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Modulation of diode laser radiation for the formation of a distance-independent backscattered signal

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Abstract. **We propose a probing regime, in which the backscattered signal energy is independent of the distance from the surface of a scattering object. This regime is implemented using a part of the laser radiation power. With respect to the efficiency of using the laser during one measurement, the proposed regime is close to the pseudorandom noise continuous wave lidar regime. Using diode lasers, the regime of the degenerate energy response function and the lidar regime can be implemented in a single device. The relations between the geometric parameters of the probing scheme and the modulation parameters of laser radiation are obtained. The dependence of the linearity range of the diode laser on the relation between the length of the receiving channel near-field zone and the length of the probed trace is substantiated.**

Keywords: *coaxial scheme, remote probing, diode laser, geometric form factor, nephelometer, lidar, backscattering, extinction, two-dimensional response function, energy response function, monitoring.*

1. Introduction

For investigating lower atmosphere layers, compact lidar systems using elastic scattering of laser radiation are of interest. In such lidars, the use of semiconductor lasers is promising, since these lasers have a high efficiency of converting the energy of the pump current into the light energy, as well as a relatively low power consumption. We would like to mention one of the first papers [1], in which the regime of pulsed probing by means of a micro pulse lidar (MPL) with a small power of the output radiation was described. In the MPL the second harmonic of radiation from the Nd : YLF laser (the wavelength $\lambda = 532$ nm) is used. The pulse power amounts to 10^3 W (10 μJ, 10 ns), and the pulse repetition rate is 2.5 kHz. This lidar is used to obtain a backscattered signal from the atmosphere at distances up to 1 km and from topographic objects at distances up to 10 km.

To date, commercial versions of the MPL are available, e.g., those produced by SESI. Pershin et al. [2] demonstrated the capabilities of a miniature pulsed elastic scattering lidar with a semiconductor laser ($\lambda = 888$ nm), the radiation power being practically safe for eyes (the pulse power 10 W, the energy 1 μJ, the duration 100 ns, the repetition rate 2.5 kHz). Using this lidar, they obtained a backward signal from the lower boundary of clouds at a distance up to 3.4 km and a backscattered signal at a distance up to 100 m. This regime is characterised by an essentially smaller size of the near-field zone (to 20 m) and it can be conditionally classified as the MPL regime, too. For miniature elastic scattering lidars with the eye-safe laser radiation power level, the near-field zone includes the range, in which the probe beam does not overlap the vision field, and the range, in which the trace dependence of the backward signal is essentially affected by the geometric characteristics and the mutual arrangement of the receiving and the transmitting channels.

A further decrease in the probing radiation power is related to the pseudorandom noise (PRN) continuous wave (CW) lidar regime [3]. For probing use is made of a semiconductor GaAlAs laser with a radiation wavelength of 780 nm. By controlling the current, the pseudorandom modulation of the radiation power in the form of rectangular pulses is implemented. The maximal repetition rate of the encoded pulses attains 8 MHz, which makes it possible to use the pulse radiation power below 30 mW, practically safe for eyes (according to ANSI, the limit power is 30 W m^{-2} at $\lambda = 780$ nm). The backward signal is determined from the cross-correlation function of the backward and the probe signal. This function provides the backward signal shape, similar to the corresponding shape in the case of pulse probing. The PRN CW regime leads to an essential increase in the relative time of laser operation (10% and more) during the measurement cycle, in contrast to the case of a conventional pulsed lidar, for which this time is smaller than 1%. Under the night conditions, the signals from the atmosphere were received from the height to 500 m and from topographic objects at a distance exceeding 10 km.

To measure the backscattering coefficient along the trace, the lidar calibration is necessary. For the calibration, it is possible to choose a molecular component of the atmosphere. Its contribution to the backward signal can be measured using the Raman signal in the case of sensing the upper atmosphere layers [4]. We mention papers [5, 6], in which the authors substantiate the possibility of using lidars with a high spectral resolution at a practically safe level of the probing radiation power. To implement these methods, the backward signal should be sufficiently strong. In the case of a miniature elastic scattering lidar, the signal from the atmosphere is rather weak and comes mainly from distances up to 100 m, so that the above methods are inapplicable. The calibration of such lidars consists in measuring the backward signal from the scattering surface with the known directional pattern of scattering (etalon scattering surface) and in determining the form

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of the backward signal from the uniform atmosphere with an extremely small extinction coefficient. The main difficulties of the experimental implementation of the absolute calibration even for a miniature lidar relate to the atmospheric effect that should be taken into account, as well as to the reliable measurement of the backward signal from the etalon scattering surface [2, 7].

One could expect that the technique of calibration using the scattering surfaces will be the simplest for PRN CW lidars because of the small power of the probing radiation [3]. In this case, the detection of a backward signal from the scattering surface is possible without using neutral filters that attenuate the backward signal. However, we should note the difficulties of implementing the coaxial probing scheme in the PRN CW regime, since in this scheme the field of view and the probe beam geometry are formed by a single objective lens. The difficulties are due to the permanent scattering of laser radiation in the transceiving channel, which leads to the necessity of using the schemes with a significant size of the near-field zone (up to a few hundred metres).

For the MPL regime, the implementation of the coaxial scheme is possible, since the receiving detector is switched on only after the exit of laser radiation from the transmitter channel. However, to measure the backward signal from the scattering surface at the traces as long as 100 m and longer, the reduction of the probe beam intensity is required, which can lead to the distortions of the geometric form factor of the transmitting and receiving channels of the lidar [2]. Using semiconductor lasers controlled via the current, one can implement different regimes of modulating the intensity of laser radiation. For solving the lidar calibration problems the desired modulation is such that the backward signal is independent of the position of the probed layer.

In this regime, the energy of the backward signal is constant along the entire probed trace, which allows the reduction of its length in the measurement of the backscattered signal from the scattering surface. As a result, the influence of atmosphere transmission is reduced. The detection of the backward signal from a relatively small scattering surface is possible without using the neutral filters. This regime can be classified as a regime with the degenerate response function.

The aim of the present work is to determine the modulation parameters for the radiation of the semiconductor laser for the probing regime with a degenerate response function. As a result of the performed analysis, we found the dependence of the radiation modulation form and the length of the probed trace on the linearity range of the diode laser.

2. Probing with a part of a laser pulse

In the case of elastic scattering the lidar signal, i.e., the power $P(t)$ of backscattered radiation, can be presented as a convolution, allowing also for the finite duration of the laser pulse [8, 9]:

$$P(t) = \int_0^L J\left(t - \frac{2z}{c}\right) R(z) B(z)\,\mathrm{d}z. \tag{1}$$

Here, c is the velocity of light; z is the distance to the scattering layer; $J(t - 2z/c)$ is the power of the laser pulse scattered from the object, located at a distance z from the lidar at the moment of time t; L is the length of the probed trace;

$$R(z) = \eta \frac{A(z)}{z^2} O(z) \tag{2}$$

is the complete calibration function; η is the coefficient, equal to the product of the transmission of the transmitting channel, the transmission of the receiving channel and the quantum efficiency of the detector; $A(z)$ is the effective area of the entrance aperture for the point located at a distance z; $O(z)$ is the geometric form factor determining the overlap of the field of view with the angular divergence of the probing beam at a distance z;

$$B(z) = \beta(z) \exp\left[-\int_0^z 2\alpha(z_1)\,\mathrm{d}z_1\right] \tag{3}$$

is the function depending only on the basic parameters of the medium; $\beta(z)$ is the coefficient of backscattering from the layer located at a distance z; and $\alpha(z)$ is the extinction coefficient inside this layer.

To calibrate a miniature lidar, one has to measure the backward signal form the etalon surface scattering the light according to the Lambert law with a reflection coefficient equal to 1 [7]. For correct estimation of the backward signal measurement error, it is desirable to choose the surfaces with different reflection coefficients [2]. As a result of such measurements, one can obtain the response functions of two types. The first type is the 2D response function

$$E_{\mathrm{td}}(t, z) = J\left(t - \frac{2z}{c}\right) R(z). \tag{4}$$

When probing a scattering surface, $E_{\mathrm{td}}(t, z)$ represents the trace dependence of the backscattered power of the laser pulse. For the pulse duration $t_{\mathrm{p}} \ll 2L/c$ one can make a replacement $J(t - 2z/c) \to J_0 t_{\mathrm{p}} \delta(t - 2z/c)$. Then for the homogeneous atmosphere [$\beta(z) = \beta_0$] with a negligibly small attenuation coefficient ($\alpha L \ll 1$) the shape of the backward signal $P(t)$ coincides with that of the full calibration function (2).

The second type of the function is the energy response function

$$E_{\mathrm{p}}(z) = \int_0^T J\left(t - \frac{2z}{c}\right) R(z)\,\mathrm{d}t,, \tag{5}$$

where $T = 2L/c$. In expression (5), the time T (below referred to as the strobe) means the interval of the receiver operation. Therefore, the length of the probed trace is $L = cT/2$. Generally, for probing a scattering surface the quantity $E_{\mathrm{p}}(z)$ is the trace dependence of the backward signal energy.

From expression (1) it follows that at a small laser pulse duration t_{p} the trace dependences for the 2D and energy response functions can be measured using the backward signal from the scattering surface. By means of expression (5) one can determine the full calibration function (2). When t_{p} is increased, the shape of the energy response function (5) does not coincide with that of the full calibration function $R(z)$ [Eqn (2)]. Indeed, if the duration of the laser pulse is equal to that of the strobe, then, depending on the distance to the scattering object, only the radiation of a part of the laser pulse (PLP) will overlap with the strobe.

Consider an ideal scheme (IS) [10], in which the field of view of the main receiving channel coincides with the angular divergence of the probe beam. We assume that in this scheme the transmitter and the receiver are small and located at one point. A single aperture, located at the distance l from the source, forms the field of view and the beam geometry. For the IS in the geometric optics approximation the trace dependence of the full calibration function has the simplest form

$$R(z) = \frac{C}{(z+l)^2}, \quad (6)$$

where l is the longitudinal dimension of the probing scheme; and C is a constant. For the receiving channel with the aperture radius a and the field of view φ the parameter l can be estimated as the ratio a/φ.

Let us study the regime in which the total energy of the strobed backward signal is measured without spatial resolution. This corresponds to the nephelometer regime. In the atmosphere sensing, the measured quantity is the energy of the backward signal $E_{\rm b}$ within the strobe T (the layer thickness $cT/2$):

$$E_{\rm b} = \int_0^L E_{\rm p}(z)B(z)\,{\rm d}z. \quad (7)$$

For a small pulse duration, the nephelometer regime has no advantages in the determination of the effective backscattering function $B(z)$, as compared to the pulsed lidar regime. However, the use of PLP may remove the dependence of the backward signal on the distance. This case will correspond to the degenerate energy response function.

Consider the nephelometer regime using PLP. First, the temporal modulation of the laser pulse is performed, namely, beginning from the maximum the amplitude of the pulse linearly decreases to zero during the time T. For this regime the trace probing is carried out in the range $0 \leqslant z \leqslant L$. The shape of the laser pulse is described by the expression

$$J_{\rm tr}(t) = \begin{cases} J_{01}\left(1 - \frac{t}{T}\right), & t \leqslant T, \\ 0, & t > T. \end{cases} \quad (8)$$

At the time of the laser pulse termination ($t = T$) the receiver is switched on and records the backward signal in the interval from T to $2T$. For the scattering surface located at the distance z, this interval is overlapped by the PLP having the power

$$J_{\rm tr}(z,t) = \begin{cases} J_{01}\left(1 - \frac{1}{T}\left(t - \frac{2z}{c}\right)\right), & T \leqslant t \leqslant T + \frac{2z}{c}, \\ 0, & t > T + \frac{2z}{c}. \end{cases} \quad (9)$$

For $z = 0$ we obtain expression (8), and for $t = T + 2z/c$ we have $J_{\rm tr}(t,z) = 0$. First, let us integrate Eqn (5) with respect to t from T to $2T$:

$$F_1(z) = \int_T^{2T} J_{\rm tr}(t)\,{\rm d}t = J_{01}\frac{2z^2}{c^2 T}.. \quad (10)$$

Therefore, for the linearly descending power of laser radiation we have the quadrature correction of the backward signal.

To implement the probing regime (8) it is necessary to use a laser with the control of the output radiation power by changing the pump current I. As an example, consider an Axcel Photonics fibre diode laser with the radiation wavelength 785 nm and the output power 1 W (it is possible to use lasers with the power 500 mW and 1.4 W as well). For such a laser the slope efficiency ${\rm d}P/{\rm d}I$ has essential oscillations near the threshold, so that the interval for modulation should be chosen from $0.1I_{\max}$ to $I_{\max}$. For the current below $0.1I_{\max}$ the regime of spontaneous radiation is implemented, in which the dependence of the generated power on the current is nonlinear. The correction of the backward signal (10) in this case is impossible.

Consider the case of the PLP with a rectangular shape. For such a pulse, the following expressions are valid:

$$J_{\rm rc}(t) = \begin{cases} J_{02}, & t \leqslant T, \\ 0, & t > T, \end{cases} \quad F_2(z) = J_{02}\frac{2z}{c}. \quad (11)$$

In this case, we obtain a linear correction of the backward signal.

For the regime with a small pulse duration the correction of the backward signal is absent, and so we obtain

$$J_{\rm p}(t) = \begin{cases} J_{03}, & t \geqslant T - t_{\rm p}, \\ 0, & t > T, \end{cases} \quad F_3(z) = J_{03}t_{\rm p}.. \quad (12)$$

Note that the laser pulse duration is $t_{\rm p} \ll T$.

By adding the intensity modulations of the probe radiation (8), (11), and (12) one can specify the ideal correction of the trace dependence of the backward signal (6). For the sum of these modulations, we have the expression

$$F_{\rm s} = \sum_{i=1}^{3} F_i = \frac{2J_{01}}{c^2 T}\left(z^2 + \frac{J_{02}}{J_{01}}zcT + \frac{J_{03}}{J_{01}}t_{\rm p}c^2 T\right). \quad (13)$$

For the IS the following condition should hold:

$$F_{\rm s} = \frac{2J_{01}}{c^2 T}(z+l)^2.. \quad (14)$$

Comparing Eqns (13) and (14), we obtain the relations:

$$\frac{J_{02}}{J_{01}} = \frac{l}{L}, \quad \frac{J_{03}}{J_{01}} = \frac{l^2}{2Ll_{\rm p}}, \quad (15)$$

where l is the longitudinal dimension of the IS (the lidar near-field zone parameter); and $l_{\rm p}$ is the spatial equivalent of the laser pulse duration ($l_{\rm p} = ct_{\rm p}$). If the linearity range of the semiconductor laser begins from $0.1I_{\max}$, then $l/L = 0.1$. In the second relation (15) the pulse power J_{03} should be chosen maximal, i.e., $J_{03} = J_{01}$. Then it is possible to estimate the minimal pulse length $l_{\rm p} = l^2/(2L)$. If $l/L > 0.1$, then $l_{\rm p} < 0.05l$ ($t_{\rm p} < l_{\rm p}/c$). Thus, the form of modulation depends on the relation between the length of the probed trace L, the parameter l and the pulse duration $t_{\rm p}$ in the MPL regime.

The peculiarities of constructing the full calibration function $R(z)$ with a decrease in the characteristic length l [see Eqn (6) are worthy of attention. When using the lenses forming the field of view and the beam geometry, the scale of the decrease can be tuned to a given value by placing the laser and the receiver in front of the focal point. Then the position of the image of the source (receiver) formed by the lens can be found using the lens formula.

In Fig. 1 the modulations of radiation denoted by 'tr' and 'rc' correspond to the PLP-using regimes and the modulation denoted by 'p' corresponds to the regime with a small pulse duration. The duration of the latter modulation $t_{\rm p}$ is essentially smaller than the strobe duration T. In the presence of only this modulation, the operation regime will correspond to the pulsed lidar operation regime. The modulation of the laser pulse is a sum of 'tr', 'rc' and 'p' modulations. With the above-mentioned Axcel Photonics diode lasers the implementation of this modulation is not difficult.

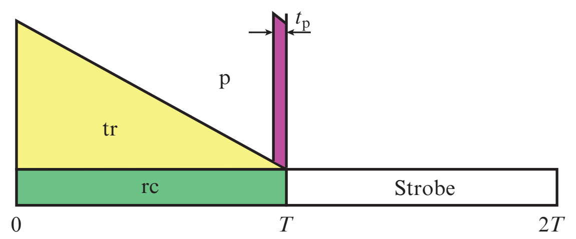

Figure 1. General view of the combined modulation of the diode laser radiation power: tr is modulation (8), rc is modulation (11), p is modulation (12).

Figure 2 presents the trace dependences of the response function $E_{td}(t, z)$ with combined modulation, shown in Fig. 1, for $l = 0.2L$, $t_p = 0.02T$ and different z. From Fig. 2 it follows that without a quadratic decrease in the backward signal taken into account, the area under curves (*3*) and (*4*) increases quadratically with distance. On the other hand, the backward signal must decrease quadratically with distance. Then, instead of curve (*4*), we will have curve (*1*). For this reason, the areas under curves (*1*) and (*2*) are equal, i.e., the energy of the backward signal can be made independent of the distance to the scattering surface.

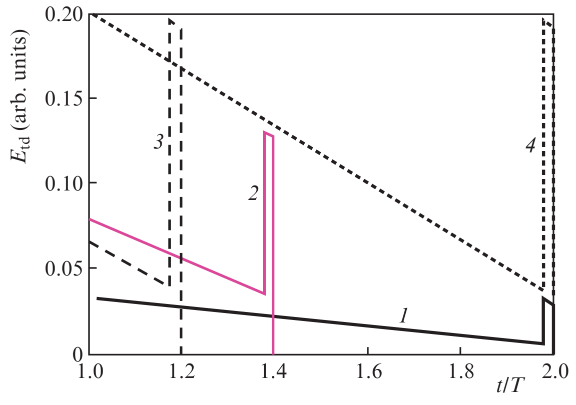

Figure 2. Example of the response function under the combined modulation of the probe radiation for $l = 0.2L$ and $t_p = 0.02T$. The distance to the scattering surface is $z = 0.5cT$ (*1*) and $0.2cT$ (*2*). Dependences (*3*) and (*4*) for $z = 0.1cT$ and $0.5cT$, respectively, are obtained without the correction of the quadratic decrease of the backward signal with the distance.

Figure 3 [curve (*1*)] presents the energy response function $E_p(z)$ under the modulation of laser radiation, corresponding to that shown in Fig. 1. Since for the trace with the length from 0 to L the backward signal does not change, this case corresponds to the degenerate energy response function. As examples, the appropriate dependences are shown for the case of quadratic correction (10) for the IS at $l \ll L$ [curve (*2*)] and

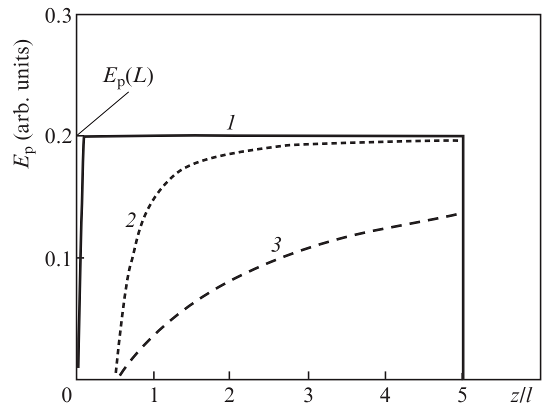

Figure 3. Trace dependences of the energy response function $E_p(z)$. Curve (*1*) corresponds to the combined modulation, presented in Fig. 1, curves (*2*) and (*3*) correspond to modulation (8) and the linearity range from $0.1I_{max}$ for $l \ll L$ (*2*) and $l = 0.2L$ (*3*).

$l = 0.2L$ [curve (*3*)]. From the presented dependences, it follows that for the linear range from $0.1I_{max}$ the distortion of the energy response function grows with an increase in the length of the near-field zone l.

It is worth noting that the backward signal $E_p(z)$ grows at $z < l_p/2 = ct_p/2$. As the pulse with the power J_p 'penetrates' into the strobe, the backward signal increases. The error caused by the partial use of the laser radiation energy in the bear-field zone does not exceed $l_p/(4L) = 0.01$. When the power is reduced by two times, the pulse duration t_p should be increased by two times.

The use of combined power modulation (see Fig. 1) in homogeneous atmosphere probing yields the shape of the backward signal in the interval from T to $2T$, which is a monotonically descending function [Fig. 4, curve (*1*)]. The dependence is determined by the fact that at $t \approx T$ the backward signal is formed by all layers, located within the range from 0 to L, and at $t = 2T$ it is formed only by the layer, located at the distance, approximately equal to L. In the case of the backward signal independent of z [see curves (*3*) and (*4*) in Fig. 2], the resulting dependence would be parabolic [Fig. 4, curve (*2*)]. Curve (*3*) corresponds to the modulus of

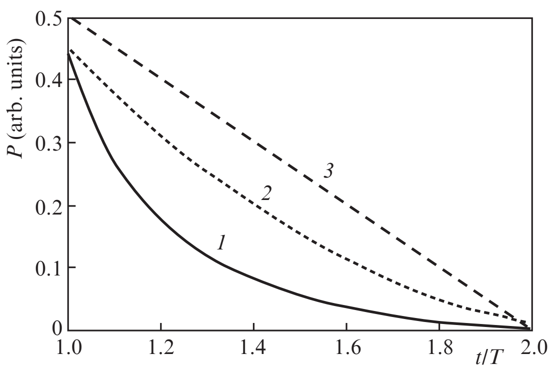

Figure 4. Typical shapes of the backward signal power distributions in the strobe for probing the homogeneous atmosphere. Curve (*1*) corresponds to curves (*1*) and (*2*) in Fig. 2, curve (*2*) is analogous to curve (*1*) without a quadratic decrease in the backward signal taken into account [corresponds to curves (*3*) and (*4*) in Fig. 2], curve (*3*) is the modulus of the derivative of curve (*2*).

the derivative of curve (*2*) and presents a linearly decreasing dependence. It follows that the power measurement of the backward signal within the strobe practically does not allow one to determine the trace dependence of the backscattering coefficient. On the other hand, this peculiarity can be used for controlling the homogeneity of atmosphere.

For the considered probing regime with the ideal coaxial scheme the backscattered signal from the surface of the scattering object does not depend on the distance z, i.e., $E_{\rm p}(z) = E_{\rm p}(L)$ (see Fig. 2). Expression (7) will contain only one calibration factor, the constant $E_{\rm p}(L)$ factored out from the integral:

$$E_{\rm b} = E_{\rm p}(L)\int_0^L B(z)\,{\rm d}z. \tag{16}$$

From Eqn (16) it follows that the ideal correction of the backward signal leads to the degeneration of the energy response function to the constant $E_{\rm p}(L)$. The measured quantity is the function of the base atmosphere parameters only, see Eqn (3).

Let the input power be 1 W and the length of the near-field zone be l = 100 m. The equivalent length of the probed trace is L = 1000 m (T = 6.6 μs). From Eqn (15) we obtain $J_{02}/J_{01} = 0.1$, $ct_{\rm p}$ = 5 m ($t_{\rm p}$ =16 ns $\ll T$ at $J_{03}/J_{01} = 1$). The modulation for this scheme is executed within the linearity range of $P(I)$, i.e., from 100 mW to 1 W. The maximal repetition rate of laser pulses is 38 kHz. The pulse repetition rate may be lower if it is necessary to reduce the contribution to the backward signal from the preceding laser pulses. The above characteristics of diode lasers are not unique, for example, they are inherent in Axcel Photonics lasers, mentioned above.

The shape of the backward signal from the homogeneous atmosphere, measured in Ref. [2], allows approximate estimates of the sensitivity of the considered method. The laser pulse energy equals 1 μJ. The detection was implemented using an avalanche photodiode with a diameter 40 μm, operating in the photon-counting mode. The total backward signal for 10^6 laser pulses amounts to ~20000 photocounts at the noise level ~3000 counts (the signal-to-noise ratio ~125). The signal photocounts are concentrated at distances exceeding 100 m from the device (20 cells, one cell corresponding to the layer depth of 5 m). In the seventh cell, the backward signal is maximal and equal to ~3000 photocounts against the noise background of 200 counts (the signal-to-noise ratio ~50). The presented values correspond to the homogeneous atmosphere with the backscattering coefficient 4×10^{-6} m^{-1} sr^{-1}. For the probing regime with combined modulation we choose the trace length L = 500 m. Then for the durations of the laser pulse and the strobe we obtain T = 3.3 μs. The backscattering signal from the layers located at the distance below 500 m is formed by the PLP, overlapping with the strobe [see Fig. 2, curve (*2*)]. For the layer corresponding to 500 m the backward signal is formed by practically the entire laser pulse [see Fig. 2, curve (*1*)]. From each layer along the trace there should be an equal number of signal photocounts within the strobe from T to $2T$ (see Fig. 3). Note that the distribution of these photocounts within the strobe is nonuniform [Fig. 4, curve (*1*)]. Let each of 100 layers contribute ~3000 photocounts into the backward signal. Then the signal-to-noise ratio for the total backward signal will equal ~500 (by four times greater than for the pulsed probing with the energy 1 μJ). Note also the equality of peak powers of laser radiation for the regimes of a pulsed lidar and combined modulation. In this case the total energy of the modulated pulse increases proportionally to its duration, and for the pulse shape shown in Fig. 2 [curve (*4*)] will amount to ~16 μJ (by 16 times greater than for the pulsed probing). The correspondence of modulation parameters to the geometric parameters of the probing scheme requires a separate study.

3. Discussion of results

For common MPL and PRN CW systems, the field of view is essentially larger than the angular size of the beam. For probing systems with the degenerate energy response function, the field of view of the receiving channel is equal to the angular divergence of the beam. The channel equivalence condition allows drastic simplification of the full calibration function (2) [see Eqn (6)]. This offers new possibilities for measuring this function by means of screens, introducing a similar transverse angular distortion into the beam geometry and the field of view (perforated screen) [11]. Such a screen is an opaque film with randomly located holes. The beam intensity decreases immediately after passing through the screen. Besides that, the backward signal from a scattering surface, located at a certain distance from the screen, decreases due to the diffraction of radiation at the screen holes. Making a correction for the screen transmission, one can measure the backward signal for the case, when the field of view and the angular divergence of the beam have proportionally increased. One can obtain the same backward signal by placing the scattering object at such a distance, that the transverse size of the beam with the screen and without it becomes equal. Without the screen, the above distance may exceed by several times the trace length in the presence of the screen. Changing the calibrated screens with different sizes of holes, we can determine the trace dependence of the backward signal without changing the distance between the device and the scattering object. This allows minimisation of the atmosphere transmission effect and the surface orientation with respect to the beam axis during calibrations. It is worth noting that if the optical equivalence condition for the receiving and transmitting channels is invalid, then the field of view and the angular divergence of the beam in the presence of the screen are transformed in a different way. Then the lidar calibration by measuring the full calibration function with perforated screens is impossible.

It is of practical interest to construct a lidar with two spatially separated equivalent channels [12]. Assume that the coaxial scheme with the full calibration function (6) is completed with the second receiving channel with the optical axis shifted by a certain distance. In this case, the ratio of backward signals in the calibration process reflects the distortion of the geometric form factor of the fields of view of receiving channels. If the geometry of the beam does not change during its propagation in the uniform scattering medium, then the ratio of the signals depends on the extinction coefficient. Then the considered modulation regime can be of particular interest for the atmosphere sensing, since it provides a minimal set of basic parameters, averaged over the probed trace.

4. Conclusions

To obtain the regime with a degenerate energy response function in an ideal coaxial scheme one has to apply the combined modulation of the probe beam power using the laser pulse, the duration of which is smaller than the strobe duration, as well as the parts of the output pulse with a linearly descending amplitude and the rectangular pulse. The combined modulation parameters depend on the geometry of the probing system. For example, the beginning of the linearity range for the dependence $P(I)$ is determined by the ratio of the near-field zone length to the spatial equivalent of the strobe duration. The duration of the probe pulse in the MPL regime depends on the ratio $l^2/(2L)$. For the coaxial scheme with $l/L = 0.1$ the diode laser is necessary having the $P(I)$ linearity range from $0.1I_{max}$ to I_{max}. For the case $l/L \ll 1$ (e.g., $l/L = 0.01$) the linearity of the diode laser should begin from $0.01I_{max}$. The regime using a PLP lidar allows simplification of the lidar calibration with a subsequent use of the results for the probing regimes, MPL and PRN CW. Besides that, the regime of combined modulation allows the monitoring of the atmosphere condition with the minimal set of basic elements.

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