AUTODYNE LIDARS OF THE SECOND GENERATION

E.P Gordov

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
Received September 13, 1994

Basic principles of the laser–detection of weak echo–signals are briefly summarised in the paper and autodyne lidars employing this way of weak signal detection while sounding the atmosphere are described. In more details considered are recent autodyne lidar modifications, namely, a parametric autodyne lidar which allows one to increase the number of optical and dynamic characteristics of an atmospheric path and a remote retroreflector retrieved from the laser–detected echo–signal due to modulation of the sounding radiation and a hybrid lidar in which the advantages of conventional cw autodyne lidars are combined with those inherent in lidars employing pulsed lasers.

1. INTRODUCTION

It was shown soon after the laser invention that spectral and kinetic characteristics of laser radiation can be significantly changed by reflection of a fraction of the generated beam back into the laser resonator.[1] In fact it is the autodyne effect inherent in any free oscillation system.[2]

Usually influence of backscattered radiation on amplitude and frequency characteristics of the laser radiation is treated as a spurious phenomenon. In particular, such a situation occurs while stable lasers for precise measurements are designed[3] as well as when hybrid CO_2 lasers are developed.[4] At the same time, high sensitivity of the radiation characteristics to weak enough influence of the reflected signal indicates that laser is a good candidate to be a measuring device. Really, the weak action (backscattered radiation) in it causes variation of macroscopic parameters (generated radiation). Activity in the area of usage of lasers as detectors for determination of weak reflected signal characteristics has started many years ago, see, for example, Ref. 5. The possibility of detecting weak signals as well as an opportunity to use the same laser for transmitting signals and detecting them attracted a number of researchers. It is quite clear that such an approach is limited by the weak reflected signal case to avoid radical variations (in reality, distortions) of the laser radiation caused by external signal frequency lock–in.[6]

Additionally, such a detecting system has to have high noise immunity to external exposure at another frequencies since only signal within an active medium gain line can change a laser operation. The fact also looks attractive that while detecting the signal by a laser one can easily make nearly heterodyne detection in which wave fronts of the local oscillator (the field generated within the cavity with the active medium) and the received echo align automatically, and mixing occurs within the resonator with the active medium instead of mixing on a photodetector plate. The latter means that only sufficiently strong signals, whose magnitude remains within the same range, however strong the reflected signal is, reach a photodetector. It allows one to work within one and the same dynamic range of the photodetector and neglect its own noise.

The listed above set of properties inherent in the intracavity detection of weak signals makes this approach next to ideally adjusted to the tasks of laser sounding of the atmosphere.[7] Naturally this circumstance stimulates the interest of this area researchers in the use of a laser autodyne. However, in spite of interesting results obtained in laser range finding[8] and wind velocity sounding,[9] the first wave of activity in the use of autodyne lidars for atmospheric study decreased quickly enough. It seems that the reason for loosing interest was in sufficiently sophisticated procedure of information retrieval from the signal detected as well as in general level of laser technology at that time.

The second increase of the interest in the intracavity laser detection in atmospheric optics took place at the beginning of 80th. Here a novel approach suggested at the Institute of Atmospheric Optics should be mentioned in which a laser was used as a detector in the atmospheric spectroscopy problems.[10,11] This approach is a logical development of ideas and technique of intracavity laser spectroscopy.[12] Briefly, it can be described as follows. Wide–band laser radiation reflected from an external artificial or natural reflector and subjected to selective absorption while travelling in the atmosphere is returned back into the cavity. If duration of the returned signal is longer than the characteristic lifetime of a photon in the cavity then the spectrum generated by the laser is changed, namely there appears a dip caused by selective absorption by a relevant atmospheric gas. The spectral response of the laser can be quite significant due to the mode competition. In a limiting case of a specular reflector, the atmospheric version of a three–mirror intracavity laser spectrometer can be proposed with the lasing active element in one of the spectrometer arm and absorbing atmosphere in the another arm. Absorption gas analysis experiments were performed with pulsed ruby and Nd lasers as well as with a cw argon laser. Spectrum generated by these lasers coincides with the absorption lines of H_2O, O_2, and NO_2. The lidar employing the argon laser provided a reliable detection of the signal for the effective reflection coefficient as low as 10^{-7}. For 70 meters long atmospheric path the concentration sensitivity to NO_2 was $5\cdot10^{-8}$. To estimate experimentally the concentration sensitivity of the solid state lasers, dips in the generation spectrum at absorption line centers of relevant gases were measured. In particular, the sensitivity to H_2O (λ = 694.38nm) has been reached to be 0.1 Torr which corresponds to the saturated vapor concentration for air temperature –50°C.

0235-6880/95/01–02 137-08 $02.00

It is quite clear from the standpoint of lasing physics that the approach developed is aside from the conventional autodyning, and below we will not discuss these interesting results.

The first publication, in which a theoretical description of operation of the autodyne lidar for wind velocity measurements was given, seems to be the paper by Churnside.[13] Signal–to–noise ratio behavior near and far above the lasing threshold determined by him is in a good agreement with his own experiments.[14] Unfortunately, while the problem was formulated, the echo influence was taken into account only via the variation of the output mirror effective reflection coefficient which makes incomplete the results obtained. From the position of electrodynamics, an influence of an external signal on the field within the cavity should be considered via the boundary conditions for the relevant Maxwell equations on the output mirror.[15]

Nowadays the problem of using a laser as an element of a lidar receiving system is discussed in literature more and more intensely. The First Workshop on Optical Amplifiers for Lidar Applications[16] and Autodyne Lidars Section in the program of the last Conferences on Coherent Laser Radar well demonstrate an increase of interest in this research.[17,18]

In this paper after brief description of basic physics of the conventional autodyne lidar operation, novel types of autodyne lidars suggested and designed at the Institute of Atmospheric Optics are considered in more details. These are a "parametric" autodyne lidar[19] using which (owing to modulation of sounding radiation) one can retrieve simultaneously a set of optical and dynamic characteristics of a remote retroreflector and the hybrid autodyne lidar which in virtue of employing a hybrid laser instead of traditional cw generators as a transceiver has an enhanced sensitivity and range of operation.[20]

2. BASICS PRINCIPLES OF THE AUTODYNE LIDAR OPERATION

Typical autodyne lidar is schematically presented in Fig. 1. Here *1* and *2* are laser cavity mirrors whose reflection coefficients are R_1 and R_2, respectively, *3* denotes an active medium, and *4* is a remote retroreflector which might be a remote mirror, an aerosol layer, or a topographic target.

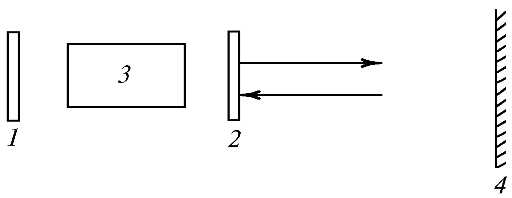


FIG. 1.

As it was mentioned above, we restrict ourselves by case of sufficiently weak signal typical for sounding. The latter case means also a possibility of avoiding completely situation when an external signal frequency matches the lased radiation.[5] A weak reflected signal returns into the laser cavity at a shifted frequency. Typical situation occurring within the cavity is shown in Fig. 2. Here the solid line shows the generation contour with the center at frequency ω, the dashed line is for the reflected signal at frequency ω', and the gain profile is pictured by the dot–and–dash line. To change significantly characteristics of the field within the cavity, the reflected signal should be at least in the domain where the gain coefficient is more then unity. The signal returned into the gain domain will be amplified, and if the geometry of the cavity allows the oscillation with the signal frequency then due to a number of passes the amplification can be quite significant. As shown in Ref. 21, an additional wave whose frequency is shifted to the opposite from signal side appears under the influence of the returned signal. By analogy with the four–wave processes, this wave was called the image one.

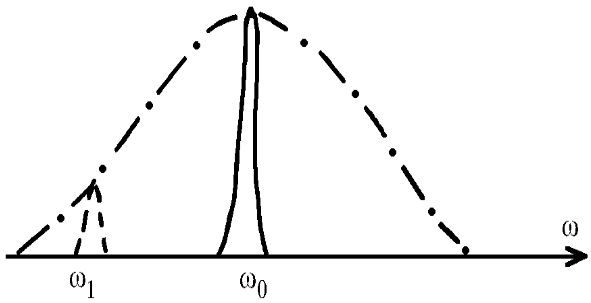


FIG. 2.

Enrichment of the laser generation spectrum under the influence of a weak external signal opens some novel possibilities of detecting the latter. The most obvious case is direct detection of the intracavity field intensity at frequency ω' (the amplified signal). One can also measure the intensity at the image wave frequency ω_1. Simultaneous measurements of both waves behavior will be informative as well. It should be mentioned that mixing of the two oscillations with amplitudes of different orders within the cavity results in beats which looks like fine–structural intensity modulation of the laser emission. A number of opportunities to make measurements in the system under consideration allows one to choose the most optimum way for determining those characteristics of the reflected signal which are of importance for a particular problem of laser sounding. As for specific ways to perform measurements of the intracavity field intensity, one can send to a photodetector the field leaving the cavity through the rear mirror of the laser[22] or the wave reflected from the laser output Brewster window.[23]

Theoretical study of the conventional autodyne phenomenon in lasers was performed many times.[2] So far the most complete and detailed consideration which includes analysis of noise behavior is given in Ref. 24 by Loudon with coworkers. It should be added that these results allow one to make optimization of optical elements of an autodyne lidar leading to maximum SNR for a chosen place for the detector.

3. PARAMETRIC AUTODYNE LIDAR

Direct use of the laser autodyning in lidars can be done when a reflected signal is frequency–shifted from a sounding radiation, what takes place when either remote retroreflector or a lidar (say, airborne or spaceborne lidar) moves. In such a way some interesting lidar systems were developed, for example, the autodyne CO_2 lidar for determination of characteristics of remote retroreflector motion[25] and the Nd:YAG lidar for remote measurements of aerosol dynamic and microphysical properties.[26] However, suggested in Ref. 19 parametric autodyne lidar has significantly larger potential. The sounding radiation in it is periodically modulated directly within the laser cavity, say by fine oscillations of the output mirror, whose frequency Ω

is chosen in such a way that the signal travelling time to and from the retroreflector is shorter than a period of oscillations. As a result, the echo returned into the cavity has the frequency different from the frequency of probing signal $\omega(t)$. Mixing of these oscillations leads to appearance of beats in the cavity with two characteristic frequencies, namely, Ω and the difference frequency $\Delta\omega(t)$. The latter explicitly depends on the distance L to the reflector. The modulation index at the difference frequency depends on the echo–signal intensity, that is, on the losses occurring at signal propagation (aerosol scattering, absorption along the path, and the target reflection coefficient). Analysis of the field appeared within the cavity under influence of the received weak signal, performed within the framework of the gas laser model, yielded the following equation for the field intensity:

$$I(t) = I_0 + \Delta I(t), \qquad (1)$$

where I_0 is the stationary solution to the laser equation for the case of immovable output mirror, and $\Delta I(t)$ are small deviations from the steady state obeying the equation

$$\frac{\mathrm{d}}{\mathrm{d}\,t}\,\Delta I(t) = m\,\frac{a(t)}{a}\,\Delta I(t) + \theta\,\cos(\Delta\omega\,t)\,\Delta I(t-\tau). \qquad (2)$$

Here m is the intensity modulation index due to mirror oscillations, $a(t)$ determines the law of the oscillations, θ is the intensity modulation index due to echo–signal effect, $\Delta\omega$ is the beats frequency, and τ is the echo–signal time delay, $\tau = 2\,L/c$. It should be added that usually one can neglect in Eq. (2) the difference between $\Delta I(t-\tau)$ and $\Delta I(t)$, or in other words, the delay can be neglected. The frequency of the beats is determined quite easily, and it has especially simple form for the sawtouth mirror oscillations:

$$\Delta\omega = \frac{\tau}{T}\,\omega - \frac{a}{l}\,, \qquad (3)$$

where T is the mirror oscillation period, $T \gg \tau$, and l denotes the laser cavity length.

A more detailed theoretical description of a parametric autodyne lidar operation has been published in Ref. 27. To derive an adequate model, convinient for experimental data processing, the basic set of laser equations are written in terms of coordinate finite differences instead of partial derivatives and the echo–signal influence is considered by the following boundary conditions:

$$E_2(a,\,t) = \gamma(t)\,E_1(a,\,t), \qquad (4)$$

$$\gamma(t) = R_0 + \exp\left(\frac{2L}{\sigma}\right)(1 - R_0^2)\,R_2\,\cos\frac{\omega\tau}{l}\,a(\tau).$$

Here E_1 and E_2, are the direct and return waves in the cavity, respectively, R_0 is the output mirror reflection coefficient, σ is the coefficient of losses along the path, R_2 is the remote mirror reflection coefficient, $\tau = 2\,L/c$.

Thus derived equations for $X(t) = E_1(a,\,t)$ and $Y(t) = E_2(-\,l,\,t)$ have the form:

$$\dot{X} = \gamma(1 - a(t)/l)\,(X - R_1\,Y) = \alpha\,X - \beta(1 + 2\,\gamma^2)\,X^3,$$

$$\dot{Y} = (1 - a(t)/l)\,(\gamma\,X - Y) = \alpha\,Y - \beta(1 + 2\,\gamma^2)\,Y^3\,, \qquad (5)$$

where positively definite constants α and β are the gain and saturation coefficients determined in a usual way. The set (5) describes field dynamics fairy well at the initial stage of generation as well as at the stage of stable beats. It should be added that on the basis of numerical simulation of the Maxwell equations (5) for the field within the laser cavity an algorithm was developed to retrieve, from beats characteristics measured, the losses along the path as well as the dynamic and optical characteristics of a remote retroreflector.

To check conclusions of theoretical analysis and to study achievable capabilities in determination of the atmospheric path characteristics, a laboratory setup of a parametric lidar based on a gas discharge cw CO_2 laser was developed.[27] Its functional scheme is shown in Fig. 3.

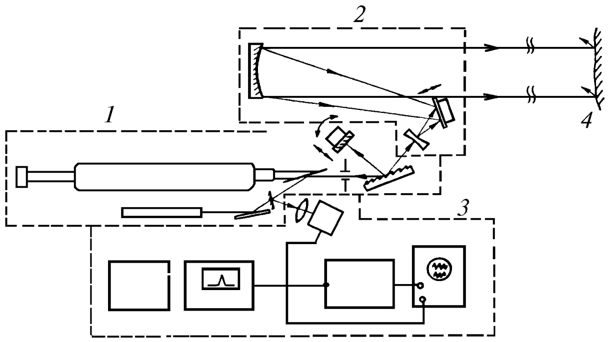


FIG. 3.

The lidar employs a cw CO_2–laser (*1*) discretely tunable over vibrational–rotational transitions, a transmitting and receiving optical system (*2*), and electronic equipment for recording signals (*3*). The laser frequency modulation within a chosen vibrational–rotational transition contour is done by changing the cavity length by means of oscillations of a mirror fixed on a piezocorrector.

Laser radiation escaping the cavity through the zero order of a diffraction grating is directed to a target by means of off–axis mirror–lens telescope with the focal length of 70 cm and 30–cm aperture. Different artificial and topographic surfaces were used as the targets, such as an aluminium mirror, a polished duraluminium plate, a brick wall, etc. Light beam reflected by a target placed at distances 110, 210, and 500 meters is collected by the same telescope and then directed back into the laser cavity.

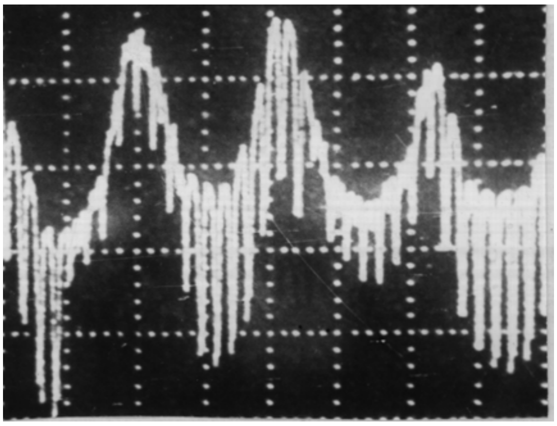
A portion of a laser beam reflected from the end of the gas–discharge tube is focused by a BaF lens onto the sensitive area of a Au:Ge photodetector cooled down to nitrogen temperature. The signal from the photodetector is amplified by a low–noise broadband amplifier and then processed with a spectrum analyzer, and displayed on the oscilloscope.

While scanning the laser radiation frequency within one rovibrational transition by means of the oscillating mirror at a frequency Ω the instant frequency of generation is shifted by $\Delta\omega$ during the light travel along the path. When the generation frequency is changed according to triangle law and magnitudes of the generated frequency deviation $\omega(t)$, and the frequency of scanning Ω are fixed, the magnitude of the beats frequency $\Delta\omega$ is constant in time except for breaks zones, and it depends on the travelling time along the path $\tau = 2\,L/c$. When the frequency of the laser radiation is varied according to sine law, the beat frequency also depends on the distance L and varies nonlinearly within each half–period of modulation. However, even in this case one can isolate dependence on L by eliminating the above nonlinearity. To provide single–valued dependence on L, the echo–signal time delay should be less then the half–period of frequency scanning.

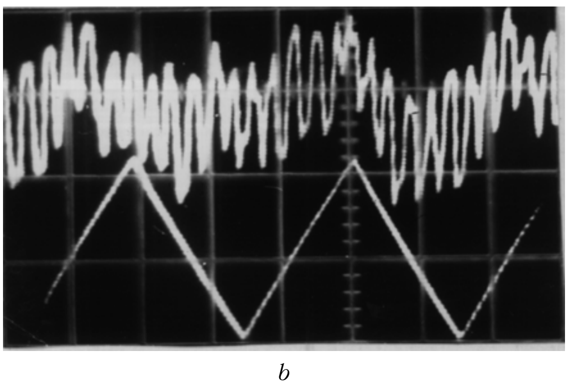
In the experiments[28] the frequency of modulation varied from 50 to 200 KHz and the resulting laser radiation frequency was tuned within 10–20 MHz range. Figures 4*a* and *b* show oscilograms of the laser intensity beats obtained when the signal reflects from immovable target at a distance 100 and 210 meters from the lidar. Here one can see the beat break at the extreme points of a sine modulation function. When the frequency was modulated following the saw–tooth function the breaks if any were significantly smaller. It is caused by existence of the dependence of the beat frequency on time at the vicinity of the extreme points which is weak in the first case and strong in the second one. The oscillograms were taken under favorable atmospheric conditions, i.e., after sunset and in the absence of wind.

The wind and an atmospheric turbulence are basic factors determining fluctuation characteristics of radiation reflected from the mirror. To decrease the atmospheric turbulence influence on determination of the path length from measured beat frequency, the laser frequency modulation period should be chosen smaller than the characteristic time of the atmospheric fluctuations.

To determine the maximum achievable sensitivity of the parametric autodyne CO_2 lidar, the setup was a little bit modified. A stabilized CO_2 laser operating by the transition $P(20)$ of the band 001–100 was employed to this end. The probing beam outgoing through the zero order of a diffraction grating was directed to a target, whose reflection or scattering should be measured, by means of a collimator. A polished aluminium plate was used as the target. It moves either periodically or with a constant velocity. In the first case the target was mounted on a piezocorrector which was oscillated by a sound generator that allowed one to choose desired frequency and amplitude of the oscillations. In the second case the target was mounted on a cart moving with the chosen velocity along the laser beam propagation direction.



a



b

FIG. 4.

The resonance frequency behavior of the modulation index at the frequency of modulation at a fixed magnitude of the echo–signal was found experimentally. The maximum signal is observed at the target velocity $V \approx 28$ cm/s, the relevant frequency is equal to 54.3 KHz. The resonant maximum magnitude decreases with increasing relative magnitude of the gain minus losses (discharge current) while the resonant frequency becomes larger. The minimum detectable reflection for per 1 Hz wideband amounts to $R_{min}/\Delta f = 7.3\cdot10^{-17}$ Hz^{-1} which corresponds to sensitivity to the returned into the cavity power $(P_{reff})_{min} = 3.65\cdot10^{-17}$W/Hz, the latter is only one order smaller than the threshold sensitivity of laser calculated for optimum parameters.

4. MULTYPURPOSE PARAMETRIC AUTODYNE CO_2 LIDAR

The above autodyne CO_2–tunable–laser–based lidar can also be used in an ordinary longpath absorption DIAL gas analysis of the atmosphere. In particular, the ethylene concentration measurements were performed along the path 0.2–1 km long and minimum detectable ethylene concentration was as low as 0.83 mln·m^{-1}.

This fact stimulated us to start a design of a multy–functional lidar aimed at performing gas analysis as well as at determination of remote retroreflector optical and dynamic characteristics. Now the stage is reached when laboratory experiments are run with a laboratory version of the setup. The lidar optical arrangement is shown in Fig. 5.

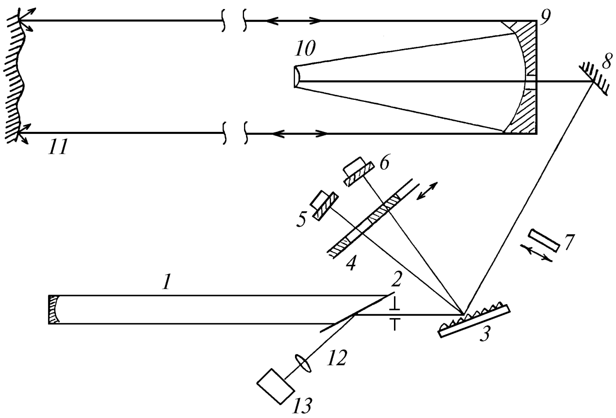


FIG. 5.

As usual, the reflected beam is directed into the laser cavity. The frequency modulated signal is used to determine the distance to the reflector and its dynamic characteristics. As a result, the target velocity and the distance to it are extracted from fine structure of the intensity beats of the intracavity field. To perform the gas analysis, a quickly tunable CO_2 laser is used. It consists of an active element *1*, an iris *2*, a diffraction grating *3*, a modulator *2* for quick wavelength switching, and two mirrors *5* and *6* mounted on peizoceramics. The probing signal escaping the cavity through the zero order of a diffraction grating *3* is directed by a mirror *8* into the transcieving Cassegrainian telescope *9* and *10*. The collimated beam is sent to the reflector *11*, and the echo–signal is returned back into the active element. Oscillations of mirrors *5* and *6* modulate both laser modes what results in the frequency shift being proportional to the distance to the target and its velocity. Comparison of losses in and off the chosen spectral line allows one to determine a concentration of a gas under study. To avoid the influence of atmospheric turbulence, the frequency of wavelength switching was chosen of 180 Hz

To obtain information on dynamic and optical characteristics of a target, another mode of lidar operation is used. According to the program a stepper motor places the modulator *4* into the position allowing cw generation by one of the modes. Measurements of the amplitude and frequency of the beats caused by the reflected signal permit one to determine relative reflection coefficient at the chosen wavelength and velocity of the target.

An additional possibility of determining optical properties of a target exists owing to the fact that the Brewster window transmits only linearly polarized field while its depolarized component is sent to the photodetector *13*. If a quarter–wave plate *7* is placed into the lidar channel then the signal reaching the photodetector will be proportional to the polarized component of the echo–signal. In such a way a polarization characteristics of the target can be determined.[29] Namely these data are of importance for detection of oil spills and searching mineral deposits.

5. HYBRID AUTODYNE CO_2–LIDAR

In spite of high sensitivity of a cw CO_2–laser–based signal detection, this application of lidars meets some obstacles limiting the lidar operation range. Moreover, the very idea of the autodyne lidar based on a cw laser has an intristic contradiction since the stronger is the influence of a weak echo on the strong intracavity field the stronger are distortions of the probing signal. In particular, operation of the laser near the threshold where the sensitivity to the echo is maximum[13] leads to weak probing signal generation and, as a consequence, to small distance of sounding.

At the same time, lidars based on pulsed lasers enjoyed privileges for number of applications since here the distance determination is a mere measurement of the travelling time, and use of short pulses allows one to deal with strong sounding fields which does not initiate nonlinear interactions in the atmosphere. The positive features of both approaches can be combined if a hybrid CO_2 laser [30] is used in the autodyne lidar. In hybrid laser the cw and pulsed sections with the active medium are placed into the same cavity. Such a configuration is employed to amplify the chosen longitudinal mode[31] and actively used in heterodyne lidars. Preliminary results show that it can be used in the autodyne lidars to enhance their sensitivity.

A geometry of a hybrid lidar is shown in Fig. 6. The mode volume is restricted by the aperture of the pulse gain section in a way to generate the TEM_{00} mode only. The cw gain section is placed at the rear side of the cavity. The pulsed section at the atmospheric pressure is placed at the front end of the cavity and pumped with an electron beam. When the cw section is pumped, radiation pulse characteristics are changed. Since the whole system is above the threshold yet the delay between the electron pump and the pulse nearly disappears. Pulse duration increases as well. This type peculiarities were observed earlier in studies of hybrid CO_2 laser operation.[32–35]

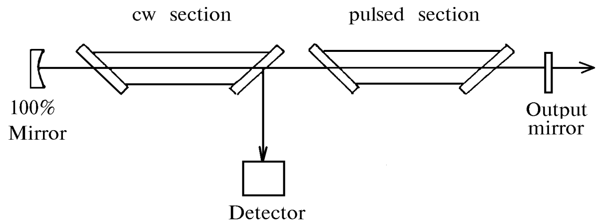


FIG. 6.

A set of laboratory and atmospheric experiments was performed using this installation. We started with the case when the system operated with nonpumped cw section. A typical signal is shown in the upper part of Fig. 7. In the left part of the figure the output pulse is shown while its echo is readily seen to the right. When the cw section was switched on the signal detected from the echo grew. Typical situation is shown in the Fig. 8. Apparent decrease of the round travel time is caused by the fact that in the second case the echo is formed by the leading edge of the sounding pulse. Thus the hybrid autodyne lidar significantly amplifies the echo–signal.

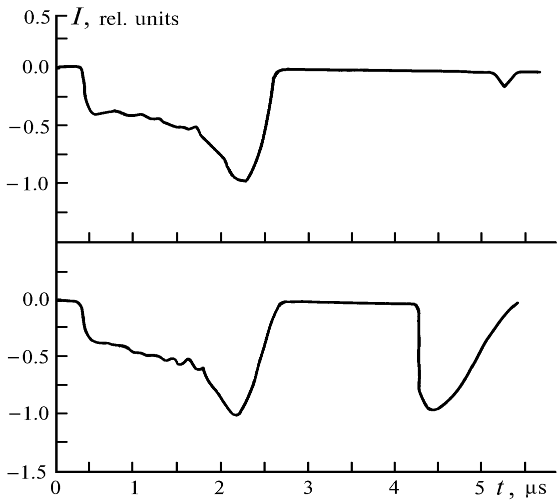


FIG. 7.

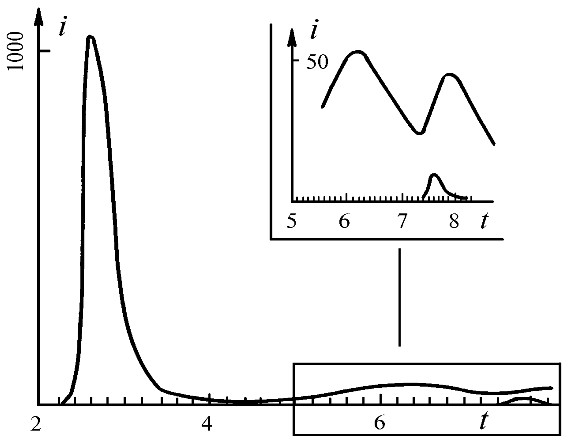


FIG. 8.

Simple estimates show that thus detected signal is at least one order of magnitude larger than the signal measured by direct detection. This circumstance makes the configuration suggested promising for foregoing study from the standpoint of applications as well as for energy redistribution in the hybrid laser cavity under the influence of the echo–signal returned into it.

The known model[33] of a pulsed CO_2 laser was used for numerical simulation of the hybrid laser reaction on the echo injected into the resonator.[36] Several approximations were adopted in calculations. First, influence of the cw section on the process of signal reception was not considered since its main role is selection of a single mode at the initial stage of the pulse generation, and only shape of the leading edge of a pulse depends on it. Second, we neglect a phase time evolution for the signal as well as for its echo. The latter can not be done for sounding along turbulent paths and for wind or the retroreflector velocity measurements.

The system of equations describing the pulsed CO_2 laser is as follows

$$\frac{di}{dt} = -\frac{i}{T_0} + \sigma\, c\, i(n_a - n_b) + \frac{n_a \sigma c}{V} + T^2 \Delta\nu \sqrt{i(t-\tau)\, i(t)},$$
$$\frac{dn_a}{dt} = -c\, i(n_a - n_b) + g_c\, n_c - (g_a + g_c)\, n_a + W_a, \qquad (6)$$
$$\frac{dn_b}{dt} = c\, i(n_a - n_b) + g_a\, n_a - g_b\, n_b + W_b,$$
$$\frac{dn_c}{dt} = g_c\, n_a - (g_c - g_{c0})\, n_c + W_c\, .$$

Here i is the laser radiation intensity, n_a, n_b, and n_c are populations of the upper and lower levels of CO_2 and N_2 molecules, respectively, σ is a cross section of stimulated emission, g_a, g_b, g_c, and g_{c0} are relaxation constants of CO_2 and N_2 molecules, W_a, W_b, and W_c are pump energies of relevant levels, $V = 100$ cm^3 is the cavity volume, T_0 is the lifetime of the photon in the cavity, $T = 0.1$ is the transmission coefficient of the output mirror, $\Delta\nu$ is an intermode frequency, c is the light speed, and τ is the time delay of the echo–signal. Numerical values of the constants were chosen the same as in Refs. 30–32. As the initial conditions we take the following:

$$i(0) = 0,\ n_j(0) = n_j^0,\ j = a, b, c,$$

where n_j^0 are the molecular level populations under standard atmospheric pressure and room temperature.

When influence of the echo–signal is not considered, Eqs. (6) lead to the solution coinciding with that found in Refs. 33–35. While performing simulations with the echo, the delay time was chosen to be not larger than pulse duration (about 10 μs), but so that it allows the echo to act on the pulse tail. Under such a condition the changes in the pulse shape were limited by two features, namely, bell–like maximum appears in the tail whose shape does not repeat the echo, and the response intensity is significantly higher than the echo. One of the typical results is shown in Fig. 8. It should be added that considering short delay times does not mean that such procedure of the echo detection is limited by short distances only, since for large delay times one can detect the echo on the pulses periodically generated by the laser. It means that the range limitation for hybrid lidar on CO_2 laser is determined by the SNR of the echo.

Since solid state lasers are widely employed in lidar nowadays[37] we have investigated the possibility of constructing a cw–pulsed autodyne lidar based on Nd:YAG lasers. Exact copy of the above hybrid scheme[20] can not be used here because of a decrease in the pulse power caused by nonlinearity of losses within the resonator. To avoid this obstacle, the lidar optical scheme was modified as shown in Fig. 9. In this case we deal with optically coupled pulsed and cw lasers instead of the hybrid one. The configuration suggested allowed experimental analysis of the echo–signal after its intracavity amplification and mixing. Preliminary results show good prospects of the work in this direction.[38]

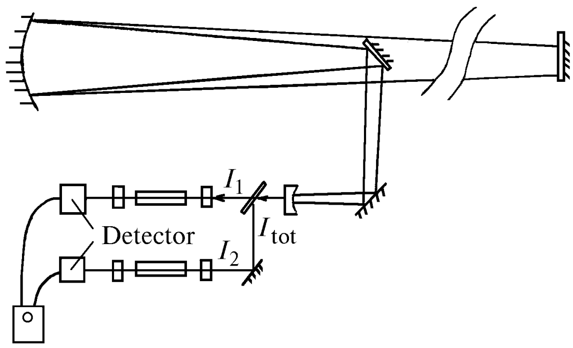


FIG. 9.

CONCLUSIONS

Thus, we have shown that use of a laser as a detector of weak optical signals gives some advantages to the autodyne lidars. One of them is high noise immunity caused by the fact that the laser reacts only on those optical signals which appears within the active medium gain contour. Important role play the fact that while receiving the signal by a laser the photodetector operates significantly above the shot noise level which allows one to neglect its influence. Here one can avoid the typical, for a conventional lidar, problem of large variation of a signal level at the detector.

High sensitivity of laser detection together with the above advantages makes it competitive with the heterodyne detection. It should be added that in autodyne systems the alignment of wave fronts of local oscillator and the echo, which is quite a technical problem, in heterodyne detection takes place automatically.

Important for applications is also a possibility of constructing multipurpose systems based on parametric autodyne lidar. Such systems would allow one to determine simultaneously the optical and dynamic characteristics of remote retroreflectors and perform gas analysis.

It should be noted that considered in the paper use of a hybrid laser as a detector significantly improves characteristics of the laser detection and opens up possibilities for novel atmospheric optics applications of this type of detection.

In conclusion, it should be added that in the course of this study a more general approach to the problem became evident. In fact, the laser detection provides a possibility of transforming an optical characteristics of weak signal into another set of optical characteristics of laser radiation, and such a detection takes place without intermediate transformation into electric signals. Prospects for the progress in understanding of this looks especially attractive in connection with the progress achieved in optical computers and optical communications.

REFERENCES

1. P.G.R. King and G.J. Steward, New Science **17**, No. 2, 180–185 (1963). G.V. Krivoshchekov and V.N. Makukha, Kvant. Elektron. **3**, No.8. 1782–1792 (1976). T.A. Murina and N.N. Rozanov, Opt. Spekstrosk. **43**, No.5, 949–956 (1977).
2. B.N. Tumanov, V.N. Levit, and A.S. Babich, Izv. Vysh. Uchebn. Zaved. SSSR, Ser. Radiofiz. **21**, No.9, 12603 (1978).
3. H. Eihler and W. Wiesemann, Zeitschrift für Angew. Physik **28**, No. 3. 125–127 (1969). P.J. Brannon, Appl. Opt. **15**, No. 5, 1119 (1976). M.S. Domanov and V.D. Shcherbatov, Kvant. Elektron. **2**, No.1, 99 (1975). R.C. Rowley and D.C. Wilson, Appl.Opt. **11**, No.2, 475–476 (1972).
4. J.L. Lachambre et al., IEEE J. Quant. Electron. **QE–14**, 170 (1978).
5. W.M. Doyle, W.D. Gerber, and M.B. White, IEEE J. Quant. Electron. **QE–3**, No.11, 479 (1967). W.M. Doyle, Electro Optics **1**, No.9, 7–9 (1971).
6. D.J. Jones and D.K. Bandy, J. Opt. Soc. Am. **B7**, 2119 (1990).
7. V.E. Zuev, *Laser Radiation Propagation in the Atmosphere* (Radio i Svayz', Moscow, 1981), 288 pp.
8. A.J. Hughes, J. O'Shaughnessy, and E.R. Pike, IEEE J. Quant. Electr. **QE–8**, No.12. 909 (1972).
9. T.R. Lawrence, D.J. Wilson, and C.E. Graven, Rev. Sci. Instrum. **43**, No.3, 512 (1972).
10.V.E. Zuev, A.P. Godlevskii, A.K. Ivanov, and Yu.D. Kopytin, Dokl. Akad. Nauk SSSR **267**, 243 (1982).
11. V.E. Zuev, A.P. Godlevskii, and Yu.D. Kopytin, Opt. Commun. **62**, No. 6, 370 (1987).
12. V.M. Baev, T.P. Belikova, and E.L. Sviridenkov, Zh. Eksp. Teor. Fiz. **74**, 43 (1978).
13. J.H. Churnside, Appl.Opt. **23**, 2097 (1984).
14. J. H. Churnside, Appl. Opt. **23**, No.1, 61 (1984).
15. L.D. Landau and E.M. Lifshits, *Electrodynamics of Continuous Media* (Pergamon Press, Oxford, 1974).
16. *Abstracts of the 1st Workshop on Optical Amplifiers for Lidar Applications*, Malvern, UK (1992).
17. *Technical Digest on Coherent Laser Radar: Technology and Applications*, 1991 (OSA, 1991), vol. 12.
18. *Proceedings of 7th Conference on Coherent Laser Radar: Applications and Technology*, Paris, France (1993).
19. A.P. Godlevskii, E.P. Gordov, A.Z. Fazliev, Ya.Ya. Ponurovskii, and P.P. Sharin, Appl. Opt. **26**, No. 8, 1607 (1987).
20. E.P. Gordov, A.V. Khachaturyan, V.M. Orlovskii, A.G. Poteryaev, and J.H. Churnside, Atmos. Oceanic Opt. **6**, No. 4, 267–269 (1993).
21. M. Harris, R. Loudon, G.L. Mander, and J.M. Vaughan, Phys. Rev. Lett. **67**, 1743 (1991).
22. M. Harris, R. Loudon, T.J. Shepherd, and J.M. Vaughan, Phys. Rev. Lett. **69**, 2360 (1992).
23. A.P. Godlevskii, E.P. Gordov, A.Z. Fazliev, Ya.Ya. Ponurovskii, and P.P. Sharin, Kvant. Elektron. **13**, No.4, 863 (1986).
24. R. Loudon, M. Harris, T.J. Shepherd, and J.M. Vaughan, Phys. Rev. **A48**, 681 (1993).
25. A.P. Godlevskii, E.P. Gordov, A.I. Zhiliba, and P.P. Sharin, Atm. Opt. **3**. No.1, 20–24 (1990).
26. S.D. Burakov, A.P. Godlevskii, and S.A. Ostanin, Atm. Opt. **3**, No. 5, 455–462 (1990).
27.A.M. Khazanov, G.A. Koganov, and E.P. Gordov, Atm. Opt. **2**, No. 8, 717–722 (1989).
28. P. P. Sharin, "*Study of possibility to sound atmospheric characteristics on the basis of intracavity phenomena in* CO_2 *laser*," Candidate's Dissertation in Physical and Mathematical Sciences, Tomsk (1992).
29. E.P. Gordov and G.S. Khmelnitskii, Atmos. Oceanic Opt. **7**, No. 1, 63–64 (1994).
30. J. H. Churnside, E.P. Gordov, A.V. Khachaturyan, et al., in: *Technical Digest on Coherent Laser Radar: Technology and Applications,* 1991 (OSA, 1991), Vol. 12, p. 198.
31. M.J. Post, R.A. Richter, R.M. Hardesty, T.R. Lawrence, and Jr. F.F. Hall, Proc. SPIE **300**, 60 (1981).
32. A. Gondhalekar, E. Holzhauer, and N.R. Heckenberg, Phys. Lett. **46A**, 229 (1973).
33. A. Gondhalekar, E. Holzhauer, and N.R. Heckenberg, IEEE J. Quant. Electr. **QE–11**, 103 (1975).
34. V.V. Likhanskii, G.D. My'lnikov, A.P. Napartovich, A.F. Semerok, and D.N. Sobolenko, Sov. J. Quant. Electr. **8**, 512 (1978).
35. S. Sinha, Appl. Opt. **27**, 2373 (1988).
36. E.P. Gordov and A.Z. Fazliev, Atmos. Oceanic Opt. **6**, No. 4, 283–284 (1993).
37. S.W. Henderson, Ch.P. Hale, P.J. Suni, and J.R. Magee, in: *Technical Digest on Coherent Laser Radar: Technology and Applications*, 1991, (Optical Society of America, Washington, D.C., 1991), Vol. 12, p. 92.
38. E.P. Gordov, G.G. Matvienko, V.A. Rybalko, and A.V. Khachaturyan, Atmos. Oceanic Opt. **7**, No. 7, 533–535 (1994).