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# Optical coherent detection through multi-scattering media by wave mixing cleaning effect in liquid crystal OASLM

UMBERTO BORTOLOZZO,<sup>1</sup> STEFANIA RESIDORI<sup>1,\*</sup>, FRANÇOIS RAMAZ<sup>2</sup>, JEAN-PIERRE HUIGNARD<sup>2</sup>

<sup>1</sup>HOASYS SAS, 120 route des Macarons, 06560 Valbonne, France

<sup>2</sup> Institut Langevin, ESPCI Paris, University PSL, CNRS, 1 rue Jussieu 75005 Paris, France

\*Corresponding author: [stefania.residori@hoasys.fr](mailto:stefania.residori@hoasys.fr)

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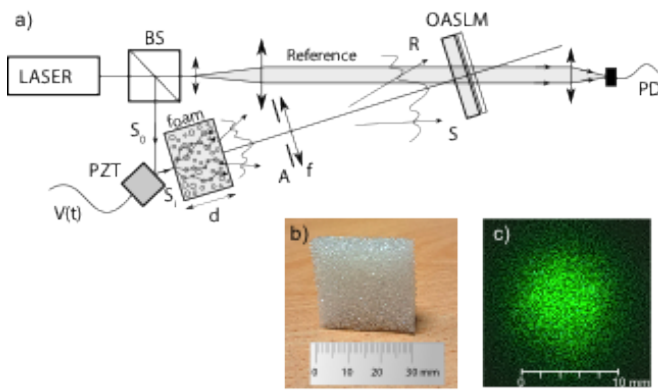
**Liquid crystal optically addressable spatial light modulators (OASLM) allow controlling the phase and amplitude of optical beams. By performing wave mixing in an OASLM we show that coherent phase detection can be achieved for light beams passing through highly scattering media, as foam layers with several cm thicknesses. Thanks to the adaptive response of our OASLM, the phase information on the speckle signal is transferred at the output of the OASLM to the plane wave reference beam, allowing the cleaning of optical distortions and the direct measurement of amplitude phase modulations with a small diameter single photodiode. A good signal-to-noise ratio is demonstrated for foam thickness up to 3 centimeters. These properties, together with the recently demonstrated sub-ms response time of our OASLM, make the method compatible to foreseen applications for imaging in biomedical tissues and turbid media.**

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Optical coherent detection requires measuring the phase with an interferometric setup, which implies superposing the optical wavefronts of signal and reference beams. When the interfering wavefronts are not spatially uniform a nonlinear medium allowing dynamic holography can be employed instead of a conventional beam-splitter [1]. The advantages of this approach are significant, as the nonlinear medium allows the interferometer to adapt to low frequency fluctuations, thus permits the detection without the need of active correction and filters out low frequency disturbances. In our setup we use a liquid crystal (LC) optically addressable spatial light modulator (OASLM), also known as liquid crystal light valve, as a Kerr-like nonlinear medium. Our OASLMs are realized by associating a nematic liquid crystal with a photoconducting substrate [2]. They can be used to perform wave mixing with a continuous reference (typical intensity of few mW/cm<sup>2</sup> in the green) and a much lower intensity (fractions of  $\mu$ W) speckled signal beam. The OASLM has been already used in a diversity of novel interferometric experiments and nonlinear applications, like adaptive holographic detection, slow light effects and vibration sensing (see, e.g., [2] and references therein). Wave mixing and adaptive interferometers have also been reported for an OASLM adapted to operate in the near infrared [3], showing the precise measurements of very small surface displacements [4]. The OASLM here employed has been optimized for wave mixing at wavelength of 532 nm and for sub-ms response time [5]. These

features make the device compatible with a speckle decorrelation times in the range of ms, thus, render it adapted for biomedical applications. Note that sub-ms LC OASLM were also developed in the past, for example with ferroelectric liquid crystals [6] or with electroclinic liquid crystals [7]. The aim of this paper is to demonstrate that, thanks to the nonlinear response of the OASLM, wave mixing provides a cleaning effect, allowing the detection of a temporal phase modulation on the signal after that it has been transmitted through a highly multi scattering thick medium, as a polyethylene foam of several cm thickness (see Fig.1). A temporal phase modulation is imposed on the signal before it enters into the foam layer. After propagation through the scattering medium the signal is transformed into a speckled beam S, which is sent onto the OASLM together with a plane reference wave R to perform the wave mixing. Thanks to the nonlinear interaction in the OASLM, the phase modulation on the input signal is transformed into intensity modulation, which is directly detected after the OASLM by measuring the intensity on the self-diffracted plane-wave reference beam with a single detector. Note that the term “self-cleaning” has been introduced for describing the transformation of multimode to monomode beams in Kerr and Kerr-like media/optical fibers [8-10]. This self-cleaning effect was also highlighted in several experiments with multimode fibers amplifiers and wave mixing in photorefractive nonlinear crystals [11,12]. In our setup the adaptive interferometer consists in a

homodyne detection where the OASLM is used instead of the beam-splitter. The nonlinear process occurring in the OASLM leads to the transformation of the multimode speckle signal into a monomode wave in the direction of the plane reference wave, following the beam coupling equations that characterize the wave mixing in a Kerr-like nonlinear medium (see, e.g. [2] and references therein). The wave mixing ensures the cleaning of the signal beam via the wave coupling and the consequent self-diffraction of the incident waves on the dynamic hologram. The diffraction of the speckled beam in the direction of the plane reference wave provides the conversion of the multimode speckles to a monomode homogeneous component and the transfer of the phase modulation in the direction of the plane reference wave, where the linear detection occurs via the photo-detector. These properties elucidate the cleaning effect, which allows eliminating the issues related to the moving speckles grains on the detector and enables the coherent detection of temporal phase modulations of the speckle signal with optimum signal to noise ratio.



**Fig. 1.** (a) Experimental setup. PZT: piezoelectric crystal for the phase modulation. PD: photodiode. The foam layer induces multiple scattering of the signal and generates a speckle beam  $S$  that interferes with the reference  $R$  in the OASLM. (b) Foam layer used as a scattering medium. (c) Speckle intensity of the signal after its passage through the foam medium.

The experimental setup is shown in Fig. 1. It consists of a single mode green laser and a holographic recording configuration in an OASLM. The laser wavelength is 532nm, total output intensity 150mW. The laser is attenuated so that the plane wave reference beam  $R$  has an intensity of  $2.5 \text{ mW/cm}^2$ . This reference wave interferes with a much low intensity signal beam, whose intensity on the OASLM ranges in typical values of  $2.5 \text{ } \mu\text{W/cm}^2$  to  $250 \text{ } \mu\text{W/cm}^2$ . The incident signal beam  $S_0$  whose diameter is 1mm is phase modulated by a PZT piezo mirror and propagates in a foam layer that induces multiple scattering of the incident signal wave. The foam layer is a bulk medium, composed of an expanded polyethylene (PE) foam sheet of closed cell type, density  $18\text{-}24 \text{ kg/m}^3$  and average cell size 0.3mm, cut in samples with thicknesses varying from 1 to 3 cm. Such a foam structure, made of small air bubbles in a polymer matrix, locally induces in its volume multiple light reflections and refractions. The resulting scattered speckle light is then projected through a lens (focal  $f=25 \text{ cm}$ ) on the OASLM whose transverse size is  $10 \times 10 \text{ mm}^2$ . An aperture  $A$  (diameter 1.5 cm) in the plane of the lens is used to control the

projected speckle size on the OASLM. The average speckle size on the OASLM is mainly determined by the focal length of the lens and by its distance from the scattering medium. The OASLM is made of a photoconductive  $\text{Bi}_{12}\text{SiO}_{20}$  (BSO) crystal, cut in the form of a thin plate, 1mm thickness, space charge diffusion length  $\sim 1 \text{ } \mu\text{m}$ , which transfers voltage due to the incident fringe pattern to a nematic liquid crystal layer,  $d_{LC} = 15 \text{ } \mu\text{m}$  thick. It permits to record highly efficient dynamic phase holograms due to a large self-induced index modulation of the LC molecules,  $\delta n = 0.2$  for contrast close to one. After their passage through the foam layer, the speckle waves interfere with the plane-wave reference beam (Fig.1). The angle between the reference and signal determines the spatial period of the fringes on the OASLM. The fringe spacing as well as the speckle grain average size are adjusted to match the holographic spatial resolution of the OASLM ( $\sim 20 \text{ } \mu\text{m}$ ). Note that, because of the weak intensity of the signal, the diffraction efficiency of the dynamic hologram is low and, even though in the Raman-Nath regime, only the first diffraction orders, corresponding to the self-diffracting signal and reference, respectively, are observed.

The propagation of a low intensity coherent signal in complex multi-scattering media is the object of several experiments based on wavefront shaping after measurement of the transmission matrix of the media [13,14]. For highly multi scattering slab medium, the propagation of the wave is described by a diffusion equation. For a very short laser pulse of energy  $E_{inc}$  ( $\text{J/cm}^2$ ) incident on the material at  $t = 0$  and negligible absorption, in the conditions of the experiment where  $L \gg z_0$ , with  $L$  the length of the medium and  $z_0$  a parameter of the order of  $\frac{2}{3}l$ ,  $l$  the average distance between the scattering centers, the detected average diffused light intensity  $I_{diff}$  ( $\text{W/cm}^2$ ) can be expressed as [15]:

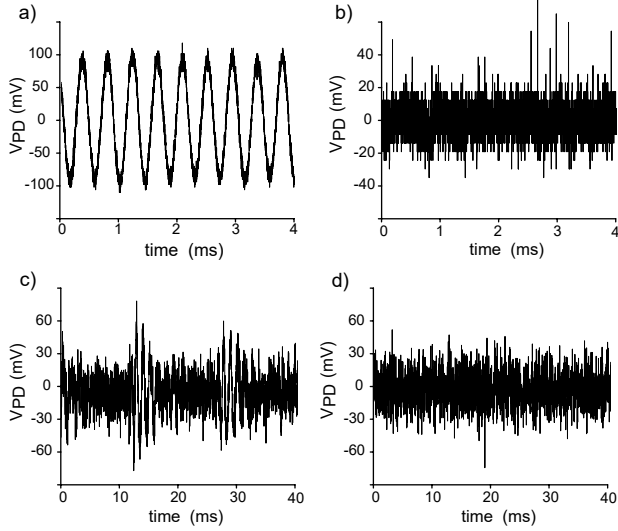
$$I_{diff} \sim E_{inc} \pi \frac{D}{d^2} \sin\left(\frac{\pi L}{d}\right) e^{-\frac{t}{\tau_{diff}}} \quad (1)$$

where  $\tau_{diff} = \frac{d^2}{\pi^2 D}$  is the diffusion time,  $D = \frac{cl}{3n}$  the diffusion coefficient,  $d = L + 2z_0$ . Eq.(1) illustrates the time dispersive properties of the multi-scattering media [16-19]. The objective of the experiment is to transmit an incident temporal phase modulated signal propagating through the scattering foam medium that induces both time dispersive properties and large spatial speckle pattern etendue. When the incident signal wave  $S \ll R$  is phase modulated with the piezo at frequency  $\Omega$  the field amplitude on the input face of the foam is of the form  $S_i = S_0 e^{i\delta\varphi \sin\Omega t}$  which can be written as a Bessel expansion series:

$$S_i = S_0 \sum_{-\infty}^{+\infty} J_n(\delta\varphi) \exp in\Omega t \quad (2)$$

If we operate in the experimental conditions of very low amplitude phase modulation  $\delta\varphi \ll 1$  at a frequency  $\Omega$  of several kHz,  $S_i$  can be approximated as  $S_i \sim S_0 [J_0(\delta\varphi) + 2ij_1(\delta\varphi) \sin\Omega t]$ . After propagation through the multi-scattering medium the detected signal on a photodiode of diameter 8 mm, detection bandpass of 2.4 MHz, shows that the incident modulated signal at frequency  $\Omega$  is fully blurred in a noisy structure arising from the random phase of each speckle grain (Fig. 2b). However, it is possible to recover the phase modulated signal on the carrier of a plane wave reference beam (Fig. 2a) by performing wave mixing between the reference and the speckle pattern interfering in the OASLM. In

most experiments with OASLM the detection is made in the direction of the multimode signal. Here the complex speckle signal wave is transferred in the direction of the plane-wave reference beam. The hologram is recorded by the interference of the two terms having the same laser frequency, respectively, the reference R and the speckle signal S term whose amplitude is  $J_0(\delta\varphi)$  and the OASLM has a local response with respect to incident fringes.



**Fig. 2.** (a) Sinusoidal phase modulation detected with the OASLM after 6mm of foam; (b) for comparison, the intensity measured on the photodiode without the OASLM. (c) Pulsed sinusoidal modulation detected with the OASLM after 25mm of foam; (d) for comparison, the intensity measured directly on the speckled signal.

The OASLM response time is of the order of 10 ms and it does not record the moving phase grating due to interference of R with the speckle signal terms amplitude  $2ij_1(\delta\varphi)S$  whose frequency is shifted by  $\Omega$ . This last signal contributes to a diffraction with  $\pi/2$  phase shift in the direction of the plane wave R. The OASLM acts as a nonlinear Kerr-like medium whose photo-induced index modulation is  $\Delta n = -n_2 \Delta I$  with  $n_2$  of the order of  $6 \text{ cm}^2/\text{W}$ . The amplitude  $\Delta\varphi_G$  of the holographic phase grating induced by interference of R and  $J_0(\delta\varphi)S$  can, thus, be written as [20]

$$\Delta\varphi_G = \frac{4\pi}{\lambda} d_{LC} n_2 |J_0(\delta\varphi)RS|, \quad (3)$$

where  $d_{LC}$  is the LC thickness and  $J_0(\delta\varphi) \sim 1$  in these conditions of small phase modulation. The intensity in the direction of the reference is given by the readout of the grating by the  $J_1(\delta\varphi)S$  wave. With the terms of interest, the detected intensity is given by

$$I = |R|^2 \left[ 1 + 4 \frac{S}{R} J_0(\Delta\varphi_G) J_1(\Delta\varphi_G) J_1(\delta\varphi) \sin(\Omega t) \right] \quad (4)$$

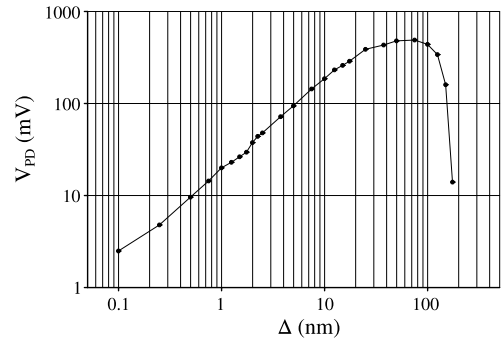
that for small amplitude grating,  $\Delta\varphi_G \ll \frac{\pi}{2}$ , and small phase modulation,  $J_1(\delta\varphi) \sim \delta\varphi/2$ , reduces to

$$I = |R|^2 \left[ 1 + \frac{4\pi}{\lambda} d_{LC} n_2 |S|^2 \delta\varphi \sin(\Omega t) \right]. \quad (5)$$

Eq. (5) outlines that for very small modulation depths at frequency  $\Omega$  the detected intensity leads to optimum linear detection of the form  $I = |R|^2 [1 + \alpha \delta\varphi \sin(\Omega t)]$ , with  $\alpha = \frac{4\pi}{\lambda} d_{LC} n_2 |S|^2$ .

The conventional On-Off response time of a nematic OASLM cell is dependent of the LC thickness and of the applied AC voltage. In the usual conditions it leads to time constants of the order of 10-200 ms. However, in recent operating conditions a sub ms response was achieved [5], thus being compatible with short decorrelation times of the speckle signal wave interfering with the reference. This is made possible by applying a high bias voltage and operating the OASLM in the transient mode effect. A fast ( $\sim$ ms) switching time can be obtained, despite the relatively thick  $d_{LC} = 25 \mu\text{m}$  LC layer, and a bias voltage of 60 Vrms, frequency of a few kHz.

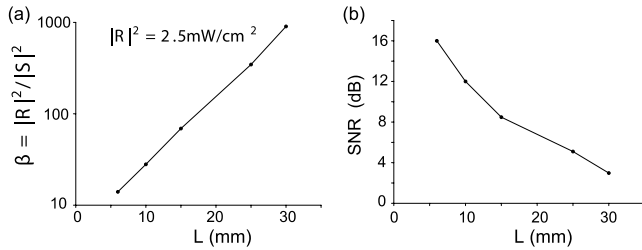
In Fig 2 (a) and (c) we show two examples of signal measured on the reference beam after the wave-mixing process has taken place in the OASLM. For comparison, in Fig.2 (b) and (d) are shown the signals detected by the photodiode when the OASLM is removed and replaced by a beam-splitter. In this case the signal is measured on the S beam, providing a conventional interferometer configuration. For the signals in (a) and (b) we use a sinusoidal phase modulation,  $f=2.345 \text{ kHz}$ . In (c) and (d) the modulating signal is a pulse sequence, frequency carrier 1.2 kHz, repetition rate 90 Hz. As shown in (a) and (c) the modulation is well retrieved on the signals measured on the reference after the wave mixing has occurred in the OASLM. On the contrary, the modulation is hardly detected on the signals measured without the OASLM.



**Fig. 3.** Signal measured on the photodiode when varying the amplitude of the phase modulation  $\delta\varphi$ , which is directly converted into  $\Delta = \delta\varphi \lambda/4\pi$ , displacement of the piezoelectric mirror.

The linearity of the phase detection is measured by varying the amplitude  $\delta$  of the phase modulation. The result is shown in Fig. 3. Here  $V_{PD}$  is the voltage recorded by the photodiode and the amplitude of the phase modulation is directly converted in the displacement  $\Delta$  of the piezoelectric mirror, the relation being  $\Delta = \delta\varphi \lambda/4\pi$  with  $\lambda$  the optical wavelength. The linearity of the measurement can be appreciated over almost three decades, for mirror displacements ranging from 0.1nm to almost 100nm. Remarkably, the minimal detectable phase modulation amplitude is consistent with previously achieved vibrometric measurements with the OASLM when working with clean plane wave beams [20]. Moreover, the experiment still achieves good results in the conditions of signal intensity on the OASLM as low as few  $\mu\text{W}/\text{cm}^2$ .

These values are of interest in applications involving detection of weak signal waves propagating in non-stationary complex media.



**Fig. 4.** (a) Reference to signal ratio  $\beta$  measured before the OASLM for different thicknesses  $L$  of the foam layer. (b) The corresponding signal to noise ratio (SNR) as a function of the foam layer thickness.

In Fig.4 we show the influence of the foam layer thickness on the signal detection. Fig.4a displays the ratio  $\beta$  between the intensity of the reference  $R$  and the signal  $S$  measured before the OASLM,  $\beta = |R|^2/|S|^2$  as a function of the scattering medium thickness  $L$ . When the thickness of the foam layer increases, because of the multi-scattering the intensity of the signal reaching the OASLM decreases. Consequently, the contrast of the holographic fringes diminishes and the signal to noise ratio (SNR) decreases accordingly, as shown in Fig.4b. The results demonstrate that coherent phase demodulation can be achieved with the OASLM even when the beam carrying the phase information is strongly scattered by a thick highly diffusing medium. The nonlinear nature of the optical wave mixing process in the OASLM allows summing up in a coherent way the phase contributions from each speckle grain, hence, allowing the coherent detection in the direction of the plane wave reference. These properties, together with the sub-ms response time, may be well suited for applications in coherent imaging through biomedical tissues or turbid media [21-25].

In conclusion, we have shown that coherent phase detection can be achieved with OASLM by performing wave mixing. The results show a good SNR despite the complex nature of the speckled signal beam after it propagates through a highly scattering medium. The SNR determines the weakest detectable signal. The relative sensitivity can be estimated by using the expression for the relative detection limit  $\delta_{lim}^{(rel)}$  of the adaptive interferometer. This is the ratio of the minimum detectable phase modulation amplitude (SNR=0 dB) with respect to the minimum detection achievable with a classical interferometer, as shown in [20]. By using the parameters of the present experiment, the relative detection limit can be estimated as  $\delta_{lim}^{(rel)} \sim 4$  for  $\beta = 10$ . This value is consistent with the value obtained directly from the experimental data by using the method described in [1]. However, a degradation of  $\delta_{lim}^{(rel)}$  is observed when increasing the thickness of the scattering layer, mainly because of the very low intensity of the diffused signal beam reaching the OASLM. For long scattering media (several cm)  $\beta$  increases up to 1000 and consequently the relative detection limit increases up to  $\delta_{lim}^{(rel)} \sim 40$ . To increase the relative sensitivity higher optical power intensity is required for the signal as well as a reduction of noise due to the photodetection chain. We believe that these results constitute advancements for applications in optical sensing whenever complex beams are concerned.

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**Data availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

**Supplemental document.** Not applicable

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