Experimental observation of spatial resonance in a speckle field with variable refractive index

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The shift in the angular selectivity curve of a holographic grating caused by spatial resonance between the speckle field and variations in the refractive index is recorded experimentally.

Interest has increased recently in the linear and nonlinear optics of speckle fields,[1] i.e., directed fields produced by a monochromatic laser source whose spatial structure undergoes large fluctuations described by Gaussian statistics. These fields have been found to have many interesting properties. For example, the surfaces of the speckle field wavefront have a rather complicated topology—dislocations occur where the amplitude of the speckle field vanishes.[2] Moreover, if the spatial structure of the speckle beam intensity is "materialized" in a light-sensitive medium (e.g., in the photolayer of a volume hologram or in an optically nonlinear medium), spatial resonance may occur between it and the induced inhomogeneities in the field traveling along the medium.[3,4] Such resonant waves (called specklons in Refs. 4, 5) are responsible for various physical effects, such as wavefront inversion during stimulated scattering,[3,4] reversal of the direction of dynamic energy transfer during self-diffraction of two beams,[5] and shifts in the spectral angular selectivity curve during the reconstruction of volume holograms.[6] In this paper we discuss the results of an experiment designed to verify the specklon theory for material with a pure phase photoresponse.

If a light beam $E(r,z)$ propagates in a medium whose dielectric permittivity $\varepsilon = \varepsilon_0 + \delta\varepsilon(r,z)$ fluctuates randomly, we can neglect the distortion of the beam caused by light scattering by the inhomogeneities $\delta\varepsilon$ if $RL \approx (\langle\delta\varepsilon^2\rangle\Delta z/\lambda^2)L \ll 1$ (Ref. 7). Here R is the extinction coefficient, L is the path length of the beam in the medium, λ is the wavelength, and Δz is the correlation length of the variations along the direction z of wave propagation. In this case, one must allow for possible correlation between the beam field and the spatial structure of the inhomogeneities. If the latter are induced by the speckle wave field $E_0(r,z)$: $\delta\varepsilon = \beta|E_0|^2$, then the effective permittivity ε_{eff} seen by the beam $E(r,z)$ is sensitive to the spatial structure of the beam. If the structure of the speckle beam field coincides with the structure of the field inducing the inhomogeneities ($E \sim E_0$), then the average dielectric permittivity (weighted by the local intensity) is given by

$$\varepsilon_{\text{eff}} = \varepsilon_0 + \langle\delta\varepsilon|E|^2\rangle/\langle|E|^2\rangle = \varepsilon_0 + \beta\langle|E_0|^4\rangle/\langle|E_0|^2\rangle = \varepsilon_0 + 2\langle\delta\varepsilon\rangle$$

and differs from the spatial average $\varepsilon_0 + \langle\delta E\rangle$, which corresponds to beams E for which $\langle EE_0^*\rangle = 0$, i.e., for which the inhomogeneity and beam structures are uncorrelated. The enhanced influence of inhomogeneities $\delta\varepsilon$ in spatial resonance with the field structure causes the gain of the backward component of the Stokes wave to increase during stimulated scattering of the pumping speckle fields.[3,4]

The present work is concerned with experimentally observing spatial resonance of a speckle field in a material with light-induced refractive index inhomogeneities $\delta\varepsilon$. For media with phase inhomogeneities, spatial resonance alters the phase velocity of the speckle wave by an amount too small to permit easy direct measurement. However, the additional phase shifts which accompany the change in wave velocity can be converted into easily measurable wave intensities by rescattering the waves with a reference wave in a static (or dynamic) holographic grating.

In the experiment we studied the efficiency of diffraction of a plane wave in a static, three-dimensional holographic grating. The grating was stored in reoxan[8] by using a speckle wave $A(r,z)$ and a plane reference wave B. Both beams were incident on the same side of the photolayer at an angle $\theta \approx 0.2$ rad symmetric about the normal to the layer. The linear absorption of the sample, of thickness $L = 1$ mm, was less than 10% at the wavelength $\lambda = 0.63\,\mu$m of the He-Ne laser. The spectral width $\Delta\theta_A \approx 0.15$ rad of the speckle wave was found from the transmission of the plane wave through a frosted plate; the condition $L \gg \Delta z \sim \lambda/\Delta\theta_A^2 > \lambda/4\theta^2$ for the hologram to be three-dimensional[9] was therefore satisfied by a comfortable margin. A diaphragm of diameter 3 mm mounted right at the photolayer limited the diameter of the interaction region during writing and readout.

In order to eliminate extraneous effects, the writing had to be done under static conditions. However, the storage process in reoxan is time-dependent: $\delta\varepsilon \sim \int^t |E_0|^2 dt'$, and dynamic energy transfer between the beams can rotate the holographic grating during the writing process and is usually significant for plane-wave gratings.[10] We avoided self-diffraction effects by making the speckle wave some 15 times more intense than the plane wave. The interaction among the writing waves in the grating doubles the contribution of the speckle wave intensity to the effective permittivity seen by the reference wave[11]; however, this is almost completely offset by the spatial resonance, which doubles the strength of the speckle wave self-interaction. The effective dielectric permittivities thus remain the same for both waves and the grating does not rotate during the writing process. The absence of dynamic effects for beam intensities chosen as above was verified experimentally—in all cases, the measured

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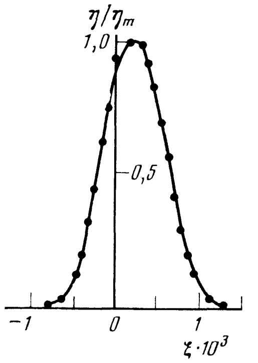

FIG. 1. Relative diffraction efficiency η/η_m as a function of the rotation angle ξ of the reading reference wave.

change in the intensity ratio of the writing beams after passage through the hologram was less than 10%.

Figure 1 shows a typical experimental curve for the diffraction efficiency η for plane wave → speckle wave scattering in a static holographic grating as a function of ξ, the angle between the read-out beam in the plane of incidence and the reference beam during the writing process. The peak efficiency (expressed as a ratio) was less than $\approx 12\%$, which corresponds to a peak average exposure of ≈ 3 J/cm^2 during the writing process. The image was read at the same wavelength $\lambda = 0.63$ μm. The peak in the angular selectivity curve was found to be shifted relative to the direction of the reference beam during the writing (this direction corresponds to maximum η for a static plane-wave volume hologram when there is no self-diffraction during storage).

This shift, which was predicted in Ref. 6, is caused by the spatial resonance of the speckle wave excited in the photolayer during readout with the fluctuations in $\beta|A|^2$. Because the structure $B(AB^*) \sim A(r,z)$ of the speckle wave is correlated with the inhomogeneities, the effective permittivity of the photolayer for the speckle wave is $\Delta\varepsilon = \beta < |A|^2 >$ higher than for the plane reading wave, for which $\varepsilon_{\rm eff}$ is given by its spatial value. Because the waves interacting in the grating do not propagate symmetrically, there is a Bragg mismatch $\Delta k \approx \pi\Delta\varepsilon/\lambda\varepsilon_0^{1/2}$; this is offset by the negative mismatch $\Delta k \approx -2\xi\theta(2\pi\varepsilon_0^{1/2}/\lambda)$ produced by the additional inclination of the readout direction. These two mismatches cancel completely when the inclination angle $\Delta\xi$ is equal to $\Delta\varepsilon/4\theta\varepsilon_0$.

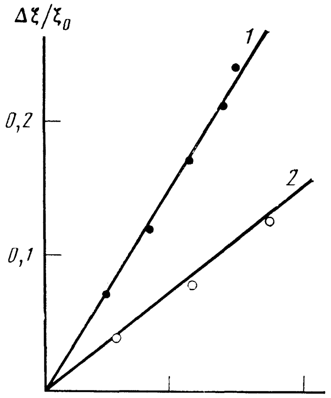

FIG. 2. Dependence of the relative shift $\Delta\xi/\xi_0$ on $\eta_m^{1/2}$.

Figure 2 shows experimental data for the angular shift in the peak angular selectivity as a function of $\eta_m^{1/2}$ (the shift is divided by the halfwidth $\xi_0 = \lambda/2L\theta\varepsilon_0^{1/2}$ of the selectivity curve, where $2\xi_0$ is the distance between the first zeros of η on either side of the peak). The theoretical result $\Delta\xi/\xi_0 = (\eta_m^{1/2}/2\pi)(<|A|^2>/|B|^2)^{1/2}$ is also shown (curve 1). Both the absolute values and the functional dependences of the theoretical and experimental results are found to be in good agreement.

For comparison, Fig. 2 also shows the experimental points and the theoretical curve 2 for the magnitude of the shift in the selectivity peak for a grating recorded by plane wave with roughly the same intensity ratio ≈ 13 as before. In this case the shift is caused by self-diffraction-induced rotation of the holograhic grating, which can as much as double the intensity of the weak reference wave during the writing process. The rotation angle of the resultant static grating depends on the additional phase shift (averaged during the exposure), which increases linearly with time and is therefore only 50% of its value at the end of the exposure.

We have thus for the first time experimentally recorded the shift in the peak angular selectivity of a holographic grating produced by spatial resonance between a speckle field and refractive index inhomogeneities.

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