Application of square pulses to sensing with LFM CW lidars

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Operation of CW lidars is analyzed for the case of sensing intensity modulated by symmetrical square pulse signals (of meander type) with a linearly variable repetition rate. The described sensing method combines the properties of both CW and pulsed lidars and thus provides simultaneous realization of their advantages in practice.

The CW lidars with linear frequency modulation (LFM) of optical radiation intensity provide the capability of detecting various pollutants with sufficient spatial resolution at low power of sensing radiation.[1]

The operation of LFM CW lidars with the radiation intensity varying following the sinusoidal law was analyzed in Refs. 1 and 2. However, practical realization of this modulation with low-level nonlinear distortions is rather complicated technical problem. It is difficult both when applying external optical modulators[1] and internal modulation of laser radiation, in particular, as applied to promising semiconductor injection lasers[3] that are characterized by significantly nonlinear dependence of the output power on the pump current.

In our experiments, we used an LFM CW lidar, in which the intensity of sensing optical radiation was modulated by symmetric square pulsed signals (of meander type) with the repetition frequency obeying a linear law. In this case, the received optical signal is converted by a photodetector, and then it comes to the input of a frequency mixer. A sinusoidal signal with the same linear modulation law is used as the base voltage.

Let the variation law of the laser pulse repetition rate be described by the following equation:

$$f_0(t) = a\,t, \quad a = \text{const}, \tag{1}$$

where t is time.

A sinusoidal LFM signal with the same frequency modulation law $f_0(t)$ is used as the base voltage for the mixer. According to Fourier series expansion of a set of square pulses,[4] the spectrum of the received signal includes components with the frequencies

$$(2n - 1)\, f_0(t - \tau) = (2n - 1)\, a(t - \tau), \tag{2}$$

where $n = 1, 2, 3, \ldots$ is a natural number; τ is the doubled time needed for the pulse to travel the sensing path.

In this case, the beat-frequency waveform at the mixer output includes components with the frequencies

$$f_{R1} = a\tau, \tag{3}$$

$$f_{R2} = \text{abs}\,(3a\tau - 2at), \tag{4}$$

. . . .

$$f_{Rn} = \text{abs}\,[(2n - 1)\, a\,\tau - 2(n - 1)\, at]. \tag{5}$$

The frequency of the first component f_{R1} is independent of time and the distance to the atmospheric layer sensed determines it. The other frequency components have no effect on the lidar operation, because their frequencies vary continuously in time and they are not accumulated in the receiver.

Thus, the signals of difference (ranging) frequency at the mixer output contain time-constant components only for the first harmonic of the pulsed sensing optical signal. Similarly to Refs. 1–3, the frequencies of the signals at the mixer input are proportional to the doubled time of sensing radiation propagation along the path to the volume sounded. This fact provides corresponding spatial resolution even when using square pulses of optical radiation.

The situation is different, when the reference signal coming to the mixer is not ideally sinusoidal and its spectrum also contains components with the frequencies

$$f_{\text{ns}} = (2n - 1)\, at. \tag{6}$$

Then, the spectrum of the difference-frequency signal at the mixer output contains, besides f_{R1} (3), the higher-harmonic components, whose frequencies f_{Rm} are also constant in time:

$$f_{Rm} = (2m - 1)\, a\tau = \text{const}, \tag{7}$$

where $m = 2, 3, 4$ is a natural number.

These harmonic components can cause noise in neighboring reception channels. However, this noise is also inherent in LFM CW lidars considered earlier[1–3] with non-ideal sinusoidal reference signal coming to the photodetector mixer and non-ideal sinusoidal variation law of the sensing optical signal.

Thus, the operating principle of LFM lidars with square sensing pulses is equivalent to the operating principle of LFM lidars presented above.[1–3]

To test experimentally the operation of an LFM lidar with square sensing pulses, we used the setup similar to that in Ref. 1 with a He–Ne laser (output power of less than 1 mW in the CW mode, wavelength of 0.63 μm) as a radiation source. The sinusoidal voltage with linearly varying frequency from a sweep-frequency generator through broadband amplifiers was applied to an ML-5 electrooptical modulator and the photodetector.

The laser radiation coming from the electrooptical modulator was then sent into the atmosphere. The backscattered signal came to a photodetector through the receiving optics (MTO-1000A objective) and a set of optical filters. The amplified signal from the photodetector, at the difference frequency f_R corresponding to the range R to the path part under study, was separated out by a tunable narrowband filter and then came to the recorder. In this case[1]

$$f_R = 2R\,\Delta F\,F_\mathrm{m}/c, \qquad (8)$$

where ΔF is the frequency deviation; F_m is the modulation frequency; c is the speed of light.

As a photodetector, we used a FEU-84 photomultiplier operating in the radio heterodyning mode.[5] The reference LFM voltage from the output of the second broadband amplifier came to the PMT modulator.

Control voltage parameters and photodetector characteristics used correspond to those in Ref. 1, i.e., the frequency deviation $\Delta F = 10$ MHz, modulation frequency $F_\mathrm{m} = 50$ Hz, transformation coefficient of FEU-84 PMT in the radio heterodyning mode equals to 0.3, photodetector dynamic range exceeds 200.

The modulation characteristic of the electrooptical modulator is significantly nonlinear[6]:

$$I/I_0 = \sin^2[(U/U_{\lambda/2})\,\pi/2], \qquad (9)$$

where I_0 is the intensity of radiation coming to the modulator, I is the radiation intensity at the modulator output, U is the voltage applied to the modulator; $U_{\lambda/2}$ is the halfwave voltage of the modulator.

The halfwave voltage of the ML-5 modulator used in our experiment was 180 V, and for the emitter to operate in the linear mode with harmonic LFM sensing signals,[1] the working point was set at a constant shift of 90 V, and the amplitude of the sinusoidal LFM voltage at the modulator was 30 V. The modulation depth of the sensing radiation intensity did not exceed 0.5.

It should be noted that the operation with harmonic sensing signals at modulation of laser radiation[1] limits the laser capacity factor at the level of 0.25. Under these conditions, the setup provided for detection of cigarette smoke at a distance longer than 50 m at the signal-to-noise ratio at the filter output no less than 3 (Ref. 1).

Operation with square pulse sensing signals in the LFM lidar was realized in the following way. Output stages of the broadband amplifier feeding the modulator were put in the clipping mode due to the increase of amplitude of the input LFM signal, and the amplitude of the input voltage was maintained at the level corresponding to the linear operation mode[1] (30 V) by regulating the amplifier supply voltage. Clipped signals came to the modulator, and this processes corresponded to lidar operation with anharmonic LFM sensing signals. The further increase in the amplitude of the input signal switched the amplifier output stages into the key mode and provided generation of square-shaped voltage pulses of the meander type at the electrooptical modulator, thus switching the LFM lidar to the mode of square pulse sensing.

New operation modes were studied in the following way. A diffusely reflecting screen was installed within the sensing path and high-intensity backscatter signal from this screen was recorded at the ranging frequency f_R given by Eq. (8) (the signal-to-noise ratio was 200). Simultaneous measurement of signals at the frequencies multiple of f_R (kf_R, $k = 2, 3, \ldots$) showed that the level of components at these frequencies [in particular, the frequency given by Eq. (7)] due to non-sinusoidal shape of the sensing signals did not exceed the noise level for the mode with both anharmonic and square pulse sensing signals. At the same time, as the signal at the input of the broadband amplifier increased, the increase of the photodetector signal at the ranging frequency f_R was observed.

The increase in the amplitude of the input signal at the frequency f_R had a monotonic character and achieved 1.25–1.27 at transition from operation with harmonic signals to operation with square pulse sensing signals. The corresponding increase of the received signal was also recorded in observing the cigarette smoke, and the lidar range increased by 12% at operation with square LFM signals.

For analysis of the results obtained we should take into account that in the general case of LFM lidar operation with anharmonic sensing pulses the spectrum of the received signal includes components with the frequencies

$$p\,f_0(t-\tau) = pa\,(t-\tau), \qquad (10)$$

where $p = 1, 2, 3, \ldots$ is a natural number. In this case, the beat-frequency waveform at the mixer output includes components with the frequencies

$$f_{R1} = a\tau, \qquad (11)$$

$$f_{R2} = \mathrm{abs}\,(2a\tau - at), \qquad (12)$$

$$\cdots\cdots\cdots\cdots\cdots\cdots$$

$$f_{Rp} = \mathrm{abs}\,[pa\tau - (p-1)\,at]. \qquad (13)$$

Similarly to Eq. (3), the frequency of the first component f_{R1} is constant and determined by the distance to the studied atmospheric layer, and other components are not accumulated in the receiving unit and therefore they have no effect on the lidar operation. If the reference signal coming at the mixer is not ideally sinusoidal and its spectrum includes components with the frequencies $f_\mathrm{ns} = qat$, then the spectrum of the difference-frequency signal, similarly to Eq. (7), includes the higher-harmonic components with time-constant frequencies

$$f_{Rq} = qa\tau = \mathrm{const}, \quad q = 2, 3, 4, \ldots, \qquad (14)$$

which can induce noise in other receiving channels and in the case of operation with other anharmonic sensing signals.

Let us estimate the effect of non-ideal base voltage on the operation of an LFM lidar with anharmonic sensing signals. The level of the higher harmonics in the base voltage is determined by the harmonic coefficient (coefficient of nonlinear distortions)[7]:

$$K_\mathrm{h} = (U_{m2}^2 + U_{m3}^2 + \ldots)^{1/2}/U_{m1}, \qquad (15)$$

where U_{m1} is the voltage amplitude of the fundamental frequency; U_{m2}, U_{m3}, ... are amplitudes of higher harmonics. Consequently, the contribution of every higher-harmonic component does not exceed K_h. According to lidar equation,[8] the effect of noise (14) increases with the increase of the number q. Since the most intense components for the close-to-sinusoidal base voltage are harmonic components with the number no higher than 5, let us consider the limiting case that the overall nonlinearity of the reference signal is due to the 5th harmonic:

$$U_{m5}/U_{m1} = K_{\mathrm{h}} \qquad (16)$$

in operating with square pulse sensing signals subject to such noise most strongly. On the assumption of a homogeneous sensing path and weak atmospheric absorption, the level of signal in the atmosphere decreases following the $1/R^2$ law.[8] The amplitude of the 5th harmonic in the spectrum of the meander-type pulsed signal makes up to 0.2 of the amplitude of the first harmonic.[4] Correspondingly, the noise level at the ranging frequency $f_{R5} = 5f_{R1}$ (14) when processing the signal at the ranging frequency f_{R1} [Eqs. (3) and (11)] is

$$K_{\mathrm{n}5} = U_{\mathrm{n}}(f_{R5})/U_{\mathrm{s}}(f_{R5}) = 5K_{\mathrm{h}}, \qquad (17)$$

where $U_{\mathrm{n}}(f_{R5})$ and $U_{\mathrm{s}}(f_{R5})$ are the voltages of noise and signal, respectively.

Taking into account the simplicity of generation of relatively low-power reference signals with $K_{\mathrm{h}} = 10^{-4}$–10^{-3}, the noise level inherent in operation with anharmonic or square pulse LFM signals can be reduced down to tenths of percent, that agrees with the experimental data obtained. It is interesting to note that the experimentally observed monotonic increase of the signal at transition from operation with harmonic sensing signals to operation with anharmonic and then square pulse signals corresponds to the increase in the amplitude of the first harmonic in their spectrum achieving the value of 1.27 for the meander signals.[4]

Our analysis showed that echoes received in the lidar schemes considered are processed by the first harmonic of the difference-frequency signal, and this allows some elements of the theory of CW lidars to be applied to their description. These elements, taken from Ref. 2, deal with the choice of such parameters as determination of resolution, frequency deviation, and modulation frequency. At the same time, the transition to operation with anharmonic and then square pulsed sensing signals allows the modulation depth of the laser radiation intensity to be increased up to 100% (in contrast to 50% reported in Refs. 1 and 2). This corresponds to the increase in the efficiency of conversion of laser output power into the power of sensing signal from 25 to 50% and to 63% for the operation modes discussed. Correspondingly, the range of LFM CW lidars can be increased by 1.4 and 1.6 times at transition to these modes.

Thus, operation with square pulse sensing LFM signals is characterized by the same properties as those inherent in CW lidars[1–3]: accumulation of the ranging-frequency signal in the receiving system, low level of sensing CW radiation power needed to provide for the practically acceptable range and spatial resolution. On the other hand, application of square pulse sensing signals in LFM CW lidars excludes the effect of nonlinearity in characteristics of optical modulators (and laser emitters with internal modulation[3]) on the system parameters and facilitates operation of submodulators due to transition of active elements in key mode. Consequently, the operating mode under discussion shows some features of pulse sensing methods as well. In this case, it seems promising to use, as a submodulator, pulse shapers[9] specially developed to control electrooptical modulators, as well as piezoelectric ultrasound sources employed in acoustic sensing of various media.

The device described in Ref. 9 uses avalanche transistors. It is characterized by simple design and high reliability and provides generation of high-amplitude square voltage pulses (100 V) with short fronts (several nanoseconds) at a high capacitive load (tens of pF). The repetition rate and duration of generated pulses are determined by the repetition rate and duration of input control pulses with the amplitude of several volts.

Depending on the type of the emitter, this sensing method can be applied: (1) to detection of various atmospheric pollutants, in particular, to remote monitoring of natural gas leakages,[2] when using He–Ne lasers generating radiation in the spectral range of 3.39 μm, (2) to remote detection of ammonium leakages under indoor conditions[3] with the use of injection semiconductor lasers based on InGaAsP/InP compounds and operating in the spectral region of 1.5 μm in the mode with internal modulation.

Thus, the results obtained indicate that rather simple technological solutions allow development of inexpensive devices for remote monitoring of atmospheric parameters with practically acceptable characteristics, in particular, spatial resolution.

The peculiarity of the atmospheric sensing method considered is that it combines the properties and, consequently, advantages of both CW and pulsed lidar methods. Application of square pulse sensing signals in LFM CW lidars favor improvement of power characteristics and increase of the range of such systems.

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