Interference pattern produced on reflection at a phase-conjugate mirror. II: Experiment

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The nature of the fringe pattern produced by interference between a wave incident upon a phase-conjugate mirror and that leaving the mirror has been studied experimentally for a phase-conjugate mirror based on degenerate four-wave mixing. The fringe locations are found to depend on the phase of the wave incident upon the mirror, in agreement with recent theoretical predictions but in contrast to the results observed for the interference pattern produced on reflection at an ordinary metal mirror. The phases of the waves that pump the phase-conjugate mirror are shown to provide the reference with respect to which the phase of the incident wave is determined.

A recent theoretical analysis[1] of the interference pattern produced on reflection at a phase-conjugate mirror (PCM) has shown that the positions of the interference fringes thereby produced depend on the phase of the incident wave. This predicted behavior is in contrast to that observed in the classic experiments of Wiener[2] for reflection at the surface of a metal mirror, in which case the resulting interference pattern has a node at the surface of the mirror, regardless of the phase of the incident field. In this paper we present experimental results that demonstrate the nature of the fringe pattern produced by interference between the wave incident upon the PCM and that reflected from it for the case of a PCM that operates by means of degenerate four-wave mixing (DFWM). These results are in good agreement with the theoretical predictions of Ref. 1 and also indicate that the phases of the waves that pump the PCM provide a reference with respect to which the phase of the incident wave becomes evident in the resulting interference pattern.

In the usual geometry of DFWM, the incident signal field and the forward-going pump wave both enter the nonlinear medium through the same face, and hence the region immediately in front of the PCM is not so accessible as it was in the classic Wiener experiment. We have therefore used the experimental setup shown in Fig. 1 to determine the relative phase between the incident and phase-conjugate fields through the use of a Michelson interferometer. In effect, the interference pattern formed in front of the PCM is projected into the half-space to the left of the beam splitter, and the intensity of a small region of this intensity pattern is measured by the photodetector. The properties of interferometers containing PCM's have also been discussed by other workers.[3,4]

At a conceptual level, our experiment involves introducing a variable phase delay into the incident beam in a region (A in Fig. 1) and observing that the position of the interference fringes does in fact depend on the phase of the field incident upon the PCM, as predicted by the theory of Ref. 1. This experiment is then repeated with the PCM replaced by an ordinary metal mirror, and the interference pattern is found to be independent of the phase of the incident optical wave, as was the case in the classic experiment of Wiener. We have also performed experiments in which the phase ϕ of the phase-conjugate reflectivity μ is varied, and again we have found that the interference pattern measured by the photomultiplier depends on ϕ as predicted by the theory presented in Ref. 1.

The experimental setup is shown in greater detail in Fig. 2. All the optical waves are derived from an argon-ion laser operating at a wavelength of 488 nm in a single transverse and a single longitudinal mode. Beam splitters are used to produce forward- and backward-going pump waves of complex amplitudes A_1 and A_2, respectively, and of approximately equal intensities, and to produce a weak beam of amplitude A_4, which acts as the signal beam. These beams interact in the nonlinear optical medium to generate the phase-conjugate beam whose complex amplitude we denote by A_3. The nonlinear optical material is fluorescein-doped boric-acid glass.[5] This material has a strong absorption feature centered at 437 nm, which resonantly enhances the nonlinear susceptibility describing the DFWM process. The sample used in our experiment has a thickness $L = 150$ μm and a fluorescein number density of approximately 10^{18} molecules/cm^3. The intensities of the interacting waves are kept well below the saturation intensity of the material, which at the laser wavelength is approximately 800 mW/cm^2. In this limit, the nonlinear coupling can be described by a third-order susceptibility $\chi^{(3)}$, which for our sample has a modulus of 3.8×10^{-3} esu. The internal transmission of the sample is greater than 95%, and hence to a good approximation absorption effects need not be considered in the theoretical description of our experiment. The phase-conjugate reflectivity $\mu = A_3/A_4{}^*$ for a PCM based on DFWM in a lossless Kerr medium is given, in the limit of a sufficiently short medium, (where $|\mu|^2 \ll 1$), by[6]

$$\mu = \frac{-12\pi i\omega}{nc}\chi^{(3)}A_1A_2L. \tag{1}$$

It should be noted that the phase of μ can be varied by changing the phase of either or both of the pump waves. In our experiment, pump-beam intensities as large as 200 mW/cm^2 were used, leading to values of $|\mu|$ as large as 0.01.

For the various experiments reported below, a variable phase retarder is placed at any of the positions marked A–F in Fig. 2. The variable phase retarder is a gas cell of 5-mm thickness containing air at a pressure between that of vacuum and atmosphere. Our experimental procedure consists

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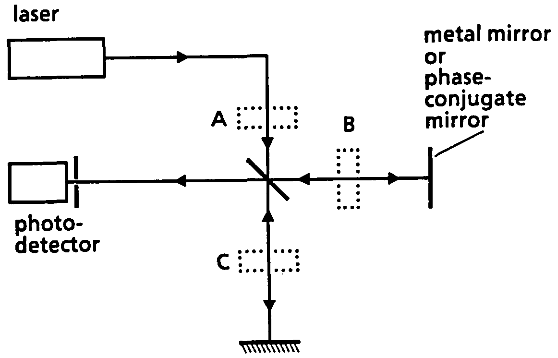

Fig. 1. Michelson interferometer used to measure the phase difference between the wave incident upon the PCM and the wave generated by the mirror. For some of the experiments reported in the text, the PCM is replaced by an ordinary metal mirror. A variable phase retarder consisting of a variable-pressure gas cell can be placed at position A, B, or C.

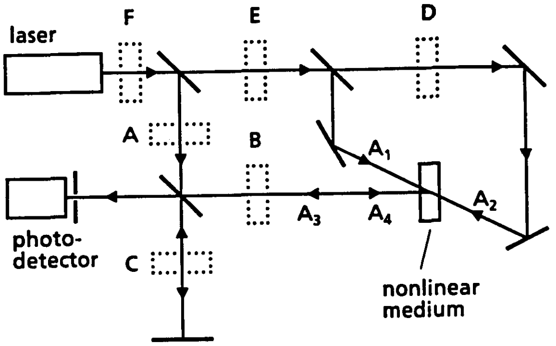

Fig. 2. Experimental setup illustrating how the phase-conjugated wave is produced by DFWM. A_1 and A_2 denote the complex amplitudes of the counterpropagating pump waves, A_4 that of the signal wave incident upon the PCM, and A_3 that of the phase-conjugate wave.

of evacuating the cell and determining how the intensity of the central portion of the interference pattern measured by the photomultiplier evolves in time as air is allowed to flow into the cell through a needle valve. In order to analyze our results, we assume that the phase delay introduced by the gas scales linearly with the gas pressure and that the pressure evolves in time as $p(t) = p_0[1 - \exp(-at)]$. Here p_0 denotes the pressure of 1 atm and a is a constant that depends on the opening of the needle valve. From our measurements for the case of the metal mirror, we have determined that $a = 0.05\ \text{sec}^{-1}$ and that the total range of phase shifts available from the cell is $\Phi_{\max} = 19.3$ rad. Hence we infer that the phase shift induced by the phase retarder evolves in time as $\Phi = \Phi_{\max}[1 - \exp(-at)]$. We infer the relative phase δ of the signal and conjugate waves by fitting the intensity I measured by the photomultiplier to the functional form $I = I_3 + I_4 + 2(I_3I_4)^{1/2} \cos \delta$, where I_3 and I_4 denote the intensities due solely to the conjugate and signal waves, respectively, in the half-space following the beam splitter.

By means of the procedure outlined above, we have deduced the relative phase δ from measurements of the locations of the interference fringes as a function of the phase shift Φ introduced by the gas cell under several different conditions. Figure 3 shows the results for the case in which the gas cell is placed in position A of Figs. 1 and 2. In this position, the cell changes the phase of the wave incident upon the PCM. As predicted by the theory of Ref. 1, the positions of the maxima of the interference pattern are observed to depend on the phase of the wave incident upon the PCM. As in the experiment of Wiener, there is no change for the case of the metal mirror. Note that displacement of the interference pattern changes at a rate twice that of the phase of the incident wave, because the interferometer measures the phase difference between the incident wave whose phase is shifted by Φ and the phase-conjugate wave whose phase is shifted by $-\Phi$. Our results are in qualitative agreement with those of Feinberg,[7] in whose work no quantitative measurement of the shift of the interference pattern is, however, reported.

The aberration-correcting properties of a PCM are illustrated by placing the gas cell at position B as shown in Fig. 4. In this configuration, the phase shift Φ produced by the

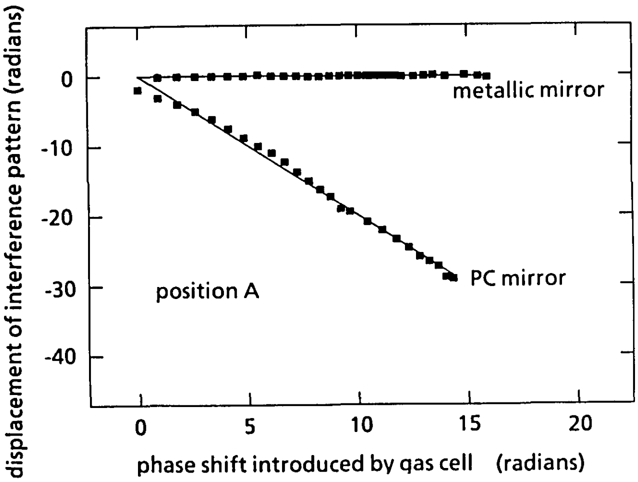

Fig. 3. Measured displacement of the fringe pattern produced by interference between the signal and phase-conjugate waves plotted as a function of the phase shift introduced by the gas cell, which is placed in position A of Figs. 1 and 2. For the case of an ordinary metal mirror, the positions of the interference fringes are seen to be independent of the phase of the incident wave.

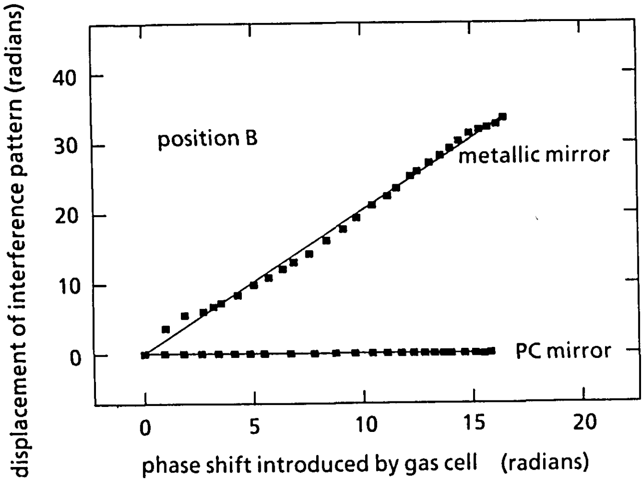

Fig. 4. Measured displacement of the fringe pattern produced by interference between the signal and phase-conjugate waves plotted as a function of the phase shift introduced by the gas cell, which is placed in position B of Figs. 1 and 2. In this configuration the PCM removes in a double pass the effect of the phase shift imparted by the gas cell.

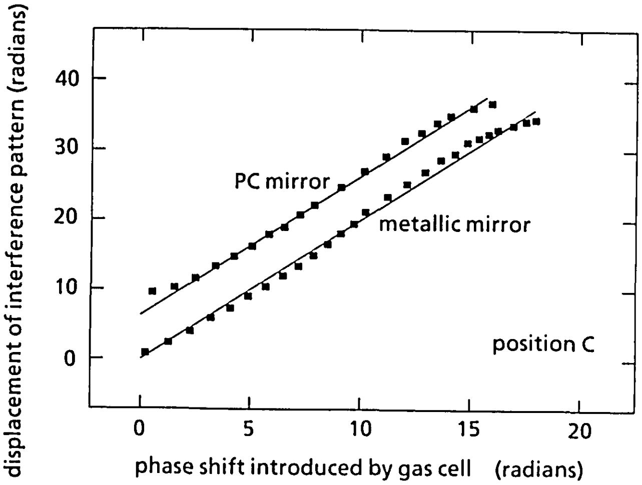

Fig. 5. Measured displacement of the fringe pattern produced by interference between the signal and phase-conjugate waves plotted as a function of the phase shift introduced by the gas cell, which is placed in position C of Figs. 1 and 2. Both mirrors are seen to behave equivalently in this case.

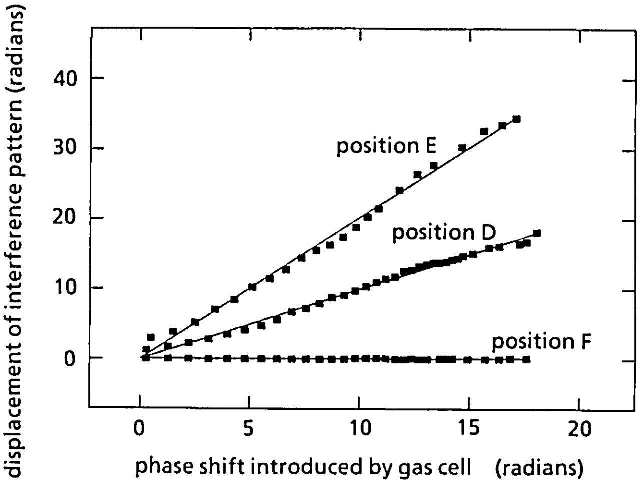

Fig. 6. Measured displacement of the fringe pattern produced by interference between the signal and phase-conjugate waves plotted as a function of the phase shift introduced by the gas cell, which is placed in position D, E, or F of Fig. 2. The phase of the phase-conjugate reflectivity μ is modified in accordance with Eq. (1) when the cell is in position D or E, which leads to a shift of the interference pattern.

second pass through the gas cell cancels the phase shift Φ introduced by the first pass since the wave returned by the PCM has its phase shifted to $-\Phi$ before passing through the gas cell and hence to 0 after the second pass. When the PCM is replaced by a metal mirror, the interference pattern shifts at a rate twice that of a single pass through the gas cell since the phase delays introduced by the two passes through the cell are cumulative.

Figure 5 shows how the phase of the interference pattern depends on the phase shift introduced by the gas cell for the case in which the gas cell is located in the reference arm of the interferometer, that is, at position C. In this case the metal mirror and the PCM behave in the same way. In plotting this figure, we have offset the measured phase for the metal mirror by 2π rad for the purpose of clarity.

Figure 6 illustrates how the displacement of the interference pattern changes as the phase of the reflectivity μ of the PCM is varied by changing the phase of either or both of the pump waves. We recall that according to Eq. (1) the phase of μ depends on the sum of the phases of the two pump waves. When the gas cell is placed at position D it shifts the phase of one of the pump waves, and when it is placed at position E it shifts the phase of both pump waves. We observe that the location of the interference pattern changes at the same rate as Φ for position D and changes at twice this rate for position E, as predicted. We have also measured the displacement of the interference pattern for the case in which the gas cell is placed at position F, immediately after the laser. In this case the interference pattern does not change as the phase Φ of the total optical field is varied. This result occurs because the PCM determines the phase of the incident signal field only with respect to the phase of the pump fields. If the phases of all the waves are shifted by the same amount, the nature of the resulting interference pattern is not modified.

In conclusion, we have repeated the classic experiment of Wiener with the metal mirror used in his experiment replaced by a PCM. We find that the positions of the fringes in the interference pattern depend on the phase of the wave incident upon the PCM, in contrast to the results for the case of a metal mirror but as predicted by the theoretical arguments presented in Ref. 1. The positions of the fringes are also found to shift when the phase of either or both of the pump waves is changed, thereby changing the phase of the reflectivity μ of the PCM in accordance with Eq. (1).

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