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Acousto-optical spectrum analysis of ultra-high-frequency radio-wave analogue signals with an improved resolution exploiting the collinear acoustic wave heterodyning

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Abstract

This article is devoted to the problem of improving the frequency resolution inherent in a parallel acousto-optical spectrum analysis via involving an additional nonlinear phenomenon into the data processing. In so doing, we examine possible application of the wave heterodyning to the real-time scale acousto-optical analysis of the frequency spectrum belonging to ultra-high-frequency radio-wave signals peculiar, for example, for radio-astronomy. The nonlinear process of wave heterodyning is realized through providing a co-directional collinear interaction of the longitudinal acoustic waves of finite amplitudes. This process, which is beforehand studied theoretically and investigated experimentally via the acousto-optical technique as well, allows us either to improve the frequency resolution of spectrum analysis at a given frequency range or to increase by a few times the current frequencies of radio-wave signals under processing. The first step along this way is connected with the experimental modeling of the acoustic wave heterodyning in solids via exploitation of the specific acousto-optical cell based on a liquid, which allows the simplest realization of a cell with the needed properties. Then, these theoretical and practical findings are used in our experimental studies aimed at creating a new type of acousto-optical cells, which are able to improve the resolution inherent in acousto-optical spectrum analyzer operating over ultra-high-frequency radio-wave signals. In particular, the possibility of upgrading the frequency resolution through the acoustic wave heterodyning is experimentally demonstrated using the cell made of lead molybdate crystal. The obtained results demonstrate practical efficiency of the novel approach presented.

Keywords: Acousto-optical spectrum analysis; Waves of the finite amplitude; Collinear wave heterodyning

1. Introduction

A major portion of modern developments in a high-speed and extremely precise optical data processing is currently connected with applying various nonlinear

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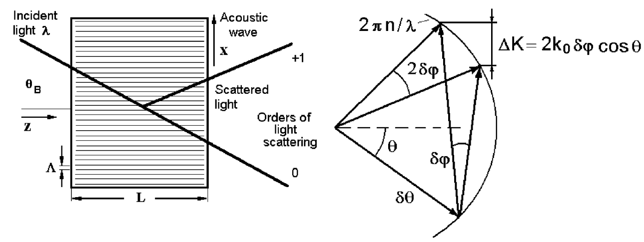
effects, such as soliton and parametric phenomena, all-optical multi-stability, etc. [1,2]. In this paper, the practical potentials related to exploiting the nonlinear process of wave heterodyning in a medium with dispersive losses are considered. In the case of wave heterodyning, beneficial analogue information incorporated into the spectrum of a signal gets converted from a high-frequency signal wave to a difference-frequency wave, so that just spectral components peculiar to the resulting difference-frequency wave are exploited during subsequent optical data processing. Usually, the precision of both spectral and frequency measurements for signals is determined by the uncertainty in the energy or momentum inherent in a photon localized in the interaction area [3]. Due to the dispersion of losses, heterodyning leads to increase in the characteristic length and/or time of propagation for the converted signal in that medium and to significant improvement in the accuracy of the optical data processing, because both spectral and frequency resolutions are in inverse proportion to the length or time of acousto-optical interaction. Here, we are reporting our investigations of the co-directional collinear longitudinal acoustic wave heterodyning through acousto-optic technique and its possible application to a real-time acousto-optical analysis of the frequency spectrum belonging to ultra-high-frequency (UHF) radio-wave analogue signals. The character of our studies is directly connected with actual absence of sufficiently effective acousto-optical materials suitable for processing ultra-high-frequency radio-wave analogue signals. Exploiting the introduced approximation, the theory of wave heterodyning in a medium with the dispersive losses has been progressed. Then, the developed theory was applied to our experiments directed to increase the accuracy of acousto-optical spectrum analyzers working in the UHF range. In fact, optical data processing with essentially improved frequency resolution has been experimentally observed within exploiting the created new acousto-optical cell based on exploiting rather effective lead molybdate crystal with resonant frequencies lying in a frequency range where conventional cell made of this material is not profitable. The obtained results confirm principally the advantages of our approach.

2. Formulating the problem: frequency performances and resolution of the Bragg acousto-optical deflector operating in a one-phonon Bragg normal light-scattering regime

Let us start from preliminary estimations of the frequency bandwidth Δf, the frequency resolution δf, and the number N of resolvable spots inherent in the Bragg acousto-optical deflector operating in a one-phonon normal light-scattering regime. A one-phonon non-collinear light scattering in isotropic medium, see Fig. 1a, is associated with the Bragg condition [4,5]



(a) (b)

Fig. 1. A one-phonon normal light-scattering regime: principal schematic arrangement for the Bragg light scattering (a) and the corresponding vector diagram determining the frequency bandwidth (b).

$$\sin\theta = -\frac{K}{(2k_0)} = -\lambda\frac{f}{(2nV)} \quad (1)$$

for normal process without changing the state of light polarization. Here, θ is the Bragg angle of light scattering, k_0 and λ are the wave number and the wavelength of light, respectively, n is the corresponding refractive index, K, f, and V are the wave number, carrier frequency, and phase velocity of the acoustic wave, respectively. The corresponding wave vector diagram is depicted in Fig. 1b. The frequency bandwidth of acousto-optical interaction Δf can be estimated through differentiating this Bragg condition in Eq. (1) as $\Delta f = \Delta\theta(2nV/\lambda)\cos\theta$, where $\Delta\theta$ is the variation of the angle of light incidence associated with the variation of the acoustic frequency Δf needed to provide the Bragg condition. In the case of light modulation, we have usually the geometry of interaction with rather wide optical beam, whose angle of spreading $\delta\theta$ is small, and rather narrow aperture of the acoustic beam, whose angle of spreading is $\delta\varphi \approx (V/fL) \gg \delta\theta$, where L is the length of acousto-optical interaction, see Fig. 1a. Assuming that $\delta\varphi \approx \Delta\theta$ and $\cos\theta \approx 1$, we yield the following approximation

$$\Delta f \approx \frac{2nV^2}{\lambda L f} \quad (2)$$

for the bandwidth of a normal Bragg acousto-optical interaction in isotropic medium. This approximate equality follows geometrically from the plot in Fig. 1b, because $\Delta K = 2\pi(\Delta f)/V$ and $2k_0\delta\varphi\cos\theta \approx 4\pi n V/(\lambda L f)$.

Generally, the momentum p of a photon is connected with the wave number k as $p = hk/(2\pi)$, where h is the Planck constant, so an uncertainty $\delta p = h(\delta k)/(2\pi)$ in the momentum is related to the uncertainty in the wave number δk of a photon. The same view is true, if one will consider the phonons. Namely, the momentum P of a phonon is connected with the wave number K as