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# Simultaneous acquisition of $\pi/2$ phase-stepped interferograms with a photorefractive $\text{Bi}_{12}\text{GeO}_{20}$ crystal: application to real-time double-pulse holography

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We present a novel method for real-time analysis of vibrations in double-pulse laser holography. Two  $\pi/2$  phase-stepped interferograms are obtained simultaneously. An experimental demonstration gives a phase measurement with an accuracy of  $4^\circ$ . © 1995 Optical Society of America

Double-exposure holographic interferometry with pulsed lasers is developing in industrial environments for vibration analysis. Most devices use photographic plates as holographic media, which prevent real-time interferogram analysis. Some designs with a photorefractive crystal as a holographic medium have already been proposed (both time-averaged interferometry<sup>1-12</sup> and double-exposure interferometry<sup>13-15</sup>) but with cw laser sources only. For double-pulse holographic interferometry the difficulty is to determine without ambiguity the sign of displacement. Indeed a single interferogram contains no information telling which exposure came first. The usual method is to record the object light holographically by interfering it with reference beams having different incident angles for the two exposures.<sup>16-18</sup> During the hologram replay the two object wave fronts are simultaneously reconstructed, each with its own reference beam. Their interference constitutes the first interferogram. Each phase shift introduced between the reference beams at replay gives a different interferogram of the two object wave fronts from the same double-exposure recording. This technique enables one to get at least the three interferograms required for solution of the set of equations and calculation of the phase modulo  $2\pi$ . To overcome this cumbersome procedure, we propose and demonstrate a novel method that provides a real-time and direct phase measurement from the simultaneous acquisition of two phase-stepped interferograms obtained from a single recorded hologram.

Our double-exposure interferometric system exploits the property that, in photorefractive materials in the pulse regime, the modulation of the refractive-index hologram depends on the pulse energy.<sup>19-21</sup> The first exposure of given energy writes the photorefractive hologram. The exact buildup time constant does not matter, provided that the hologram is fully formed before the second exposure. This second exposure is performed with a pulse of lower energy such that it does not destroy or significantly modify the previously written hologram. Thus no additional hologram

is recorded. The reference beam only reads out the previously recorded photorefractive hologram, retrieving the first exposure object wave front that interferes with the transmitted beam (the second exposure object wave front). The interference between the two beams provides the required information on the object vibrations. Our experimental demonstration is conducted with a  $\text{Bi}_{12}\text{GeO}_{20}$  crystal cut along the  $(\bar{1}10)$ ,  $(110)$ , and  $(001)$  crystallographic faces. The grating wave vector is along the  $[001]$  axis, and the incident face is  $(\bar{1}10)$ . In spite of the crystal optical activity ( $35^\circ/\text{mm}$  at 532 nm) and because of the 9-mm sample thickness, the diffraction efficiency does not depend on the incident polarization.<sup>22</sup> However, in each crystal slice only the light polarized along the  $[110]$  direction is diffracted.

Because during the second exposure the two beams only read out the hologram, after the crystal and in the direction of the object beam, we get the following total amplitude:

$$A^c = \left\{ \|A_0\| (1 - \sqrt{\eta}) \exp[i\varphi(t + \Delta t)] + \|A_R\| \sqrt{\eta} \exp[i\varphi(t)] \exp[i(\psi + \pi/2)] \right\} \times \exp[-(\alpha + \delta\alpha)l/2]. \quad (1)$$

$A_0$  and  $A_R$  are the incident object and reference beam amplitudes,  $\eta$  is the diffraction efficiency of the hologram,  $\phi = \varphi(t + \delta t) - \varphi(t)$  is the phase variation induced at the point of observation by the displacement of the object between the two exposures,  $\alpha$  is the linear absorption coefficient,  $\delta\alpha$  accounts for a potential induced absorption, and  $l$  is the interaction length.  $\delta\alpha$  is mainly induced by the reference beam during the first exposure.  $\psi$  is the phase shift between the recording fringe pattern and the resulting index grating that is due to the photorefractive mechanism, and  $\pi/2$  is the phase shift induced by diffraction over an index grating. In our crystal and with the orientation we have chosen, we have  $\psi = \pi/2$ .

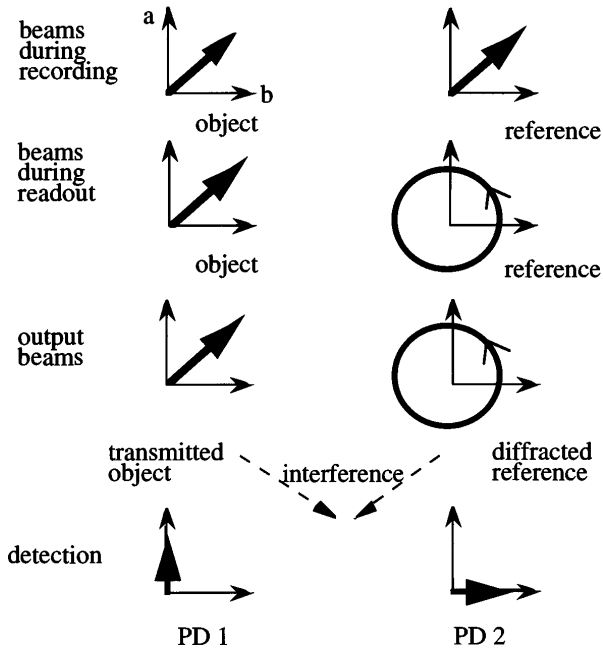


Fig. 1. Beam polarizations (large arrows) during a double exposure in orthogonal axes  $a$  and  $b$ .

We set the reference beam intensity  $I_R = \|A_R\|^2$  much larger than the object beam intensity  $I_O = \|A_O\|^2$ . Because we deal with low diffraction efficiencies and with  $\eta I_R \ll I_O$ , the detected signal derived from Eq. (1) is

$$I^c \approx I_O^c [1 - m \cos(\phi)] \exp[-(\alpha + \delta\alpha)l]. \quad (2)$$

Intensity  $I_O^c$ , proportional to  $I_O$ , takes into account the losses of the optical components set after the crystal. It corresponds to the intensity detected without the photorefractive sample. The modulation ratio  $m$  can be derived from Eq. (1). The presence of the factor  $I_O^c$  makes it necessary to perform a preliminary measurement of its value. Moreover, because the value of  $m$  may depend on the pulse energy,  $m$  must also be determined so that the cosine can be computed from the measured detected intensity  $I^c$ .

A second experiment, with an additional  $\pi/2$  phase shift on the reference beam during the second exposure, permits the measurement of the total output intensity  $I^s$ :

$$I^s \approx I_O^s [1 - m \sin(\phi)] \exp[-(\alpha + \delta\alpha)l], \quad (3)$$

with  $I_O^s$  the measure intensity on the object beam without the crystal.

These two double exposures plus the preliminary measurements of  $I_O^{c,s}$  permit unambiguous determination, for any point of the object, of the modulation ratio  $m$  and of the phase displacement  $\phi$  (modulo  $2\pi$ ).

These measurements of both the sine and the cosine can be performed simultaneously in a unique experiment with the two polarization components of light. The principle is illustrated in Fig. 1. The large arrows in the set of orthogonal axes  $a$  and  $b$  represent the polarization vectors of the object and reference beams. For the optical activity to be taken into account, this set of axes rotates in the depth of the material with the beam polarizations. During the hologram writing, in

any slice of the crystal, the two beams are linearly polarized along the bisector of the two orthogonal axes. During the readout (second exposure), we introduce a  $\pi/2$  phase shift on one polarization component (along the  $a$  axis) to transform the reference beam linear polarization into a circular one. Because of the chosen crystallographic cut, the diffracted reference beam has the same polarization as the incident reference beam. The elliptically polarized beam resulting from interferences between the transmitted object and diffracted reference beams is divided by a polarizing beam splitter into two linearly and orthogonally polarized beams. Photodiode PD 1 (PD 2) is placed to detect the intensity reflected (transmitted) by the beam splitter corresponding to the beam with its polarization along the  $a$  ( $b$ ) axis. This intensity satisfies relation (2) [relation (3)]. As before, a calibration is necessary for one to measure the background intensities  $I_O^{c,s}$ . This is done by measurement of the PD 1 (PD 2) signal  $I_O^c$  ( $I_O^s$ ) during a low-energy exposure, for which there is no hologram recording. A third photodiode, PD 0, placed on the reference beam behind the crystal, allows us to compensate for the variation of the total laser energy between the calibration and the second exposure.

Because of the low energy used for calibration, induced absorption is negligible, and the two signal and the reference intensities detected by the three photodiodes are

$$\begin{aligned} I^c(\text{cal.}) &= I_O^c \exp(-\alpha l), \\ I^s(\text{cal.}) &= I_O^s \exp(-\alpha l), \\ I^{\text{ref}}(\text{cal.}) &= I_O^{\text{ref}} \exp(-\alpha l). \end{aligned} \quad (4)$$

The double exposure is then performed, and we measure during the second pulse:

$$\begin{aligned} I^c(t + \delta t) &\approx r I_O^c [1 - m \cos(\phi)] \exp[-(\alpha + \delta\alpha)l], \\ I^s(t + \delta t) &\approx r I_O^s [1 - m \sin(\phi)] \exp[-(\alpha + \delta\alpha)l], \\ I^{\text{ref}}(t + \delta t) &\approx r I_O^{\text{ref}} \exp[-(\alpha + \delta\alpha)l]. \end{aligned} \quad (5)$$

Coefficient  $r$  takes into account the energy fluctuation between the calibration and the second exposure. From systems (4) and (5), we derive

$$\begin{aligned} 1 - m \cos(\phi) &\approx \frac{I^c(t + \delta t)}{I^c(\text{cal.})} \frac{I^{\text{ref}}(\text{cal.})}{I^{\text{ref}}(t + \delta t)} = I_{\text{tot}}^c, \\ 1 - m \sin(\phi) &\approx \frac{I^s(t + \delta t)}{I^s(\text{cal.})} \frac{I^{\text{ref}}(\text{cal.})}{I^{\text{ref}}(t + \delta t)} = I_{\text{tot}}^s, \end{aligned} \quad (6)$$

where  $I_{\text{tot}}^c$  and  $I_{\text{tot}}^s$  are normalized intensities.

From relations (6), the values for  $m$  and the phase shift can be easily computed as follows:

$$\begin{aligned} m^2 &\approx (1 - I_{\text{tot}}^c)^2 + (1 - I_{\text{tot}}^s)^2, \\ \cos(\phi) &\approx (1 - I_{\text{tot}}^c)/m, \\ \sin(\phi) &\approx (1 - I_{\text{tot}}^s)/m. \end{aligned} \quad (7)$$

The experimental setup is as follows. The source is a frequency-doubled Nd:YAG laser that delivers pairs

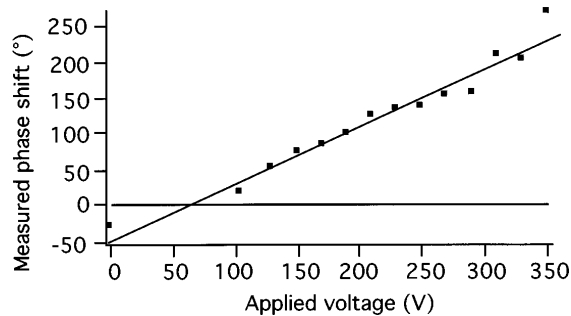


Fig. 2. Experimental data of the measured phase shift versus the applied voltage.

of pulses of 10-ns duration delayed by 50  $\mu$ s. The beam is split into two beams that intersect at 60° (fringe spacing of 0.5  $\mu$ m) and overlap in the crystal. The intensity ratio between the reference and the object beam is equal to  $10^5$ . The total energy incident upon the crystal is 20 mJ/cm<sup>2</sup> during the first exposure and 2 mJ/cm<sup>2</sup> for the second exposure. The Bi<sub>12</sub>GeO<sub>20</sub> crystal is 9 mm thick along the beam-propagation direction. Both entrance and exit faces (8 mm  $\times$  7.5 mm) are antireflection coated first to prevent unwanted reflections and second to make their transmission independent of polarization. Under these experimental conditions we observe that the buildup of the grating is a few nanoseconds long and that the refractive-index modulation induced by the second exposure is negligible. A longitudinal electro-optic modulator placed on the reference beam introduces the  $\pi/2$  phase shift between the two exposures. On the object beam a transverse electro-optic modulator (previously calibrated) simulates the vibrating object. It introduces a known phase shift (proportional to the applied voltage) between the two exposures. As explained above, a polarizing beam splitter placed behind the crystal directs the  $I^c$  and  $I^s$  signals to photodiodes PD 1 and PD 2. Because of the optical activity, a half-wave plate is set before the polarizing beam splitter to bring back the  $a$  and  $b$  axes along the beam splitter axes.

The measured phase shifts as a function of the voltage applied to the transverse electro-optic modulator are presented in Fig. 2. The points are distributed along a line. Its slope, 180° for 226 V, is the one that we expected (the  $V_\pi$  applied voltage that introduces a phase shift of 180° was independently measured to be  $220 \pm 15$  V for this modulator). The offset ( $-50^\circ$  at zero applied voltage) is attributed to optical thickness variations of the longitudinal Pockels cell when the  $\pi/2$  phase shift is introduced. The rms of the phase error between  $-50^\circ$  and  $280^\circ$  is estimated to be approximately  $4^\circ$ , i.e.  $\lambda/90$ . The determination of the phase results from digitization of a series of four intensity measurements and is thus marred by uncertainties. The discrepancy observed between experimental data and the calculated curve is attributed mainly to numerical errors. The accuracy is thus directly related to the linearity of the three photodiodes. The contribution of these relative numerical errors on the

phase uncertainty is larger for low values of  $m$ . We calculate this value for each measurement. It varies from point to point from 0.15 to 0.30 because of pulse energy fluctuations. Increasing  $m$  will improve the measurement accuracy.

We have presented a novel method that permits simultaneous measurement of the sine and the cosine of a phase shift during the second exposure of a sole double-exposure experiment. The phase is determined modulo  $2\pi$ . An experimental demonstration is conducted here for one single pixel of the output plane. We will apply this method to a full analysis of two-dimensional object deformations using a laser source with adequate coherence length (a ruby laser, for instance), relay optics, and CCD cameras.

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