Application of amplitude-phase conversion of laser radiation frequency in specialized frequency-modulation lidars

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We discuss theoretical grounds for the amplitude-phase method of coherent radiation frequency conversion. Potentialities of this method are demonstrated by its application to generation of two-frequency and two-band radiation in specialized frequency-modulation (FM) lidars with heterodyning and broad-band frequency modulation, respectively. Problems that arise in the development of electro-optical modulators for implementing this method are briefly considered and the ways of their solution are discussed.

1. Introduction

Sensing of the atmosphere with cw and quasi-cw laser radiation using the frequency modulation technique has been actively discussed during two recent decades. This approach attracts attention of researchers because it is equivalent in power to sensing with pulsed radiation and makes it possible to achieve high spatial resolution and to record returns from weakly absorbing atmospheric components. However, most papers devoted to FM sensing have so far dealt only with the possibility of constructing, in principle, FM lidars employing some or other scheme, for example, the double, FM–FM, or FM–AM modulation.[1–4] Bread-board models constructed following these schemes are capable of operating only under laboratory conditions. Their use in field studies is limited because of fluctuations in characteristics of the devices comprising the entire instruments as well as due to fluctuations of sounding and return radiation in an inhomogeneous atmosphere.

To eliminate the influence of temporal fluctuations in the device characteristics, specialized designs of FM lidars have been developed. These approaches use shifting of the heterodyne frequency followed by its conversion, multiple heterodyning, and dual frequency modulation.[3,5,6] To reduce fluctuations due to the inhomogeneous atmosphere, specialized broad-band FM designs are used.[7] For these designs to be implemented, special electro-optical generators are needed to produce two-frequency or two-band radiation. Such generators should ensure efficient conversion of sounding radiation energy at different values of the frequency modulation index and different laws of its variation.

2. Amplitude-phase conversion of a single-frequency oscillation into a two-frequency one

The initial single-frequency oscillation can be written in the following form:

$$e(t) = E \sin\varphi(t), \tag{1}$$

where the oscillation phase $\varphi(t)$ varies according to the law $\varphi(t) = \omega_0 t + \varphi_0$; E, ω_0, φ_0 are its constant amplitude, frequency, and the initial phase.

As known from the theory of modulated oscillations, a decrease (suppression) of amplitude of the initial (carrier) oscillation and formation of two symmetrical side bands are possible at phase modulation with particular indices.[8,9]

An oscillation with phase commutation can be presented by the following analytic expression:

$$e(t) = E \begin{cases} \sin\omega_0 t & \text{at } T(2p-1)/2 < t \le Tp, \\ \sin\omega_0 t + \theta & \text{at } Tp < t \le T(2p+1)/2, \end{cases} \tag{2}$$

where $T = 2\pi\Omega$, $\Omega = \omega_0/k$, θ are the period, frequency, and phase change; $k \gg 1$ is an integer number, and $p = 0, 1, 2, \ldots$.

At $\theta = \pi$, upon expansion in a Fourier series, the oscillation (2) takes the form:

$$e(t) = [2E/\pi]\, \Sigma\{[1/n] \times$$
$$\times [\cos(\omega_0 + n\Omega)t - \cos(\omega_0 - n\Omega)t]\}, \tag{3}$$

where $n = 1, 3, 5$ is the number of a harmonic of the expansion over the phase change frequency. Thus, oscillation (2) is a two-band multiple-frequency oscillation with the difference frequency between spectral components equal to 2Ω and the suppressed component at the carrier frequency. The initial phases of components inside a band are the same, while the difference between the initial phases of components of the lower and upper bands is π.

The next task of this study is to find methods to convert oscillation (2) into a two-band oscillation. Such methods could be implemented in specialized designs of FM lidars with conversion of the heterodyne frequency and its modifications, for example, heterodyning in the side bands. Another task is to find methods for formation of two-band

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multiple-frequency oscillation of a special shape for broad-band FM lidars.

2.1. Formation of a two-frequency oscillation

We can suppose, based on the theory of modulated oscillations[8,9] and analysis of peculiarities of the spectrum (3), that it is possible to form a two-frequency oscillation by suppressing the parasitic components in spectrum (3), when applying amplitude modulation with some oscillation $S(t)$, that meets the following requirements.

In modulating the single-frequency oscillation with the oscillation $S(t)$, an amplitude-modulated oscillation is formed, in which the frequency interval between the carrier and the nearest side component, as well as between a side component in both bands is equal to 2Ω, the initial phase of the carrier oscillation differs by π from the initial phase of the side components, and the initial phases of the side components inside the bands are the same.

The simplest oscillation, which meets these requirements, is the oscillation of the form $S(t) = S_0 \cos(2\Omega t + \pi)$, where S_0 is its constant amplitude, and π is the initial phase. If oscillation (2) is modulated with the oscillation $S(t)$, the resulting oscillation has the spectrum of the following form:

$$e(t) = [2E/\pi] \times \Sigma\{M_n [\cos(\omega_0 + n\Omega)t - \cos(\omega_0 - n\Omega)t]\}, \quad (4)$$

where M_n are the coefficients of Fourier series for spectral components with the number n, the amplitude of which is determined as

$$E_n = [2E/\pi] M_n = [2E/\pi] \{(1/n) - (m/2) [(1/n - 2) + (1/n+2)]\} = (2E/\pi)(1/n) - (2E/\pi)(m/2)(1/n - 2) - (2E/\pi)(m/2)(1/n + 2), \quad (5)$$

where m is the amplitude modulation coefficient.

It is seen from Eq. (5), that the first term determines the spectrum of coefficients in the Fourier series (3), while the second and third terms describe the suppression of its components. The degree of suppression depends on the modulation coefficient m. Upon solving Eq. (5) and allowing for the condition $E_3 = 0$, we find the optimal modulation coefficient $m_{opt} = 5/9$. The resulting oscillation in this case is almost two-frequency, because the amplitude of spectral components $E_n \le E_1/15$ for $n \ge 5$. If the modulation coefficient varies within 0.85 to 1.15 of m_{opt}, the coefficient of nonlinear distortions does not exceed 1%.

Complete suppression of the side components with $n \ge 3$ can be achieved by using the $S(t)$ oscillation of the form $S(t) = S_0|\sin\Omega t|$ for amplitude modulation. Then the resulting oscillation has the following spectrum:

$$e(t) = [2E/\pi] [1 - m] \Sigma \{[1/n] \times [\cos(\omega_0 + n\Omega)t - \cos(\omega_0 - n\Omega)t]\} + [\pi Em/4] [\cos(\omega_0 + \Omega)t - \cos(\omega_0 - \Omega)t]. \quad (6)$$

The amplitude of the spectral components depends on the coefficients of Fourier series. For $n = 1$ $E_1 = [2E/\pi] [1 - m] + [\pi Em/4]$ and for $n \ge 3$ $E_n = [2E/\pi n][1 - m]$. At $m_{opt} = 1$ the spectrum consists of two valid components at the frequencies $\omega_0 + \Omega$ and $\omega_0 - \Omega$, while the parasitic components being suppressed. If the modulation coefficient varies within 0.7 to 1 of m_{opt}, the coefficient of nonlinear distortions of the output oscillation does not exceed 1%.

2.2. Formation of a two-band oscillation

The modulated oscillations found in Section 2.1 can also be used for formation of a symmetrical two-band spectrum for a broad-band FM differential absorption and scattering lidars. Toward this end, we should solve the set of equations when varying not only the amplitude modulation coefficient, but also the value of the phase commutation.

If the oscillation of the type $S(t) = S_0|\sin\Omega t|$ is used, we obtain the following expressions for amplitudes of the spectral components:

$$E_0 = E\,(1 + \cos\theta)/2; \quad (7)$$

$$E_1 = [(1 - m)/\pi + \pi m/8]\, E\,(1 - \cos\theta); \quad (8)$$

$$E_n = mE\,(1 + \cos\theta)/(1 - n^2), \text{ for } n = 2, 4, 6, \ldots, \quad (9)$$

$$E_n = E\,(1 - \cos\theta)\,(1 - m)/\pi n, \text{ for } n = 3, 5, 7, \ldots. \quad (10)$$

Expressions (7)–(10) allow the spectral composition of the resulting oscillation to be determined at any m and θ. However, in our opinion, forming oscillations should be sought by using synthesis of oscillations with complex harmonic composition of k oscillations, for example,

$$S(t) = \Sigma\, S_k \cos(2k\Omega t + \pi), \quad (11)$$

where S_k are partial amplitudes, rather than by phase commutation. This leads to simpler technical implementation. Then the expressions for Fourier coefficients have the form

$$E_n = [2E/\pi] \{(1/n) - \Sigma\,(m_k/2) [(1/n - 2k) + (1/n + 2k)]\}, \quad (12)$$

where m_k are the partial amplitude modulation coefficients. Using such an approach to searching for the forming oscillations, we can take into account the influence of nonlinearity in modulation characteristics of real electro-optical modulators, which are used for amplitude-phase conversion, on the spectral composition of the output radiation.

2.3. Brief discussion of the results obtained

In Section 2.1 we have demonstrated the possibility of obtaining two-frequency radiation without the parasitic components and determined possible deviations of the modulating voltage parameters from the optimal ones, at which spectral characteristics of output radiation hold sufficiently stable. The difference frequency of the output oscillation depends on the phase commutation frequency Ω. Its stability is uniquely related to the stability of the modulating voltage frequency and to the instability introduced by commutating devices. The value of the difference frequency stability that can be achieved, given master oscillators are under thermostat conditions, may be within 10^{-6} range as narrow. Some lidar measurements need tuning of the difference frequency. It can be obtained sufficiently easily by making use of the amplitude-frequency conversion. The minimum frequency difference achievable in tuning depends on the steepness of the modulation characteristic of modulators and on the width of a laser line. The maximum frequency difference depends on the upper boundary frequency of the modulator frequency characteristic and the ratio between the frequencies of modulated and modulating oscillations.

In Section 2.2 we have discussed a possibility of forming a two-band symmetrical spectrum of laser radiation to be used in broad-band FM differential absorption and scattering lidars. Power equivalence of the bands and efficiency of their formation play an important part in such systems. Using Eqs. (5)–(10), and (12) for spectra of output oscillations and taking into account the amplitude-phase character of the conversion, that is, use of additional energy of amplitude modulation and phase commutation for the formation of the side bands, one can readily find that the power of the latter ones makes up about 60% of the power of the initial single-frequency oscillation and the conversion coefficient is equal to unity, neglecting the loss, which is inevitable in real designs of electro-optical modulators.

3. Electro-optical devices for the amplitude-phase frequency conversion

We have already described in detail the electro-optical generators of two-frequency coherent radiation that use the amplitude-phase conversion.[4,6,10] Therefore, in this section we place special value on the development of devices generating two-band radiation.

Different concepts of design are used for construction of broad-band FM lidars, capable of recording returns from weakly absorbing components when sensing the turbulent atmosphere. However, most systems employ external electro-optical modulators, regardless of the modulation mode used: two-frequency modulation, modulation with partial conversion of the initial radiation (frequency modulation coefficient below unity), or multifrequency modulation (frequency modulation coefficient above two).

The reviews, we refer here to, show that most of the commercially available modulators do not meet the development needs in heat power to be dissipated, or in crystal aperture, or in the frequency range. If for the near infrared (up to 2 μm) one can find modulators for conversion with the frequency up to 600–1000 MHz and the modulated power of several tens milliwatts, then for the middle infrared (3–5 μm) it is quite problematic. Tantalate and lithium niobate crystals, which are quite widely applied in this spectral regions, have the tangent of the dielectric loss angle far exceeding 10^{-3}, what restricts their application in broad-band systems. The way out could be tried by using new crystals of the KTp isomorphic modifications such as, for example, KTA or RTA. These crystals have the dielectric loss tangent as low as $5\cdot10^{-4}$ and the heat strength, which is 10 times higher than that of lithium niobate. However, they are still under development.[7] Development of broad-band modulators for the far infrared (8–10 μm) is even more problematic, because the problem of thermal gradient in crystals comes to the fore. The use of quasi-cw lasers or long pulse operating modes solves this problem only partially. A cascade arrangement of modulators or use of multichannel modulation has been proposed in Ref. 7. However, this complicates technical implementation of the amplitude-phase conversion and sacrifices its advantages due to versatility of control over the parameters of output radiation by using only the controlling voltage.

4. Conclusion

The use of the amplitude-phase conversion of single-frequency coherent radiation allows the two-frequency and two-band radiation to be obtained. The two-frequency radiation is of high quality from the viewpoint of spectral purity, while the two-band radiation is of high quality too, but from the viewpoint of power equivalence between the bands. This allows improvement of high-stable FM heterodyning lidars and upgrading of broad-band FM lidars. The basic problem arising in technical implementation of this conversion is the development of high-efficiency electro-optical modulators, which should be capable of operating at high power of the initial single-frequency radiation and of the modulating actions, while providing for a wide range of frequency conversion.

References

1. E.P. Gordov and G.S. Khmel'nitskii, in: *Abstracts of Reports at the First Inter-Republic Symposium on Atmospheric and Oceanic Optics,* Tomsk (1994), Part 2, pp. 44–45.
2. R.R. Agishev, L.R. Aibatov, and Yu.E. Pol'skii, Atmos. Oceanic Opt. **7**, Nos. 11–12, 882–885 (1994).
3. E.D. Hinkly, ed., *Laser Monitoring of the Atmosphere* (Springer Verlag, New York, 1976).
4. G.I. Il'in, O.G. Morozov, and Yu.E. Pol'skii, Atmos. Oceanic Opt. **8**, No. 12, 1055–1057 (1995).
5. Yu.N. Dubnishchev, ed., *Laser Measuring Systems* (Radio i Svyaz', Moscow, 1983), 380 pp.
6. G.I. Il'in, O.G. Morozov, and Yu.E. Pol'skii, Atmos. Oceanic Opt. **10**, No. 2, 138–140 (1997).
7. J.F. Kelly, B.D. Cannon, S.W. Sharpe, R.L. Sams, and T.A. Blake, Proc. SPIE **3127**, 64–103 (1997).
8. A.A. Kharkevich, ed., *Spectra and Signals* (GIRML, Moscow, 1962), 504 pp.
9. A.S. Vinitskii, ed., *Modulated Filters and Tracing FM Reception* (Sov. Radio, Moscow, 1969), 548 pp.
10. G.I. Il'in, O.G. Morozov, and Yu.E. Pol'skii, Atmos. Oceanic Opt. **11**, No. 5, 447–450 (1998).