustment of the laser operating point to the point of the steepest slope in the amplification curve. In such a way the maximum amount of increase in the variable component of laser signal can be obtained (Fig. 2). For simplicity, let us study the Lorentz profile of the laser amplification line.

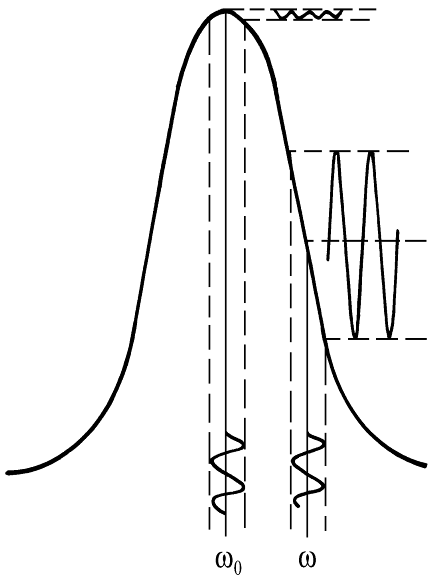

Fig. 2. Change in the amplitude of variable component of laser signal as a function of the position of laser operating point in the amplification profile.

The amplification factor as a function of the frequency has the form[6]

$$\kappa(\omega) = \frac{S}{\pi} \frac{\Delta\omega_{0.5}}{(\omega - \omega_0)^2 + \Delta\omega_{0.5}},$$

where S is the normalized integral intensity of the line, ω_0 is the frequency of its center, and $\Delta\omega_{0.5}$ is the line halfwidth. The parameter $\kappa(\omega)$ has the steepest slope at frequencies

$$\omega_{1,2} = \omega_0 \pm \Delta\omega_{0.5} . \quad (3)$$

As a rule, the laser operating point is adjusted to the peak in the curve $\kappa(\omega)$, i.e., $\kappa'(\omega) = 0$. This condition is used in the operation of lasing frequency stabilization systems practically in all cases.[8–9] These systems hold the laser operating point at the peak of the curve by means of minimization of an error signal. In our case the operating point of the laser must be held starting from the condition of maximum signal. This problem is not simple from the viewpoint of its engineering implementation. We used a slowly moving output mirror of a CW CO_2–laser in order to study the laser sensitivity to periodical low–power external radiation as a function of the operating point position in the amplification profile. Diagram of the experimental configuration is shown in Fig. 3. The cavity of the gas–charge laser is formed by the difraction grating G and mirror M clamped on a piezocorrector. A stabilization system AFC controls the position of the mirror in order to hold the laser operating point at the peak of the amplification curve. The radiation is extracted through zero order of diffraction grating and is incident on the pyroelectric detector PD. The radiation is directed to the reflector R being the surface of a piezoceramic modulator at which the alternating voltage from an acoustic generator (AG) is applied in order to modulate the reflected signal in phase. A signal from the photodetector is fed to the lock–in filter LF controlled by the acoustic generator voltage. The detected signal is fed to the *OY* input of the memory oscillograph. A sawtooth voltage is applied to the *OX* sweep and the piezocorrector of the output mirror *M* thereby providing linear time variation of the lasing frequency. The attenuator *A* (a set of disperse absorbers) is placed on the path of a laser beam. Modulation of the scattered radiation enables us to eliminate the spurious radiation scattered by the attenuator. The obtained dependence of the photodetector signal amplitude on the voltage applied to piezocorrector (or position of the laser operating point in the amplification profile) is plotted in Fig. 4*a*.

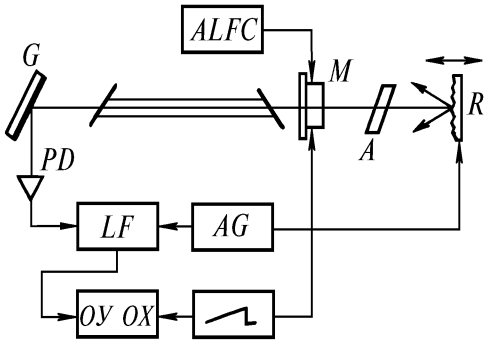

FIG. 3. Diagram showing the experimental configuration in the study of the effect of the position of laser operating point on the amplitude of the variable component of laser signal.

An approximately 15–fold increase of the photodetector signal amplitude was observed in the sensitivity maximum, i.e., at one of the frequencies $\omega_{1,2}$. However, due to steep slope of the curve $k(\omega)$, the laser turned out to be extremely sensitive to any perturtions of the cavity parameters caused by mechanical, acoustic, thermal, and optical factors. Despite well–reproducible results obtained with the above–mentioned technique (spread in value was no more than 5 % for 10 realizations), we failed to hold the laser operating point at the steepest slope position for a long time. We succeeded in increasing the intracavity detection sensitivity, but the reproducibility of the results sharply worsened and the spread of results reached 100%. We explain this phenomena by imperfect system of stabilization of lasing frequency, in which the standard principle of automatic lasing frequency control (ALFC) according to the amplification maximum, i.e., the error signal minimum (and maximum in our case) was used. Therefore, one of the ways of further increasing the sensitivity of the coherent intracavity detection is to develope the method and the efficient system of the ALFC capable of holding the laser operating point at the point of the steepest slope in the amplification curve.

In conclusion we present the results of joint action of the observed mechanisms of increasing the coherent detection efficiency. The results of comparison of sensitivities of traditional and intracavity optical mixing under different conditions are shown in Fig. 4*b*.

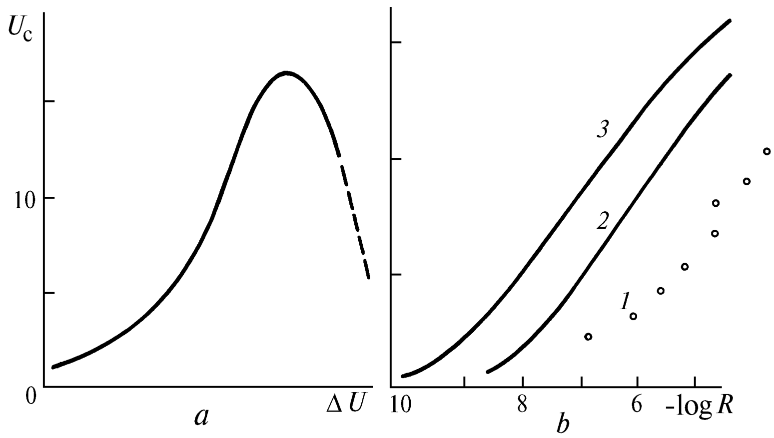

FIG. 4. Photodetector output signal as a function of displacement of the laser output mirror determined by voltage on the piezocorrector (a) and a comparison of sensitivity (b) for: 1) traditional extracavity mixing, 2) intracavity mixing when the laser operating point is adjusted to the point of the steepest slope in the amplification curve, and 3) intracavity mixing for the same position of the operating point and minimum pump level.

One might expect the sensitivity increase by 2.5–3 orders of magnitude. However, it actually increases by less than 1.5 orders of magnitude. This can be explained, first of all, by the amplification of the laser radiation fluctuations when creating the conditions for maximum increase of sensitivity. Elimination of the factors engendering the laser radiation fluctuations influences noticeably the efficiency of the coherent detection. The second reason is in the decrease of the gain, which rises the threshold pump power and reduces intracavity losses. However, the decrease of the gain does not correlate with the decreased amount of sensitivity increase to be expected.

Thus the noticeable gain (2.5–3 orders of magnitude) of the laser sensitivity to the external optical radiation can be reached by means of change of intracavity losses or pump level as well as by adjusting the laser operating point to the point of the steepest slope in the amplification curve only when the effect of the laser noise and fluctuation sources is completely eliminated or minimized.

REFERENCES

1. S.A. Akhmanov, V.M. Gordienko, L.A. Kosovskii, et al., Izv. Akad. Nauk SSSR, Fiz. **55**, No. 2, 194 (1991).
2. R.M. Hardesty, *Optical and Laser Remote Sensing* (Springer Verlag, Berlin, Heidelberg, New York, 1983).
3. S.W. Henderson, Ch.P. Hale, J.R. Magee, et al., Opt. Lett. **16**, No. 10, 773 (1991).
4. I.V. Samokhvalov, Yu.D.Kopytin, I.I. Ippolitov, et al., *Laser Sounding of the Troposhere and Underlying Surface* (Nauka, Novosibirsk, 1987).

5. A.P.Godlevskii, V.E.Zuev, Yu.D. Kopytin, et al., Opt. Commun. **62**, No. 6, 370 (1987).
6. K. Smith and R. Thomson, *Numerical Simulation of Gas Lasers* [Russian translation] (Mir, Moscow, 1981).
7. S.V. Lazarev, Prib. Tekhn. Eksp., 1993 (to be published).
8. V.G. Gudelev, and V.M. Yasinskii, Prib. Tekhn. Eksp., No. 1, 215 (1980).
9. S. Okajima, et al., Infrared Phys. **25**, No. 3, 569 (1985).