RECORDING THE TEMPORAL RADIATION CHARACTERISTICS OF SPECTRALLY RESOLVED LIGHT SIGNALS

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It is proposed to extract data on the temporal characteristics of an optical signal by spectrally resolving the radiation and recording the nonlinear-optics effect of the resolved radiation. The recording should be made in two planes, with the spectrum image sharp in one of them and out-of-focus in the other. The dependence of the nonlinear effect on the phase relations of the spectral components of the radiation is analyzed. It is shown that if the spectral instrument is suitably chosen it is possible to determine (to within inessential constants) the phases of the spectral components from the frequency dependence of the nonlinear effect.

The literature contains two suggested methods of recording short-duration optical signals, requiring neither fast scanning of the signals nor auxiliary short-duration light pulses. It is likewise unnecessary to resort to a priori information on the temporal characteristics of the investigated radiation [1, 2].

We emphasize that we are interested in recording signals whose time dependences are not known beforehand. If the signal is known to be single-pulse, to find its duration it suffices to measure the second-order intensity correlation function [3, 4]. Literature dealing with such measurements is listed in [5] together with additional possibilities afforded by suitable reduction of the data (possibility of reconstructing the waveform of a single pulse).

On the other hand, for radiation with arbitrary time dependence, data on the second-order autocorrelation function are insufficient for an unambiguous determination of the temporal picture.

It was proposed in [1] to record the third-order intensity autocorrelation function; this would permit a reconstruction of the time variation of the intensity of an arbitrary signal. This method has not yet been implemented. Its shortcoming is that it calls for repeated measurements (using many "flashes" of the investigated radiation), i.e., it is feasible only if the signal is highly reproducible.

The method described in [2] was proposed in two variants. The variant realized there required repeated measurements, i.e., reproducibility of the signal. The second variant, which may work in the case of single action of the signal (one "flash"), had not been implemented.

In this paper is described one more method of recording light signals, requiring no use of fast actions on the radiation and no application of auxiliary short-duration radiation. A brief exposition of the idea of the method is contained in [6, 7]. No multiple repetition of the signal is proposed, and there is no need for beforehand information on the temporal characteristics. It is possible that its realization turns out to be simpler than that of the methods described in [1, 2].

The method is based on the fact that spectral resolution of a signal followed by nonlinear transformation makes it possible to reconstruct the phases of the spectral components from the yield of the nonlinear effect. On the other hand, the presence of complete information on the spectrum means, of course, the presence of complete information on the time variation of a complex signal.

We examine first the form assumed by a signal acted upon by a spectral instrument.

Let the investigated radiation

\[ E(t) = \text{Re} \mathcal{S}(t) \exp \left( -i\omega_gt \right) \]
be specified on the segment $-T/2 < t < T/2$, and be zero outside this segment. We denote the Fourier spectrum of the complex field $\mathcal{E}_S(t)\exp(-i\omega_st)$ by $\mathcal{E}(\omega)$, viz.,

$$\mathcal{E}(\omega) = \frac{T}{2} \int_{-T/2}^{T/2} \mathcal{E}_S(t) \exp(-i\omega_st + i\omega t) \, dt. \quad (1)$$

We assume that at the exit from the spectral instrument the spectrum is of the form

$$\mathcal{E}(\omega, t, \Gamma) = \int G(\omega' - \omega, \Gamma) \mathcal{E}(\omega') \exp(-i\omega't) \, d\omega',$$

where $G$ is the slit function of the instrument, $\Gamma$ the width of the slit function, and the frequency $\omega$ is uniquely related to the coordinate in the image plane of the spectrum. Strictly speaking, it would be necessary here to recognize that the spectral instrument causes additional phase shifts of the spectral components, and introduce in (2) the factor $\exp[i\Psi(\omega')]$. If the $\Psi(\omega')$ dependence is linear, the subsequent propagation does not change. The quadratic dependence of $\Psi(\omega')$ can be eliminated by focusing. In an arbitrary case, however, the function $\Psi(\omega')$, whose form must be established beforehand for the employed spectral instrument, must be included in Eq. (1) and taken into account in the subsequent calculations. We shall use below only expression (2).

Note that expression (2) can be replaced by an analogous expression pertaining to the temporal representation of the signal

$$\mathcal{E}(\omega, t, \Gamma) = \exp(-i\omega t) \int g(t'-t) \mathcal{E}_G(t') \exp[i(\omega - \omega_G)(t'-t)] \, dt'.$$

This equation can be obtained from (2) by substituting in it (1) and changing to the Fourier transform of the function $G$

$$\int G(\omega' - \omega) \exp[i(\omega' - \omega)(t'-t)] \, d\omega' = g(t'-t). \quad (4)$$

We introduce a notation for the intensity ($I$) and the time integral ($U$) of the radiation intensity at the exit from the spectral instrument

$$I(\omega, t, \Gamma) = |\mathcal{E}(\omega, t, \Gamma)|^2,$$

$$U(\omega, \Gamma) = \int_0^\infty I(\omega, t, \Gamma) \, dt. \quad (6)$$

Expression (6) reduces with the aid of (5) and (2) to the form

$$U(\omega, \Gamma) = \int |\mathcal{E}(\omega, t, \Gamma)|^2 \, dt = \int \delta(\omega' - \omega'') G(\omega' - \omega) G^*(\omega'' - \omega) \times$$

$$\times \mathcal{E}(\omega') \mathcal{E}^*(\omega'') \, d\omega' \, d\omega'' = \int \mathcal{E}(\omega')^2 |G(\omega' - \omega, \Gamma)|^2 \, d\omega'. \quad (7)$$

At a low width of the slit function ($\Gamma \to 0$) Eq. (7) leads to the natural result

$$U(\omega, \Gamma) \sim |\mathcal{E}(\omega)|^2,$$

i.e., the energy at the exit from the instrument is proportional to the spectral intensity. In the general case the spectral intensity is averaged over a spectral interval determined by the width of the slit function. The quantity $U(\omega, \Gamma)$, as seen from (7), contains no information on the phases of the spectral components. At the same time, the characteristics of the field $\mathcal{E}(\omega, t, \Gamma)$ contain dependences on the phases. To illustrate this circumstance, we consider a case with a slit function $G$ of Gaussian form

$$G(\omega' - \omega, \Gamma) = \frac{1}{\sqrt{\pi}} \exp[-(\omega' - \omega)^2/\Gamma^2], \quad (9)$$

in which case the pulsed response of the instrument is

$$g(t'-t) = \Gamma \exp[-(1/4)(t'-t)^2/\Gamma^2]. \quad (10)$$