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Imaging properties of intensity travelling waves and possible fields of their application*

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The properties of a volume recording of an intensity travelling wave, formed as a result of interference of two waves of different frequencies, are considered. It is shown that, when such a travelling wave is recorded in a medium capable of the stimulated Raman scattering at a resonance frequency equal exactly to the frequency difference of the interfering waves, so-called sfift volume dynamic hologram is obtained. Such a hologram provides the effective energy transfer from one of the interfering waves into another, because the shift is equal to a quarter of a period in this case. The simple interpretation of the process of the energy transfer in a shift hologram is presented.

It has been shown earlier that a spatial material model of an intensity travelling wave, formed as a result of interference of two electromagnetic waves of different frequencies, is analogous to a hologram in that it has the property of transforming one wave of the pair into its counterpart [1]. The only difference in this case is that the waves are mutually transformed (one into another) not only with respect to their spatial configuration, but also to the field oscillation frequency. It can be easily proved that the frequency of an incident electromagnetic wave, reflected from the travelling wave structure, undergoes such a Doppler shift that it becomes exactly equal to the frequency of the second wave of the pair of waves, which takes part in the formation of a given hologram.

However, in the study mentioned above the subject concerning the medium, wherein such travelling waves can be recorded, and the ways in which the properties of the medium may affect the properties of a hologram have not been touched upon. While mentioning that such a hologram can be used as a radiation converter, nothing was said about its convertion efficiency. The present paper discusses the recording possibility of the intensity travelling wave in a medium capable of the stimulated Raman scattering (SRS) at a resonance frequency equal exactly to the frequency difference of the waves which participate in the formation of this travelling wave. It has been shown that in this case a so-called shift volume dynamic hologram is obtained and that such a hologram provides the effective energy transfer from one of the waves forming the hologram into another.

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* This is the English version of the original Russian paper published in the Zhurnal Tekhnicheskoi Fiziki, Vol. 49, No. 1, 1979, which, at the suggestion of the author, has been decided for publication to enable our English reading readers to get acquainted with the results presented, and results which were obtained by some other authors in the new field of dynamic volume holography.

Let us discuss this point taking as an example two plane waves characterized by different values of both wave vector $\boldsymbol{k}$ and the frequency ω. The wave functions of such waves may be expressed in the following manner:

$$\Psi_1(r, t) = a_1 e^{i(k_1 r - \omega_1 t + \varphi_1)}, \tag{1}$$

$$\Psi_2(r, t) = a_2 e^{i(k_2 r - \omega_2 t + \varphi_2)}. \tag{2}$$

The total field of intensity is to be found by adding $\Psi_1(r, t)$ to $\Psi_2(r, t)$ and multiplying the obtained result by a conjugate value:

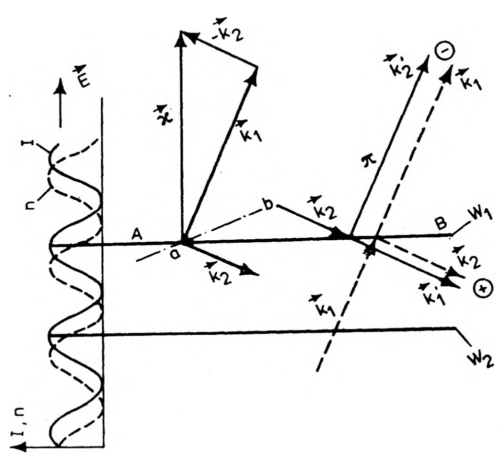
$$I(r) = a_1^2 + a_2^2 + 2 a_1 a_2 \cos[\boldsymbol{\kappa r} + \Omega t + (\varphi_1 - \varphi_2)], \tag{3}$$

where

$$\boldsymbol{\kappa} = \boldsymbol{k}_1 - \boldsymbol{k}_2, \tag{4}$$

$$\Omega = \omega_2 - \omega_1. \tag{5}$$

The expression (3) defines a plane travelling wave of intensity which is characterized by the wave vector $\boldsymbol{\kappa}$ and the intensity oscillation frequency Ω. The geometry of the wave which corresponds to this expression is shown in the figure. As it is seen from this figure, the surfaces W_1 and W_2 of antinodes of the intensity travelling wave are perpendicular to its wave vector $\boldsymbol{\kappa} = \boldsymbol{k}_1 - \boldsymbol{k}_2$, n — refractive index of the medium. The velocity, at



The process of wave transformation during recording of the intensity travelling wave in the medium capable of the induced Raman scattering. $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ are the wave vectors of plane waves whose interference leads to the creation of the intensity travelling wave, characterized by a wave vector $\boldsymbol{\kappa}$. AB is the surface of intensity wave antinodes. The graph illustrating the distribution of the intensity of the travelling wave I and the refractive index n induced by this wave vs. the coordinates is shown in the left part of the figure. The diagram of reflection of the waves characterized by the wave vectors $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ from the interface of two media coinciding with the surface of antinodes AB is shown in the right parts of the figure which such a wave travels, may be found by equating the cosine argument in (3) to the constant value and by taking the time derivative of the projection of the vector radius r on the wave vector $\varkappa$

$$v = -\frac{1}{|\varkappa|}\frac{d\varkappa r}{dt} = -\frac{\Omega}{|\varkappa|}. \tag{6}$$

The direction of the intensity wave travel is determined by the vector $\varkappa$, the wave travels either in the direction of the vector $\varkappa$, or in the opposite direction. The sign of travel can be found by the following reasoning: If $|\boldsymbol{k}_1| > |\boldsymbol{k}_2|$, then the value of $\Omega = \omega_2 - \omega_1$ is negative, and, in accordance with (6), the derivative of the wave point vector radius projected into the intensity wave vector $\varkappa$ will be positive, i.e. the wave will travel in the direction indicated by the arrow of the vector $\varkappa$. Conversely, if $|\boldsymbol{k}_1| < |\boldsymbol{k}_2|$, the wave will travel in the opposite direction. As it is seen from the figure this rule leads to conclusion that the intensity wave travels in the general direction of the electromagnetic wave, which is characterized by the larger absolute value of the wave vector $\boldsymbol{k}$.

Let us assume that the intensity travelling wave is propagating in a certain medium whose molecules possess the natural oscillation frequency ω_0. Then it is possible to express the intermolecular oscillations through the following equation (2):

$$\ddot{\xi} + \beta\dot{\xi} + \omega_0^2\xi = \frac{1}{m}F = \frac{1}{m}\frac{\partial\mu}{\partial\xi} = \frac{1}{2m}\frac{a}{\partial\xi}I(r), \tag{7}$$

where ξ — oscillation coordinate, β — damping constant, m — mass of molecule, F — driving force, U — potential energy, a — polarizability of molecule, $I(r)$ — intensity of acting field.

If the intensity $I(r)$ is defined by (3), then, in the case when the frquency of the intensity field oscillations is near to the resonance frequency and the damping β is small, the solution of the equation (7) takes the following form:

$$\xi = \xi_0 + \frac{1}{2m}\frac{\partial a}{\partial\xi}a_1 a_2\cos\left[\varkappa r + \Omega t + (\varphi_1 - \varphi_2) - \frac{\pi}{2}\right]. \tag{8}$$

Deviation of ξ from ξ_0 results in an increment of polarizability $\Delta a \approx \xi(\partial a/\partial\xi)$, which will be proportional to the deviation of the permittivity ε from the undisturbed value, at small values of a.

Considering these relations, we obtain:

$$\varepsilon = \varepsilon_0 + \Delta\xi\cos\left[\varkappa r + \Omega t + (\varphi_1 - \varphi_2)\frac{\pi}{2}\right]. \tag{9}$$

Comparing (9) with (3), we find that the intensity travelling wave induces a dielectric constant travelling harmonic ε in the medium, and by the same means it induces a refractive index harmonic n, which travels at a velocity similar to that of the intensity wave, while lagging behind the latter by a quarter of a period.

Steabler and Amodei [3], who investigated the process of recording the simple three-dimensional hologram in the crystal of lithium niobate, proved both experimentally and theoretically that a refractive index harmonic, which is shifted by a quarter of a period with respect to the generating two-wave interference pattern, possesses the property of performing a directional transfer of energy from one of these waves into another. The mechanism of such transfer is rather simple (see figure). It is not difficult to understand that the result of the interaction between the light and the refractive index harmonics is determined by the processes occurring in the areas of maximum light intensity, i.e. on the surfaces of the travelling wave antinodes. Due to the fact that the refractive index harmonics lags behind the intensity harmonic by a quarter of a period, the surfaces of antionodes fall within refractive index distribution slopes decreasing in the direction of the wave movement (see the graph in the left hand part of the figure).

The diagram of the interaction between the refractive index harmonic and the "blue" and "red" waves, $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$, which form the intensity travelling harmonic, is shown in the right part of the figure. The waves, which are characterized by $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$, meet on the surface of antinodes AB at equal phases and both waves are reflected from the interface of two media, which are featured by different refractive indices. The medium possessing the lower value of n is above the line AB, while the medium possessing the higher value of n is below this line. As it is seen from the figure, the reflection conditions of the waves having the wave vectors $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ are different. The "blue" wave $\boldsymbol{k}_1$ is reflected from the medium possessing lower refractive index and does not change its phase. That is why it is transformed into the wave $\boldsymbol{k}_1^1$, which is in phase with the "red" wave $\boldsymbol{k}_2$ which, in turn, has passed directly through the interface AB. It is obvious that the waves $\boldsymbol{k}_1^1$ and $\boldsymbol{k}_2$ will amplify each other in the process of interference. The "red" wave $\boldsymbol{k}_2$ is reflected from the interface AB, like from the more dense medium, and looses half of its wavelength. As a result, this wave is transformed into the wave $\boldsymbol{k}_2^1$ which is in antiphase with the "blue" wave $\boldsymbol{k}_1$, which passed directly through the interface AB. Such waves, being added, attenuate each other. Thus, it is easy to see that the approach used led to the well known result, the energy of the blue anti-Stokes wave is pumped into the red Stokes component.

The fact that the process of the stimulated Raman sccattering of two interacting waves can be considered as a process of formation of the dynamic shift three-dimensional hologram, allows to employ the theory and the ideas, which have been developed in the art holography earlier. The study [4] has disclosed, among others, that the shift phase hologram may perform complete energy transfer from one plane wave to another.

This result was obtained by taking account of the dynamic character of the process, i.e. the fact that the proper hologram is changed due to redistribution of energy between the two waves, as they pass through the body of the hologram. In the study [5] the case of dynamic transformation of waves possessing complex wavefronts is discussed, and the conditions, under which the distortions of wave transformed become minimum, are specified. In general terms, these conditions indicate the necessity of using a sufficiently thick hologram. In study [1] the apparent infringement of the conditions for mutual wave transformation are discussed. In particular, the intensity wave front AB does not coincide with the bisector ab of the angle confined between the vector $\boldsymbol{k}_1$ and the vector $\boldsymbol{k}_2$ and it seems at first sight that this circumstance prevent the transformation of the wave $\boldsymbol{k}_1$ into the wave $\boldsymbol{k}_2$. In fact, these infringements are precisely compensated by the relativistic departures from the law of mirror reflection, when we shall take account of the fact that the mirrors are travelling with a certain velocity.

Proceeding from the studies listed, it can be concluded that when the intensity travelling waves are being recorded in a medium capable of the induced Raman scattering, then it is possible to perform a complete energy transfer between two waves and obtain the amplified output wave of the prescribed waveform.

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Отображающие свойства бегущих волн интенсивности и их возможные применения

Рассмотрены свойства объемной записи бегущей волны интенсивности, образованной в результате интерференции двух волн с различными частотами. Показано, что когда такая бегущая волна записывается в среде, способной к вынужденному комбинационному рассеянию с резонансной частотой, точно равной разности частот интерферирующих волн, образуется так называемая сдвиговая динамическая голограмма. Такая голограмма обеспечивает эффективный перенос энергии от одной из интерферирующих волн к другой, поскольку сдвиг в этом случае точно равен четверти периода. Представлено простое объяснение процесса переноса энергии в сдвиговой голограмме.