LFM LIDAR WITH FREQUENCY CONVERSION

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The principles of LFM lidar constructing based on electrooptical device of a single-frequency coherent radiation conversion into the double-frequency radiation are discussed. Theoretical estimates of the lidar potentiality and the results of its model testing are presented.

One of the promising directions in the development lidar complexes is based on the application of cw lasers and methods of linear frequency modulation. It is caused, on the one hand, by the energy equivalence of a short pulsed lidar with high peak power and a continuous-wave lidar with small average power and longer observation time and, on the other hand, by the possibility to obtain higher spatial resolution, simplicity, and low cost of the technical realization of LFM lidars in comparison with the pulsed schemes.

The main demands to the development of the lidars with linear frequency modulation of the sounding beam intensity were defined and their supposed characteristics were estimated in Ref. 1. According to further investigations, the choice of the modulated parameter and energy losses caused by it is a shortcoming of the lidar scheme proposed in Ref. 1.

The analysis of the possibility of creating a continuous-wave LFM IR lidar for differential absorption and scattering application which is constructed on the base of a He–Ne laser operating in the range of 3.39 μm by two transitions: 3.3922 and 3.3912 μm can be found in Ref. 2. In the first examination[2] it turns out that high reproducibility of the laser radiation wavelengths and their differential frequency and the stability and equivalence of radiation power at both frequency components are necessary for accurate detection of the spatial distribution of a gas microconcentrations.

Besides, the possibility of a continuous frequency tuning in accordance with a given law and at a given rate is required in investigating fine and hyperfine structures of absorption spectra. The fulfilment of the above-stated demands is possible if one uses our wide-range electrooptical device converting a single-frequency coherent radiation into a double-frequency one[3] and a set of single-frequency cw lasers.

The use of quantization of the radiation phase in a highly effective lithium niobate crystal controlled by means of two pairs of electrodes on its lateral sides gives a possibility to maintain a continuous frequency tuning in the range of 0–0.04 GHz. However, according to experimental findings, there is a strong dependence of spectral characteristics of the converted radiation on the change of the applied voltage. It causes undesirable amplitude modulation of the components at the operating wavelengths.

Besides, the use of two controlling voltages worsens the universality of the source in measurements when the frequency change by a given law and at a given rate is needed, in particular, in the LFM case. Further analysis of phase characteristics of nonlinear electrooptical 3 *m* crystals made it possible to find the modulation coefficient and simplify the process of obtaining tunable radiation using the only controlling voltage. The achievement of the above-mentioned advantages is possible if one accounts for the features of the phase modulation characteristics of the crystals belonging to a certain class.

Theoretical investigations of the output spectrum of the tunable source under quantization of the radiation phase with regard for the features of its phase characteristics show the presence of two components equidistant from the initial laser radiation frequency ω by the quantization frequency ω' and having equal amplitude. The radiation spectrum is described by the expression

$$E(t) = E_0 J_{2k+1}(z/2) \{\sin [\omega + (2k+1)\omega'] t - \sin[\omega - (2k+1)\omega'] t\}, \quad (1)$$

where E_0 is the light wave amplitude at the crystal input; z is the parameter determined by the characteristics of the crystal and the controlling field; $J_k(z)$ is the Bessel function of the first kind of the kth order. When $\pi/4 < z < \pi/2$, we have $J_1(z) \ll J_n(z)$, $n = 3, 5, \ldots$, what provides high degree of spectral purity of the output radiation. The experimental investigations of the spectrum performed on the device with a scanning Fabry–Perot interferometer confirmed theoretical results (Fig. 1).

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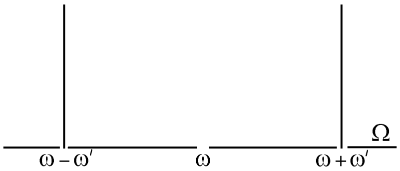

FIG. 1. Output radiation spectrum.

Let us note some essential characteristics of the device converting single-frequency coherent radiation into a double-frequency one which gave us the possibility to use it for constructing a model of an LFM lidar. The maximum frequency conversion coefficient is 0.64 and depends on the amplitude of the control voltage. The coefficient of nonlinear distortions does not exceed 1% when the conversion coefficient is 0.58. The instability of the spectral component amplitude is determined by the value of 10^{-5} and is caused by the use of well-known technical solutions for stabilization of the control signal amplitude. The instability of the differential frequency is simply connected with that of the conversion voltage frequency and is characterized by the value of 10^{-6}. This is caused by both the use of crystal-control and thermostabilization of the master oscillator and the possibility to construct an effective loop of automatic frequency control. The exact dependence of the conversion frequency on the quantization frequency simply makes it possible to realize any law of its change including LFM. The operating wavelengths of the device range from 0.4 to 4.5 μm when a lithium methaniobate crystal is used.

The model of the LFM lidar (Fig. 2) provided detection of the atmospheric inhomogeneities at a distance no more than 100 m at a signal–to–noise ratio above 5. A He–Ne laser with the continuous radiation power of 2 mW was a source of sounding radiation. The conversion of radiation frequency occurred in the device developed using the electrooptical modulator ML–5.

The receiving optics was constructed based on MTO–1000A lens with the focal length of 1000 mm and 100 mm in diameter. The photomultiplier FEU–84 was used as a photodetector, from the output of which the signal entered the spectrum analyzer, then it was detected, converted to a digit form by means of 1113PV1 ADC, and transmitted for processing into an IBM PC XT compatible microcomputer MS 1502. The nonlinearity of the modulation frequency change during the LFM period, instability of the controlling voltage converter, and instability of the voltage giving the operating point on the characteristics of the electrooptical crystal made a negligible contribution into the error of determining the distance to the sounded part of the path.

Let us estimate technical characteristics of the LFM lidar assuming that its resolving power is 5 m and maximal range is 2 km. The frequency deviation of the laser emitter is determined by the resolving power of the lidar

$$\Delta f = c / 4\Delta R. \qquad (2)$$

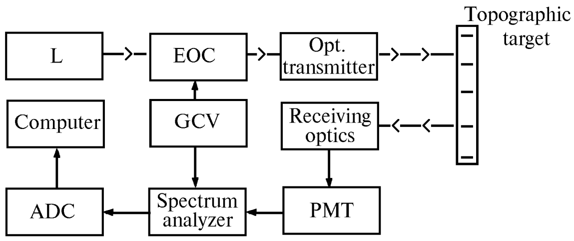

FIG. 2. Schematic of the LFM lidar breadboard construction: laser L, electrooptical converter EOC, and generator of controlling voltage GCV.

Substituting this value into Eq. (2) we obtain Δf=15 MHz. For correct measurements, the modulation period should be considerably greater than the delay time of the backscattering signal from the maximum distance. When R = 2 km, the delay is $1.3\cdot 10^{-5}$ s and the modulation period is 10^{-4} s. The beat frequency of the received and emitted signals for the atmospheric layer at the distance R is equal to

$$f_{\rm r} = 2R\, \Delta f\, f_{\rm m} / c \qquad (3)$$

where $f_{\rm m}$ is the modulation frequency.

When substituting our data, we obtain $f_{\rm r}$=2 MHz and meet the necessity to realize a 100–channel spectrum analyzer with the filter bandwidth of 20 kHz.

The lidar can operate in two modes: the direct detection mode and the heterodyning mode. Let us define the threshold power of the signal for both cases under certain assumptions.

The minimum detectable signal in the direct detection mode can be defined by the expression

$$P_{\rm thr} = (l^2\, \Delta f)^{1/2} / \Delta, \qquad (4)$$

where l is the dimension of the photocathode sensitive area (2 mm), Δf is the pass band of the receiving device which is determined by the frequency deviation in this mode; D is the detecting capacity of the photodetector of a given type (10^9 cm·Hz $^{1/2}$/W). Substituting our data into Eq. (4) we obtain $P_{\rm thr} = 5.5\cdot 10^{-9}$ W.

For the heterodyning mode the expression for the threshold power has the form

$$P_{\rm thr} = N\hbar c\Delta f / \eta\lambda, \qquad (5)$$

where $\hbar$ is the Planck constant, N is the noise factor characterizing the noise increasing in the process of detecting optical signals (for FEU N = 2), Δf is the filter pass band which is determined by the beat frequency of the received and emitted signals in this mode, λ is the radiation wavelength, η is the quantum efficiency of the photodetector (0.1 for FEU–84). Substituting our data into Eq. (5) we obtain $P_{\rm thr} = 1.4\cdot 10^{-13}$ W.

Thus, the use of the heterodyne reception leads to an increase in the lidar sensitivity. In this case the required radiation energy for operating at distances up to 2 km is 10^{-4} and the necessary laser power is 1–2 W.

The estimation of the selectivity with respect to the velocity of the sounded objects was an additional aspect studied during the experimental investigations of the lidar model. The symmetric structure of the sounding signal spectrum leads to similar Doppler frequency shift of both spectral components. The presence of the Doppler shift is not observed in the direct detection mode and the lidar operates at a constant intermediate frequency; but in the heterodyning mode the Doppler shift leads to an increase or a decrease in the sounding frequencies with respect to the central frequency of the laser. The detection channel of the Doppler shift is constructed here in accordance with a simple scheme comparing two frequencies: the conversion frequency divided by two and the differential frequency between the central frequency of the laser and the received radiation frequencies of the backscattering signal.

Thus we have developed the principles of constructing LFM lidars with frequency conversion based on an electrooptical frequency doubler. The lidar is characterized by high stability of the sounding radiation parameters what gives a possibility to speak about the improvement of its metrological characteristics, by the possibility to record Doppler frequency shifts caused by the velocity of the sounded layer movement, as well as by a simple optical scheme. The estimations done and the experimental results obtained confirm the possibility of creating lidar of the given class.

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