DETECTION OF A COHERENT LIGHT SOURCE IN STRONGLY SCATTERING MEDIA

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An experimental method of processing of an optical signal transmitted through a stochastic medium is proposed. The method is reduced to modulation of a received radiation with a phase knife–edge plate incerted into a telescopic system. By way of example, the experimental results on detecting a laser beam scattered by optically dense screens are given. It is shown that the direction toward the radiation source is determined quite reliably at optical thicknesses $\tau < 12$, with a coherent radiation intensity being half as many as the scattering background.

When a coherent optical radiation propagates through light scattering media, at large optical thicknesses a limiting thickness exists at which a reference light wave is no longer observed due to superposition of the scattered field. At the same time, even though the wave transmitted through the medium and the scattered wave are compared in their amplitudes (criterion for detection based on brightness contrast), the physical parameters still persist by which they can be discriminated.

In this paper we consider the feasibility of detecting an incident coherent radiation by curvature of its wavefront in the special case in which the scattering background forms a speckle structure. Such speckle structures appear, e.g., when an image is reconstructed from a hologram.[1]

Actually, the scattered radiation is a random combination of spherical waves, whereas the coherent radiation has, as a rule, a plane wavefront which arrives at the observation point from a fixed direction. In a telescopic system these waves are focused in different planes thereby allowing us to act upon one of the field components.

If we restrict ourselves to the scattering media in the form of localized layers, the problem will be solved in a rather simple way. In this case the image plane of a layer can be found in which the scattered waves are focused, while the unknown coherent wave is localized in some region. If a phase knife–edge plate is placed in this plane, the coherent radiation at the point of its image will be modulated. At the same time the phase of spherical waves will change as a whole, that may not produce a noticeable effect in the observation plane.

Thus to detect the coherent radiation transmitted through a layer of the scattering medium, it is suggested to modulate radiation with a phase knife–edge plate in the image plane of the layer of the medium. Such a phase modulation of the field was proposed in Ref. 2 to measure the small–scale fluctuations of a field transmitted through a randomly inhomogeneous medium.

We investigated experimentally the suggested optical scheme (Fig. 1). A collimated light beam of an LG–38 laser (at the wavelength $\lambda = 0.63$ μm with $d = 6$ mm and linearly polarized radiation) was used as an object to be detected. The scatterers were the screens made of oiled tracing paper with small random holes perforated in them. A telescope had two lenses with $F = 100$ mm and $f = 72$ mm. The screen was placed at the distance $z = 455$ mm from the objective and the phase knife–edge plate was placed between the focal plane and the short–focus lens. The observation was performed at large distance $R = 5.89$ m from the output lens of the telescope, so that the observation plane was the image plane at linear magnification $m = R/f = 82$. A Kastler plate oriented at the angle $\varphi = 45°$ to the polarization plane was used as a phase knife–edge plate. A system of image recording was constructed based on the FPU–14 photodiode matrix (32×32 elements spaced at 250 μm) the data from which entered the Elektronika–60 computer.

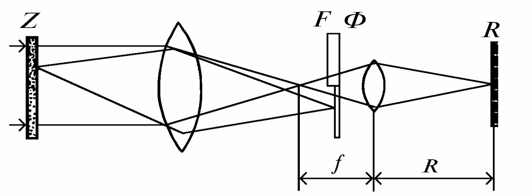

FIG. 1. Optical scheme of the experimental setup.

Before proceeding to the description of experimental results, let us discuss the validity of modeling a layer of the scattering medium by a screen made of oiled tracing paper with random small holes perforated in it. A coherent wave transmitted through a scattering medium is known to be attenuated exponentially. Its intensity is equal to

$$I_c = I_0 \exp(-\tau), \tag{1}$$

where I_0 is the incident wave intensity and τ is the optical thickness of the scattering medium. The radiation intensity at a random point behind the medium is a sum of both coherent (1) and incoherent or scattered I_s components

$$I = I_c + I_s . \tag{2}$$

In problems on detecting the radiation sources the main parameter is the ratio of these values

$$U = I/I_s = 1 + I_c/I_s . \tag{3}$$

In optical systems forming the image of radiation source the quantity U is referred to as brightness contrast.

The problem on detecting the coherent radiation sources is complicated by a chaotic speckle structure observed in the image plane. It is depicted, e.g., in Fig. 2. Here, even with relatively high brightness contrast of the source it is difficult to separate out the image of the source against the background of the speckle structure.

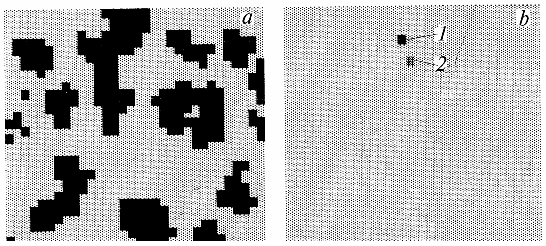

FIG. 2. Example of determining the coordinates of the coherent radiation source: a) speckle structure of the image of laser source ($I_c/I_s = 0.46$, $\tau = 12.5$); b) coordinates of the initial (1) and detected (2) beams.

In our experiments the coherent radiation was primarily formed due to radiation propagated through random holes in the screens. Nevertheless, the concept of optical thickness introduced by formula (1) was also used as a characteristic of the screen transparency. The intensity I_s was produced by light scattered after passage through the optically dense tracing paper. It should be noted that the optical thicknesses in the experiments reached large values ($\tau > 10$); therefore, to detect the incident radiation intensity I_0, a dense filter with the transmission $\exp(-10)$ was used.

In a random pattern representing speckle structure observed in the receiver plane, a characteristic size of individual spots, referred to as individual speckles, was $l = 0.83$ mm, so that in the plane of location of the phase knife–edge plate they had the size $l_f = 10$ μm.

As a result of transverse displacement of the phase knife–edge plate in the plane of the scattering screen image Φ, the phase plate edge modulates the amplitude of coherent wave. In this case within the characteristic dimensions of individual speckles l there occurs redistribution of brightness in the vicinity of the point of the source image. That is, the brightness at the receiver image point changes strongly, while the remaining speckle pattern fluctuates much weaker.

To illustrate the efficiency of the examined method, we restrict ourselves to measurements with two positions of the phase knife–edge plate. Needless to say that this resulted in the spread of the reconstructed coordinates of the source within an individual spot of speckle structure.

The measurement procedure was as follows. The image of initial beam was previously recorded in order to determine its coordinates (x_0, y_0) and intensity I_0. Then we inserted a scattering screen and doubly recorded the image of the speckle–structure in the form of a 32×32 frame. First, we measured $I_1(x, y)$ without the phase knife–edge plate. In the second case the knife–edge plate bisected the wavefront and we measured $I_2(x, y)$.

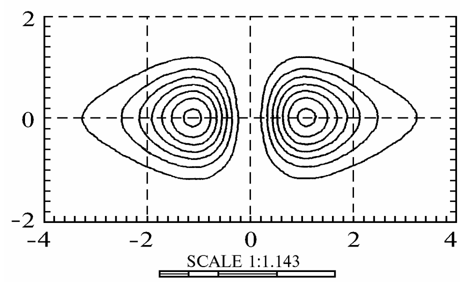

FIG. 3. Intensity distribution of the Gaussian beam modulated by the phase knife–edge plate.

It is clear that in the second case the coherent wave was fully suppressed at the point of the source image, i.e., on the optical axis, due to the phase shift by π. Depicted in Fig. 3 is the intensity distribution $I_0(x, y)$ observed in the image plane without a scattering medium.

The brightness contrast U [see Eq. (3)] was determined in terms of the first image $I_1(x, y)$ by the formula

$$U = I_1(x_0, y_0)/\langle I_1(x, y)\rangle , \tag{4}$$

where an averaging denoted by angular brackets was made over the region excluding the vicinity of the image point (x_0, y_0) whose dimensions were of the order of an individual speckle.

Using both frames, we find the value

$$K(x, y) = \frac{|I_1(x, y) - I_2(x, y)|}{I_1(x, y) + I_2(x, y)}, \tag{5}$$

which characterizes the speckle–structure fluctuations and is called the modulation contrast. The use of this one (to determine the coordinates of the source image) in place of the brightness contrast is called the method of modulation contrast.

In the method of modulation contrast the radiation source coordinates are determined as coordinates of a point of the speckle structure at which the change of the intensity is maximum

$$K(x_c, y_c) = \max. \tag{6}$$

Figure 2 illustrates the case of limiting detection of a coherent source for a scattering screen with optical thickness $\tau = 12.5$. In Fig. 2*b*, $x_0 = 7$, $y_0 = 15$ are the coordinates of the initial beam and $x_c = 4$, $y_c = 14$ are the coordinates of the detected beam. An error in determining the coordinates was 3.16 of matrix graduation which is smaller than the characteristic size of individual speckle $l = 3.33$.

For screens with large optical thickness, the coordinates of the point $K(x, y) = \max$ became chaotic, i.e., the source image was no longer reconstructed. To study the applicability limit of the aforementioned method, we first measured the maximum value of K for a screen with large optical thickness $\tau > 12$ for which the coherent portion of intensity (1) can be neglected. Depicted in Fig. 4 is a plot of K vs longitudinal displacement of the phase knife–edge plate. As seen from the figure, the effect of the phase knife–edge plate on the scattered radiation intensity I_s minimizes when the plate is placed in the image plane of the scattering screen. In this case the minimum modulation contrast is equal to 0.24 and obviously determines the level of noise which is peculiar to the given experimental setup.

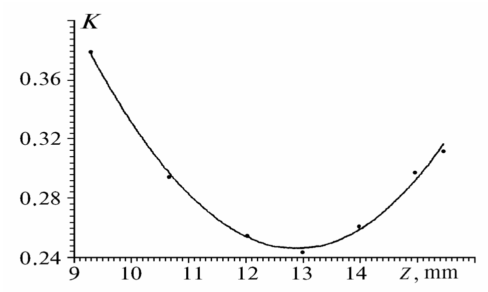

FIG. 4. Modulation contrast level vs longitudinal position of the phase knife–edge plate for an optically dense scattering screen.

Let us show that it is the noise level for $K = 0.24$ which determines the foregoing limitation on the value of the screen optical thickness $\tau < 12$. To do this, we studied experimentally the brightness and modulation contrasts at the point of the source image for screens with different optical thicknesses increasing from $\tau = 9.7$ to $\tau = 12$.

It should be noted that in an ideal situation in which the coherent portion of the intensity is fully suppressed due to the phase knife–edge plate and the incoherent portion does not change, we obtain

$$U = (I_c + I_s)/I_s , \qquad K = I_c/(I_c + 2I_s) . \tag{7}$$

As a result, the parameters U and K are related by the simple expression

$$K = (U - 1)/(U + 1). \tag{8}$$

Figure 5 shows that the screens with the optical thicknesses within the examined range satisfy this relation.

Both quantities K and U entering into Eq. (7) are determined by the same parameter, namely, by the ratio of coherent and scattered portions of the intensity I_c/I_s at the point of the source image. Moreover, the procedures of measuring K or U can be used for independent determination of the absolute values of I_c and I_s. For example, by the procedure of measuring the brightness contrast the coherent portion of the intensity is found by simple subtraction of the intensity at the point of the source image and in its vicinity

$$I_c = I_1 - \langle I_1 \rangle. \tag{9}$$

In the experiment we used this procedure to determine the optical thicknesses of the screens using Eq. (1). To do this, we used the measured value of the radiation intensity I_0 without a screen.

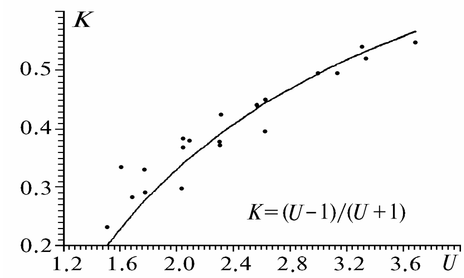

FIG. 5. Modulation contrast vs the brightness contrast.

With the increase in the optical thickness of screens, both modulation and brightness contrasts reduce due to the increase in the ratio I_s/I_c. In particular, it follows from Eq. (7) that

$$K = 1/(1 + 2I_s/I_c). \tag{10}$$

Figure 6 depicts the experimental values of modulation contrast for screens with different optical thicknesses. The modulation contrast is seen to reduce to the noise level $K = 0.24$ at $\tau = 12$. This restricts the feasibility of determining the source coordinates by optical thicknesses $\tau < 12$ in the above–described experiment.

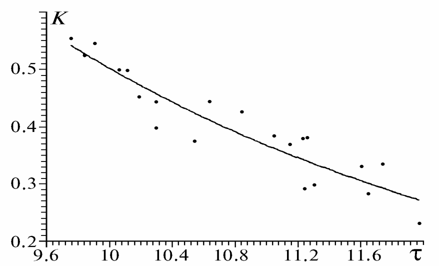

FIG. 6. Modulation contrast vs the optical depth.

Thus we have shown the efficiency of the method of modulation contrast for determining the coordinates of a coherent radiation source against the background in the form of speckle structures. In this case the potential of the experimental setup was limited by optical thickness $\tau = 12$.

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2. A.G. Borovoi, N.I. Vagin, V.V. Demin, et al., Opt. Atm. **1**, No. 4, 53–56 (1988).