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Abstract: Open channels are peculiar incidents modes that are transmitted by a diffusing medium with high efficiency (up to 100%). Digital holography is used to analyze the correlations of the transmitted field, and to test open channel theory. Quantitative agreement is obtained.

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1. Introduction

”Consider radiation passing through a slab of material. In the absence of disorder, energy flows in an orderly fashion and is distributed among a set of modes or channels defined by the angle of incidence, which remains constant as the light propagates through the slab. Break up the slab into random pieces and the orderly progression of energy is disturbed: the modes are mixed up; lots of energy is scattered back to where it came from and if the disorder is really bad very little energy makes it to the far side of the slab [1]”. Although true in most cases, this limitation of transmission can be overcome by using open channels. Indeed, Dorokhov et al. [2] says that peculiar mode of the incident field, called open channels, are transmitted through a diffusing medium with high efficiency. Neglecting absorption, up to 100% of the incident energy can be transmitted.

Although many experiments have been made to control the structure of the incident field in order to prepare open channels [3–6], this theoretical prediction of Dorokhov, made more than 25 years ago, have not been yet verified quantitatively. Indeed, the number of channels to control is too large. To test the open channel theory, we have considered another Dorokhov’s prediction. If T is the average transmission, N_1 the size of the basis od modes that sustains the field outgoing from the sample, and N_2 the number of modes that effectively transmit energy, one must have:

$$N_2 = (3/2)TN_1 \tag{1}$$

We have tested experimentally this prediction by measuring correlations on the outgoing field with digital holography. The agreement we got is very good.

2. Setup

Figure 1 shows the holographic setup we used to measure correlations. The diffusing sample S is a ZnO powder slab with thickness $l = 22\ \mu$m deposited on a microscope cover slide. In order to maximize the collection of both input and output fields, the sample is positioned between two microscope objectives: MO1 (NA = 0.9 air, x60) in the powder side, and MO2 (NA = 1.4 oil, x60) in the cover slide side. A tank (DL) filled with viscous diffusing liquid is positioned in front of MO1 to randomize the illumination field in both time and space. The outgoing field E_2 interfere with two orthogonally polarized reference beams $R(p)$ whose off axis angles are slightly different. It is then possible to extract E_2 from the interference pattern that is recorded by the camera.

3. Holographic results

To extract the complex amplitudes $E_2(p)$ of the outgoing field for both polarizations $p = 1,2$, we have reconstructed holograms in the MO2 pupil plane. The 1340×1040 recorded frames were cropped to 1024×1024, two phase holograms were calculated with successive frames and holograms are reconstructed in pupil plane. Figure 2 (a,d) shows

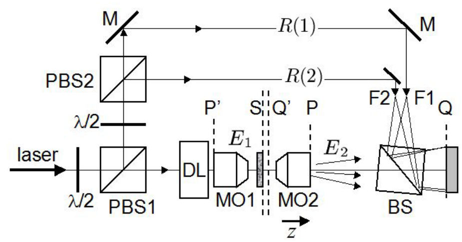

Fig. 1. Experimental setup. E_1: incoming field; E_2: outgoing field; $R(1)$, $R(2)$: reference fields of polarization p=1 and p=2; PBS1, PBS2: polarized beam splitters; $\lambda/2$: half wave plate to control E_1, $R(1)$ and $R(2)$ respective power; BS: beam splitter; M: mirror; DL: diffusing liquid; MO1 and MO2: microscope objectives; Q, Q': camera plane, and camera conjugate plane with respect to MO2; S: sample outgoing plane. P' and P: MO1 and MO2 pupil planes.

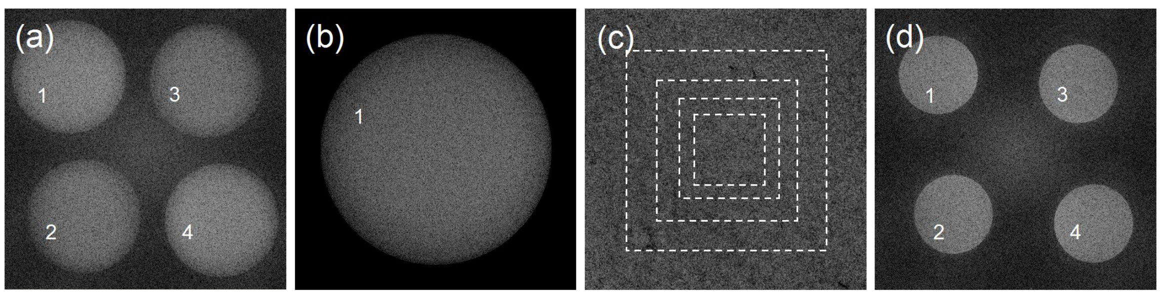

Fig. 2. (a,d) Reconstructed image made in MO2 pupil plane. (b) Zoom of the bright zone 1 of (a). (c) Field in the sample plane for polarization $p = 1$ obtained from bright zone 1. Images a,b,c were obtained with a ZnO sample and image d without.

the holographic images of the pupil for polarization $p = 1$ and 2 and for grating orders ± 1. Since the curvature of the reference field fits with the pupil to camera distance, the reconstruction is made by a simple Fourier transform, and the ± 1 and $p = 1, 2$ images are all on focus. Figure 2 (a) is made with a diffusing sample, and the pupil size corresponds to the numerical aperture of MO2 (NA=1.4). Figure 2 (a) is made without sample, and the pupil size corresponds to the MO1 pupil (NA=0.9), whose image is in focus because MO1 and MO2 form an afocal optical system.

4. Correlation results

From the measured outgoing field $E_2(x, y, t, p)$ (where x, y are the transverse coordinates, t the time, and $p = 1, 2$ the polarization), we have measured the 2 times correlation :

$$K_2(t, t') = \frac{\sum_{x,y,p} E_2(x, y, t, p) E_2^*(x, y, t', p)}{\sum_{x,y,p} |E_2(x, y, t, p)|^2} \quad (2)$$

and its statistical average $\langle |K_2|^2 \rangle$. One can show that $\langle |K_2|^2 \rangle$ is related to N_2 by: $N_2 \langle |K_2|^2 \rangle = 1$. Measuring N_2 or $\langle |K_2|^2 \rangle$ is thus equivalent.

To obtain an extra control parameter, the MO2 position along z was adjusted by a motorized micrometer device. For $z \sim 0$, the camera conjugated plane Q' coincides with the exit plane S of the sample, and the S plane is in focus on the camera. This configuration maximizes the correlations due to open channels. When $z \neq 0$ increases, the measurement plane Q' no longer coincides with S and $\langle |K_2|^2 \rangle$ decreases. Controlling z is thus an experimental way to decrease and even eliminate the open channel correlations. This is expected to occur when z becomes much larger than the transverse size of the sample L, which can be varied by truncating the recorded holograms.

In Fig. 3, we plotted $M^2 \langle |K_2|^2 \rangle / 1024^2$ as a function of the MO2 position z, and as a function of the size M in pixels of the truncated zone of the hologram. For $M = 1024$, $L = 77 \mu$m. The plots are made for $M = 1024$ (red diamonds),

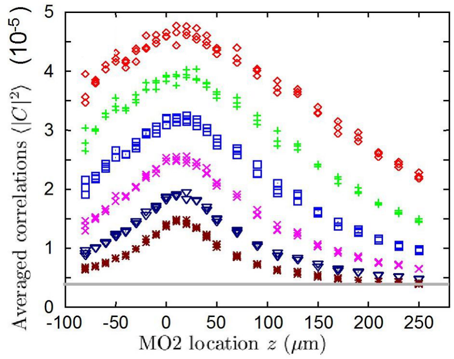

Fig. 3. Averaged correlation $\langle |K|^2\rangle$ measured with ZnO plotted as function of MO2 position z. Calculations are made with $M \times M$ pixels with $M = 1024$ (red diamonds), 362 (green crosses), 256 (bleue rectangles), 181 (purple crosses), 128 (dark blue triangles) and 90 (brown stars). Solid grey line is $1/N_1 = 3.83\ 10^{-6}$.

362 (green crosses), 256 (blue rectangles), 181 (purple crosses), 128 (dark blue triangles) and 90 (brown stars). As expected $\langle |K_2|^2\rangle$ is maximum for $z \simeq 0$, and decreases with $|z|$. When the sample size M decreases, the geometrical losses increase, and one observes a decrease in $M^2\langle |K_2|^2\rangle/1024^2$. Moreover, the peak of correlation becomes narrower, and the correlation reaches a plateau for small M and large z (*e.g.* $M = 90$ and $z = 250$ μm). This plateau is reached when geometrical losses are large, i.e. when $z \gg L$.

We compared this plateau with the correlation $\langle |K_1|^2\rangle = 1/N_1$ that would be expected without open channels. The usual relation that defines the number of geometrical modes N_1 should be corrected here to account for the refractive index n of the medium in which the output field is collected (factor $\times n^2$), and for the detection solid angle (factor $\times[\mathrm{NA}]^2/n^2$) where NA is the numerical aperture of the detection objective. One thus gets:

$$N_1 = 2\pi[\mathrm{NA}]^2 L^2/\lambda^2 \tag{3}$$

where L is the transverse size of the sample and λ the wavelength in vacuum. For NA=1.4 and L=77 μm, we get $1/Ng = 3.83\ 10^{-6}$ (solid gray line on Fig.3) in good agreement with the plateau of correlation curves $M^2\langle |K_2|^2\rangle/1024^2$. This agreement validates our correlation-based theoretical approach and proves that we have correctly evaluated the number of geometrical modes by Eq.3.

To calculate the correlation that is expected without lateral geometrical losses of the slab sample, we have extrapolated the maximums of the curves of 3 to $L = \infty$. We got $N_1/N_2 = 18.6$ for $T = 1/25$. This result is in good agreement with Eq.1, since $(2/3)\ 25 = 16.6 \simeq 18.6$. It validates Dorokhov's open channel theory [2] .

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