HIGHLY SENSITIVE RADIATION DETECTION WITH A TWO-FREQUENCY LASER. DYNAMIC DESCRIPTION

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A theoretical investigation of the dynamic sensitivity of a two-frequency laser detector is presented in which the laser is also used as the source of sounding radiation. It is shown that, under conditions determined in the paper, the dynamic sensitivity of the two-frequency laser detector can substantially exceed the sensitivity of the single-frequency one. Based on the theoretical analysis and the experimental results of Ref. 9, a highly sensitive lidar scheme with a two-frequency laser detector is proposed. In this scheme the sensing is performed with the strong beam, while the signal is detected with the weak beam, generated at a transition coupled with the sounding beam. It is found that in this sounding regime nonlinear stabilization of the sounding beam intensity takes place. It is also noted that in addition to the highly sensitive regime there also exists a regime of two-frequency laser emission in which the laser detector sensitivity can decrease even below that of single-frequency laser detection.

INTRODUCTION

One of the principal directions that have been pursued in order to increase the functional capabilities of lidar systems used for the investigation of atmospheric parameters is the application of new high-sensitivity detection schemes. One such scheme is based on laser detection (LD) of the optical signal being analyzed. The foundations of laser detection were discussed in Refs. 1 and 2. Much attention has been paid to its study and utilization in a lidar system called laser detection lidar (LD-lidar).[3–7] In LD-lidars. a variant of detection is realized in which the same laser is used both as the sounding emission source and the element of the detection device that amplifies the return signal nonlinearly. It has been noted that an advantage of LD-lidar is its high sensitivity and that it is noiseproof.[3] In Ref. 8 it was noted that in the near-threshold region of laser generation laser detection is characterized by an anomalously high sensitivity. However, it is obvious that it is not promising to try to make use of this result in a real lidar system designed for a considerable sounding distance, since. In the near-threshold regime, only radiation of weak intensity is generated. The authors of Ref. 9 proposed a way to solve this dilemma – detection on a two-frequency laser.

In the present paper we provide a theoretical foundation for the high dynamic sensitivity of the detection scheme which employs a two-frequency laser generating on linked transitions. Two variants have been studied: A – the sounding and recording are performed on a single wavelength. B – the sounding is conducted on one wavelength, while the recording is realized on laser radiation generated on an adjacent transition. The conditions are determined under which it is possible to achieve a substantially higher sensitivity using the two-frequency laser than with the single-frequency laser. In variant A, an increase in the sensitivity of two-frequency LD is accompanied by a decrease of the intensity of the sounding beam. However, in variant B, a highly sensitive two-frequency LD (as compared to the single-frequency one) is realized when the sounding is carried out using the strong beam while the recording is realized on the weak beam generated on a transition coupled with the sounding beam. Data which we have obtained on the nonlinear stabilization of a strong sounding beam in the course of generation of a weak beam on a linked transition are an essential factor in the improvement of the principal characteristics of the lidar system under consideration. The gain in the dynamic sensitivity of two-frequency LD in the generation regime on the linked transitions can reach several orders of magnitude. It was noted that in addition to the highly sensitive regime there also exists such a two-frequency laser generation regime in which there arises a great sensitivity decrease in comparison with the single-frequency LD. The results of an experimental study of the detection sensitivity of a He-Ne laser generating on the two linked transitions $3S_2 - 2P_4$ (0.63 μm) and $3S_2 - 3P_4$ (3.39 μm) are presented in Ref. 12.

DYNAMIC DESCRIPTION OF LD ON A TWO-FREQUENCY LASER

The essence of laser detection is that the weak signal which is to be analyzed is introduced into the

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laser resonator, where its mixing with the field within the resonator and nonlinear amplification of the resulting signal occur. Under certain conditions this makes it possible to lift the signal substantially above the noise in the photodetector path in the course of the photorecording. The principal factor limiting the photorecording sensitivity remains the laser noise and the acquired amplitude and phase fluctuations of the return signal acquired during the propagation of the signal through the atmosphere. The problem of nonlinear transformation of the return signal fluctuations within the laser resonator and their subsequent influence on the photorecording sensitivity requires a statistical description of detection on a two-frequency laser and will be considered separately. In order to obtain a system of equations describing the dynamics of detection on a two-frequency laser, we shall follow the standard scheme that was used for the description of LD-lidar dynamics, e.g., in Ref. 6. We expand the polarization of the active laser medium in Maxwell's equation for a quasiplanar beam into a series in the resulting field amplitude $E = E_1 + E_2 + E_r$, where E_1, E_2 are the field strengths of the fields generated by the laser and is the amplitude of the return signal reflected from the companion mirror and introduced into the laser resonator. The dependence of the polarization P on the field inside the resonator E in the description of laser dynamics based on the Lamb model is well known.[10] Let us expand P in a series in E and keep only the cubic terms and lower. Let us make use of the boundary conditions on the resonator mirror of the laser R_1, assuming that the phase of the sounding beam varies only slightly during the time $t = 2L/c$, i.e., $\Phi_r(0, t-2L/c) - \Phi_r(0, t) \approx 0$. This makes it possible to proceed to a system of ordinary differential equations for the slow amplitudes and on the basis of that for the intensities.

$$\dot{I}_1 = A_1 I_1 - \beta_{11} I_1^2 - \beta_{12} I_1 I_2;$$
$$\dot{I}_2 = A_2 I_2 - \beta_{22} I_2^2 - \beta_{21} I_1 I_2, \tag{1}$$

$I_{1,2} = |E_{1,2}|^2$ are the intensities of the beams generated in the laser resonator R_0 (R_1), carrying information on the conditions of the propagation of the sounding signal in the outer resonator R_1 (R_2). In obtaining Eq. (1) it was assumed that generation on both transitions was singlefrequency, but that tuning of the frequency was central. The coefficients β_{12} and β_{21} in Eq. (1) characterize the coupling of the modes being generated through the population of the total level; β_{11} and β_{22} are the saturation coefficients of the active laser medium; $A_{1,2}$ determines the pumping excess $k_{1,2}$ (of linear amplification) over the cumulative linear losses $\kappa_{1,2}$

$$A_{1,2} = k_{1,2} - \kappa_{1,2}, \tag{2}$$

where $\kappa_{1,2} = \rho_{1,2} - \frac{1}{2L}\ln(R_0 R_1')^{-1}$; $\rho_{1,2}$ are the linear losses in the laser resonator; l is the optical length of the laser resonator; $R_1' = R_1(1+\delta)$; R_0 and R_1 are the reflection coefficients of the laser resonator mirrors; δ characterizes the presence of feedback due to the passage of the sounding signal up to the companion mirror (or a natural target) with reflection coefficient R_2. For coherent detection ($r > r_0$, $\tau > \frac{2L}{c}$; r and τ are the radii of spatial and temporal coherence of the signal being detected in the detection aperture plane; L is the optical path length between the mirror R_1 and the target R_2; c is the speed of light; r_0 is the radius of the detection aperture) and for incoherent detection $\left(r < r_0, \tau < \frac{2L}{c}\right)$ δ has the form[4]

$$\delta^c = B_c \frac{2(1 - R_1)\sqrt{R_2}}{\sqrt{R_1}} \exp(2\alpha L); \tag{3}$$

$$\delta^{nc} = \left(\frac{r_0}{2L}\right)^2 \frac{(1 - R_1^2)\sqrt{R_2}}{R_1} \exp(2\alpha L), \tag{4}$$

where $\alpha = \alpha_1(\omega) + \alpha_2$ is the sum of the coefficients of selective ($\alpha_1(\omega)$) and nonselective (α_2) losses in the atmosphere, and B_c characterizes the extent of spatial and temporal coherence. If modulation of the return signal exists, $\delta = \delta^{cc(nc)}(t)$. We will be interested in modulation with period much greater than the characteristic setting-up time of laser generation. Let us introduce the new variables $x = \frac{\beta_{11}}{A_1} I_1$ and $y = \frac{\beta_{22}}{A_2} I_2$, where we have introduced the notations $\eta_{12} = \frac{\beta_{12} A_2}{\beta_{22} A_1}$ and $\eta_{21} = \frac{\beta_{21} A_1}{\beta_{11} A_2}$. Taking this into account, system of equations (1) takes a form convenient for further analysis:

$$\dot{x} = A_1 x\,(1 - x - \eta_{12} y);$$
$$\dot{y} = A_2 y\,(1 - y - \eta_{21} x). \tag{5}$$

Depending on the generalized coupling coefficients η_{12} and η_{21} of the x and y beams, i.e., I_1 and I_2 in the scheme of LD under consideration, three stationary and one nonstationary regimes of laser generation are possible; 1) $\eta_{2j} > 1$. $\eta_{12} < 1$. Under these conditions of LD, only the single-frequency laser generation regime with the stationary values is stable: $I_1^0 = \frac{A_1}{\beta_{11}}$ $(x = 1)$, $I_2^0 = 0\,(y = 0)$; 2) $\eta_{12} > 1$, $\eta_{21} < 1$. This situation results in a simple inversion of the stable single-frequency regime: $I_1^0 = 0$ $(x = 0)$, $I_2^0 = \frac{A_2}{\beta_{22}}$ $(y = 1)$; 3) $\eta_{12} > 1$, $\eta_{21} > 1$. Under these conditions two-frequency generation is unstable. This is a regime of competing transitions. Depending on the correlations between η_{12} and η_{21} as well as the initial conditions, stationary generation "survives" only on one of the transitions. 4) The conditions of LD when $\eta_{12} < 1$, $\eta_{21} < 1$ are of some practical interest for us. Then there is a stable generation regime on the linked transitions with the stationary intensity values x^0 and y^0

$$x^0 = \frac{1 - \eta_{12}}{1 - \eta_{12}\eta_{21}}; \tag{6}$$

$$y^0 = \frac{1 - \eta_{21}}{1 - \eta_{12}\eta_{21}}. \tag{7}$$

Based on Eqs. (6) and (7) let us find expressions for the dynamic sensitivity of two-frequency LD, i. e., $m_{11}^{1,2} = \frac{\delta I_{1,2}}{I_{1,2}}$, where $\delta I = I(A + \Delta A) - I(A)$.

$$m_{11}^1 = (1 - \eta_{12})^{-1} \frac{\delta A_1}{A_1}; \tag{8}$$

$$m_{11}^2 = (1 - \eta_{21})^{-1} \frac{\delta A_2}{A_2}. \tag{9}$$

In the case of weak coupling between I_1 and I_2, when $\eta_{12} \to 0$ and $\eta_{21} \to 0$, Eqs. (8) and (9) go over to expressions for the dynamic sensitivity of two-frequency LD with independent generation of I_1 and I_2, which is equivalent to the dynamic sensitivity of the single-frequency LD variant m_1

$$m_1 = \frac{\delta A}{A}. \tag{10}$$

For strong coupling, when, for example, $\eta_{12} \to 1$, $\eta_{21} \ll 1$ (i.e., the condition $\eta_{12}\eta_{21} \ll 1$ is preserved) I_1 and I_2 are related to each other by Eqs. (6) and (7): I_1 is the weak beam, while I_2 (with respect to I_1) is the strong beam. In this situation, the resonance denominator $(1 - \eta_{12})^{-1}$ begins to play a decisive role in expression (8). This causes a substantial (by several orders of magnitude) increase in the dynamic sensitivity of two-frequency LD, as compared with single-frequency LD. As to recording on the second beam, according to Eq. (9)

$$\frac{\delta I_2}{I_2} \to \frac{\delta A_2}{A_2},$$

since $\eta_{21} \to 0$. This result is symmetric with respect to inversion of the conditions: $\eta_{12} \to 0$, $\eta_{21} \to 1$. Thus, detection on a laser with linked transitions, when sounding and recording are conducted on the same frequency, has a noticeable advantage as far as dynamic sensitivity is concerned (in comparison with single-frequency LD) only when sounding with a beam of weak intensity. Therefore, for sounding at a considerable distance, the scheme of crossed LD is more promising: the sounding is conducted at one wavelength, the recording is carried out on the transition linked to it. On the basis of, for example, Eq. (7), we obtain

$$\frac{\delta I_2}{I_2} = \frac{-\eta_{21}}{1 - \eta_{21}} \frac{\delta A_1}{A_1}. \tag{11}$$

In the limit $\eta_{21} \to 0$ (the case of weak coupling between I_1 and I_2), as follows from Eq. (11),

$$\frac{\delta I_2}{I_2} \to 0.$$

We note further that for $\eta_{21} < 0.5$, i.e., when $I_2 > I_1$, the coefficient multiplying $\frac{\delta A_1}{A_1}$ is less than unity. Using the strong beam to record variations in the conditions of laser generation at the frequency of the weak beam, along with the weak action of I_1 on I_2 ($\eta_{21} \to 0$), results in a decrease in the sensitivity of two-frequency LD in comparison with single-frequency LD. This theoretical inference agrees with the experimental data given in Ref. 11, where a substantial decrease (by a factor of 10^2–10^3) of the dependence of the intensity fluctuations of a He-Ne laser at the wavelength 0.63 μm, produced by fluctuations of the discharge current during simultaneous generation at the wavelength 3.39 μm, was recorded. The authors of Ref. 11, however, did not assign any importance to the existence of a generation regime of the He-Ne laser on linked transitions, where a substantial increase in the sensitivity occurs.

Let us consider the inverse situation: $\eta_{21} > 0.5$ ($\eta_{21}\eta_{12} \ll 1$), when, according to Eqs. (6) and (7), $I_1 > I_2$. As follows from formula (11), in the limit $\eta_{21} \to 1$, the resonance denominator $(1 - \eta_{21})^{-1}$ plays a decisive role that results in a substantial (by several orders of magnitude) increase in the dynamic sensitivity of two-frequency LD, as compared with single-frequency LD. Hence we conclude that the most advantageous (as regards sensitivity) variant of two-frequency LD is the following: sounding is carried out on the strong beam, while recording is carried out on the transition linked to the sounding beam. The experimental results on two-frequency detection using a CO_2 laser generating on linked transitions, given in Ref. 9, lead to the same conclusion. Naturally, an increase (decrease) of dynamic sensitivity cannot be infinitely great, as follows formally from expressions (8), (9), and (11), since it is noise-limited. Thus, in the scheme of crossed two-frequency LD, for example, the weak beam is, first, noisier; second, to a greater extent than the strong beam, it tracks random modulations, which the sounding beam acquires during its propagation through the atmosphere. The principal limiting factor is unstable behavior of the considered nonlinear system (1) near the boundary of the nonequilibrium transition from one stablestate to another. The conditions 1) $\eta_{12}\eta_{21} = 1$; 2) $\eta_{12} = 1$, $\eta_{21} = 1$, or $\eta_{12} = 1$, $\eta_{21} \leq 1$; and 3) $\eta_{21} = 1$, $\eta_{12} \leq 1$ lead the system that describes the dynamics of two-frequency LD to a metastable state. The height of the potential barrier separating the three stable states from the unstable one, as well eй the average transition time between them, depends not only on the dynamic and statistic characteristics of the laser beams generated but also on the conditions of propagation of the sounding beam through the atmosphere. Calculation of those characteristics is the object of separate investigation. Thus, the problem of quantitative bounds on the limiting increase (decrease) of the sensitivity of two-frequency LD must be solved taking into account this remark within the framework of a statistic description of two-frequency LD and the photorecording scheme.

On the basis of the theoretical results that have been obtained here, we draw the following conclusions; 1. Lidar with two-frequency LD is the most effective when sounding is conducted by a strong beam, while recording is carried out on a weaker one linked with it on an adjacent transition in the generation process. 2. For generation on linked transitions, an effective nonlinear stabilization of the intensity of the strong beam is possible.

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