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SPATIAL SELF-MODULATION OF LIGHT AS A RESULT OF ABSORPTION

V.M. Komissarov
P.N. Lebedev Physics Institute, USSR Academy of Sciences
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We investigate here the process of spatial self-modulation of light upon absorption (SSMA). The self-modulation is the result of the scattering of the interfering coherent waves interacting in the absorbing medium.

The gist of the SSMA phenomenon can be explained in the following manner. Assume that at the initial instant of time $t = 0$ two plane linearly polarized waves of equal amplitude and frequency are incident from the left on the boundary ($x = 0$) of an absorbing medium. In the linear approximation the field in it can be represented in the form

$$\frac{1}{2}E_0 e^{-i\omega t} + \text{KC} = \frac{A}{2} e^{-i\omega t + ikx - \alpha x}\left(e^{iqy} + e^{-iqy}\right) + \text{KC}, \qquad (1)$$

where $k = (\omega/c)\sqrt{\varepsilon'}$, $\alpha = (1/2)(\omega/c)\varepsilon''/\sqrt{\varepsilon'}$, and $q = k \tan(\theta/2)$. The dielectric constant is $\varepsilon = \varepsilon' + i\varepsilon''$, where $\varepsilon'' \ll \varepsilon'$. As a result of the absorption, a power $Q(r, t)$ is released per unit volume and is proportional to the square of the modulus of the field $|E|^2$. This leads to uneven heating of the medium, which in turn causes a change in the dielectric constant of the medium:

$$\epsilon_1 \approx (\partial\epsilon/\partial T)_p T_1. \qquad (2)$$

Assuming that the entire released power goes over into heat and that the time of observation is small compared with the characteristic time of equalization, due to thermal conductivity, of the temperature of the unevenly heated matter ($t \ll 1/\chi q^2$), we obtain

$$T_1 = \frac{1}{\rho C_p}\int_0^t Q(r, t)dt. \qquad (3)$$

The result is a periodic change, with respect to the coordinate y, of the dielectric constant of the medium. This leads to the appearance of a number of spatial spectra of the scattered field E_1, i.e., to SSMA.

Thus, in essence this effect is close on the one hand to stimulated scattering of light due to absorption (SSA) [1, 2], and on the other hand to the effect of thermal self-focusing and defocusing of light [3]. This is natural. In a macroscopic description, the wave phenomena connected with self-action of light through a medium can be unified under the term self-diffraction of light, taking it, as in the linear theory [4], in a broad sense, i.e., including in self-diffraction the aggregate of all the phenomena occurring during the propagation of the waves in the medium whose inhomogeneities are produced by the wave field itself.

We continue the description of SSMA with an example of two interacting waves. In the given-field approximation ($|E_0| \gg |E_1|$) we obtain for the summary field $E = E_0 + E_1$ from Maxwell's equations and from (2) - (3)

$$\Delta E + \frac{\omega^2}{c^2}\epsilon E + \frac{\omega^2}{c^2}\gamma |E_0|^2 (Et - \int_0^t E dt) = \frac{\omega^2}{c^2}\gamma |E_0|^2 E_0 t. \tag{4}$$

Here $\gamma = (\partial\varepsilon/\partial T)_p(\alpha cn/4\pi\rho C_p)$. If we introduce the complex amplitude $B(r, t) = E\exp(-ikx + \alpha x)$, then at sufficiently small angles θ (the period of the inhomogeneity is large compared with the wavelength, $q^{-1} \gg \lambda$) we can seek it in the approximation of the parabolic equation

$$\frac{\partial B}{\partial x} = \frac{i}{2k}\frac{\partial^2 B}{\partial y^2} + \frac{ik\gamma}{2n}(2A\cos qy)^2(Bt + \int_0^t B dt)e^{-2\alpha x}$$
$$- \frac{ik\gamma}{2n}(2A\cos qy)^3 t e^{-2\alpha x} \tag{5}$$

under the condition $B(x = 0) = 2A\cos qy$. We investigate the initial stage of the development of the process. Expanding $B(t)$ in powers of t, we obtain

$$B = \cos qy(\beta_{10} + \beta_{11}t + \dots) + \cos 3qy(\beta_{31}t + \beta_{32}t^2 + \dots)$$
$$+ \cos 5qy(\beta_{52}t^2 + \dots) + \dots \tag{6}$$

For the coefficients β_{1k} we obtain a consecutively solvable system of equations. The scattered field is a set of spatial spectra, with the spectra of higher order appearing at later instants of time. The amplitudes of the spectra of the low order experience changes. Let us write out, for example, the explicit expression for the amplitude of the third spectrum with accuracy to $O(t^2)$

$$\beta_{31}t = \frac{ik\gamma}{2n}A^3 t\left[\frac{2(e^{-sx-2\alpha x} - e^{-9sx})}{8s - 2\alpha} - \frac{e^{-2\alpha x} - e^{-9sx}}{9s - 2\alpha}\right], \tag{7}$$

where $s = iq^2/2k = i(k/2)\sin^2(\theta/2)$. It is seen from this expression that the rate of growth of the scattered spectra depends on the relation between $(k/2)\sin^2(\theta/2)$ and the absorption coefficient α. The maximal growth rate is reached under the condition $|s| \ll \alpha$. For the spectrum number m, the condition is more stringent $(m^2/2)|s| \ll \alpha$. Let us compare the intensity of the spectrum excited in this manner with the intensity of the ordinary SSA due to the interaction of a wave of strongly exciting light and weak light waves of initial scattering by entropy fluctuations. From [1] we can obtain

$$I' \sim \langle |E_0'|^2\rangle \left(\frac{k\gamma}{2n}\right)^2 \frac{A^4 t^2}{\alpha^2}, \tag{8}$$

where $\langle |E_0'|^2\rangle$ is the mean square of the amplitude of the initial scattering by the entropy fluctuations. From (7) with $|s| \ll \alpha$ we obtain

$$I_3' \sim A^2\left(\frac{k\gamma}{2n}\right)^2 \frac{A^4 t^2}{\alpha^2}. \tag{9}$$

Since $\langle |E_0'|^2\rangle \ll A^2$, we get $I_3' \gg I'$. Consequently, a noticeable effect can be obtained in this case in weaker light fields. A theoretical investigation of SSMA at large times $t > t_y \approx \alpha((k\gamma/2n)A^2)^{-1}$ is difficult, for in this case the amplitude of the scattered light becomes comparable with the amplitude of the exciting radiation, and the given-field approximation is not valid here.

The spectra with higher numbers are apparently intensely excited in this case.

We present an estimate of the characteristics of the settling times t_y. For example, for radiation with wavelength $\lambda \simeq 10^{-3}$ cm at an intensity $I_0 \simeq 10^5$ W/cm^2, if the scattering element is MgF_2, we obtain $t_y \simeq 3 \times 10^{-6}$ sec. The time of relaxation of the process of thermal conductivity is $(\chi q^2)^{-1} \simeq 3 \times 10^{-2}$ sec for $\sin^2(\theta/2) \simeq 10^{-3}$. Since the settling time is inversely proportional to the intensity of the exciting light, at large powers for picosecond time intervals, the SSMA, just like SSA, can occur already as a result of excitation of intramolecular oscillations [1, 2].

In conclusion we note that small-angle scattering at small values at t can be regarded in this case as a 4-photon parametric process, in which two photons of the exciting radiation with wave vectors $k_{+1}(k, q, 0)$ and $k_{-1}(k, -q, 0)$ are transformed into two scattered photons $k_+(k_x, 3q, 0)$ and $k_-(k_x, -3q, 0)$. The fastest growth is possessed apparently by the spectrum scattered at the unshifted frequency ($|k_\pm| = |k_{\pm 1}|$). Indeed, in (7) the term proportional to $\exp(-9sx)$ is not multiplied by the weakening factor $\exp(-2\alpha x)$.

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E R R A T U M

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On p. 395, the fourth and fifth lines below Eq. (1) should read: "The frequency of the flute oscillations in the system withouth feedback was $\omega^*/2$" instead of ". . . was ω^* [2]."