Real-time holograms generated by second-harmonic cross correlation of object and reference optical wave fields

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Three-dimensional holographic images of extended diffusing objects are simultaneously recorded and reconstructed by optical cross correlation in a second-order nonlinear crystal. An interaction geometry in which the phase-matched object and reference fields propagate slightly noncollinearly is particularly convenient for producing these second-harmonic-generated holograms. © 2000 Optical Society of America

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Since the very beginning of optics, many efforts have been devoted to the registration, transformation, and manipulation of the spatial structure of light wave fronts. Holography was one of the main achievements in this context; it is the first method capable of three-dimensional imaging. Nonlinear optics only recently produced results that are relevant to these fields if not for improvements in the space quality of powerful laser beams obtained through phase conjugation by three- and four-wave mixing. In our previous publications, we demonstrated that the second-harmonic cross correlation in a thin crystal of the field propagating from an illuminated object \( E_O \) with a reference field \( E_R \) is a process that shares many features with holography. In fact, the two fields at fundamental frequency \( \omega \) (wave vector \( k_1 \)) can be written as

\[
E_O = A_O(x,y) \exp[i(k_1L_O(x,y) + \omega t)], \tag{1}
\]

\[
E_R = A_R \exp[i(k_1L_R(x,y) + \omega t)], \tag{2}
\]

where \( A_O \) is the object-field space-dependent amplitude, \( A_R \) is the uniform reference-field amplitude, and the iconals \( L_O(x,y) \) and \( L_R(x,y) \) represent the distribution functions of the optical paths of the object and the reference fields, respectively. For quasi-collinear interaction, the frequency-doubled field \( E_{2\omega} \) generated in the nonlinear crystal is given by

\[
E_{2\omega} \propto E_o E_r = A_O^2(x,y)
\times \exp[i(2k_1L_O(x,y) + 2\omega t)]
+ 2A_O(x,y)A_R \exp[i(k_1[L_O(x,y)
+ L_R(x,y)] + 2\omega t)]
+ A_R^2 \exp[i(2k_1L_R(x,y) + 2\omega t)]. \tag{3}
\]

By taking into account that \( 2k_1 \) is the second-harmonic wave vector \( k_2 \), we can rewrite the second term of relation (3) as

\[
E_{2\omega}^\parallel = A_O(x,y)A_R
\times \exp\left[i\left[k_2 \left(\frac{L_O(x,y) + L_R(x,y)}{2} + 2\omega t\right)\right]\right], \tag{4}
\]

where \( E_{2\omega}^\parallel \) represents the wave field reconstructed by the immaterial structure formed in the nonlinear crystal that we call a second-harmonic-generated (SHG) hologram. In fact, Gabor’s theory of holography leads to a field term identical to \( E_{2\omega}^\parallel \) that produces a virtual holographic image of the object (see below). Nevertheless, relation (3) does not include the term that in Gabor’s theory corresponds to the reconstructed real image. Thus the nonlinear crystal acts as a holographic plate in that the frequency-doubled radiation wave front reconstructs a virtual image of the object. According to Eq. (4), the space-dependent phase of the reconstructed wave is determined by the iconal \( L_O(x,y)/2 + L_R(x,y)/2 \). By using the laws of holography and lens array systems, we can predict position, scale, and resolution of the reconstructed image. In particular, for a plane reference wave the iconal above implies that the virtual reconstructed image has a transverse size equal to that of the object and a longitudinal size two times larger. We proved our theory by studying the impulse response of SHG holograms in experiments in which a pointlike source was used as the object as well as by reconstructing one-dimensional and two-dimensional objects.

In this Letter we provide experimental evidence that the SHG hologram of a real three-dimensional object displays all the characteristics of a conventional hologram. The reconstructed images have transverse and longitudinal sizes as predicted by theory.

The experimental setup used for the measures is shown in Fig. 1. Note that for the sake of clarity the figure is not to scale; the real distances are those quoted in millimeters. The output beam \( \vec{P} \) of a Q-switched amplified Nd:YAG laser (Quanta-Ray GCR-4, Spectra-Physics, Inc., Mountain View, Calif.; 18-ns pulse duration, 10-Hz repetition rate) was split into two beams, \( \vec{P} \) and \( \vec{\gamma} \), i.e., reference and object beams, of which \( \vec{P} \) was spatially filtered to produce a
diffraction-limited beam. The beams, with \( \sim 100 \text{ mJ} \) per pulse each, were manipulated by the optical elements detailed in the figure. In particular, beam \( \alpha \) passed through diffuser \( S \) (two ground-glass plates treated with HF randomly moved from shot to shot) and produced the scattered light that transilluminated the object to be recorded. The \( \beta \)-barium borate crystal used in phase-matching I (BBO I; Akadimpex Budapest, Hungary) with its cross section of 5 \( \times \) 5 mm (0.3-mm thickness) determined the actual aperture of the optical setup. The measurements of location and shape of the image reconstructed by the SHG hologram were made by imaging through lens \( L_5 \) (see Fig. 1) onto the sensor of a CCD camera (PE2015, Pulnix Europe, Basingstoke, UK).

The small aperture of our optical system produced a relatively large depth of focus. Therefore, to allow significant characterization of the three-dimensional (3-D) properties of the reconstructed image, an object with remarkable longitudinal size (\( z \)-axis) had to be used. As illustrated in the upper inset in Fig. 1, the object was composed of two straight metal wires located at positions A and B, 33 mm apart along the \( z \)-axis, oriented in two different directions. We obtained a focused image of each wire such as those displayed in Figs. 2(a) and 2(b) by shifting the CCD camera from \( A' \) to \( B'' \) (Fig. 1). This proves that the real image reconstructed by our SHG hologram has 3-D characteristics. As we mentioned above, the second-harmonic wave fronts reconstruct a virtual image (\( A' \) and \( B' \) in Fig. 1) with the same transversal size of the real object and located at double the distance from crystal BBO I along bisector \( B_5 \). Thus the distance of \( A' \) to \( B' \), which we call \( \delta' \), is twice the distance of \( A \) to \( B \) (\( \delta' = 66 \text{ mm} \)). The depth of the image, \( \delta_{\text{exp}}'' \), evaluated as the distance of \( A'' \) to \( B'' \) (\( \delta_{\text{exp}}'' = 16 \text{ mm} \)) can be readily compared with the distance, \( \delta_{\text{th}}'' \), calculated from the transformation operated by lens \( L_5 \) on positions \( A'' \) and \( B'' \). The calculated value (\( \delta_{\text{exp}}'' = 17.5 \text{ mm} \)) is in good agreement with the measured value. This proves that the virtual image reconstructed by our SHG hologram is longitudinally stretched by a factor of 2 compared with that of the object.

We now examine the properties of the reconstructed image on the transverse plane. We first note that, by defining the longitudinal magnification operated by lens \( L_5 \) as \( m_L = \delta''/\delta' \), from the data above we get \( (m_L)_\text{th} = 0.27 \) and \( (m_L)_\text{exp} = 0.24 \). In addition, if we accept a definition of the transverse magnification, \( m_T \), as \( m_T = \sqrt{m_L} \), which holds for thin objects, we get \( (m_T)_\text{th} = 0.51 \) and \( (m_T)_\text{exp} = 0.49 \). The actual values of the transverse magnification with which the two wires are imaged are definitely different from each other, as is evident in Fig. 2, because \( \delta' \) is comparable with the focal length of lens \( L_5 \). A thin object is thus more suitable for use in studying the transverse geometrical properties of SHG holograms. We then decided to make a SHG hologram of a two-dimensional (2-D) object located at position \( C' \), mid point between \( A \) and \( B \). The object (see the lower inset of Fig. 1) was a black-and-white photocopy upon a transparency of the logo of the Insubria University (diameter, 25 mm). The real image displayed by the CCD at position \( C'' \) (Fig. 1) is shown in Fig. 3. Its diameter is 1.25 mm. As we already mentioned, the virtual image reconstructed by the SHG hologram at point \( C' \) is 2.5 mm in diameter (the same size as the object) and is located 167 mm from the crystal BBO I (twice the distance of the object from the crystal). Therefore our experimental result confirms the theory if the transverse magnification of lens \( L_5 \) is 0.50. By measuring
the positions of C and C" we calculated a magnification $m_T = 150/(83.5 \times 2 + 130) = 0.505$. We finally note that the values of the transverse magnification in the reconstructed 3-D object image previously evaluated from the longitudinal magnification are also similar to 0.50, which leads to the conclusion that SHG holograms have the same 3-D properties as conventional holograms.

To conclude the comparison between ordinary and SHG holograms we discuss two features that are relevant for ordinary holograms, i.e., the contrast of the image and the diffraction efficiency. As for the contrast, in the case of the two metallic needles it was better than 1:20 for both of them. In the case of the Insubria logo, instead, the contrast was somewhat less because, as a result of the photocopying process, the black part of the logo was not absolutely opaque in the IR region. As for the diffraction efficiency, for SHG holograms it should be identified with the conversion efficiency of the second-harmonic cross-correlation process (i.e., the ratio of SHG field intensity to reference-field intensity). In the experiments discussed above, the efficiency was $\sim 2\%$.

As a final remark, we point out that a distinctive feature of a SHG hologram is its potentially ultrafast optical response. In fact, second-harmonic cross correlation can operate over a bandwidth as broad as that of Fourier-transform-limited pulses of femtosecond duration.$^9$ We thus suggest that a method for recording–reconstructing dynamic holograms in real time with extremely fast optical response could arise from our idea.$^6$

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