Fidelity of optical phase conjugation by degenerate four-wave mixing in semiconductor glasses and ruby

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The fidelity of phase conjugation by degenerate four-wave mixing in ruby and semiconductor-doped glasses has been measured by means of our own modified Twyman–Green interferometer [Opt. Lett. **14**, 183 (1989)] implementing two phase conjugate mirrors. It is shown that the fidelity of phase conjugators with an OG530 color filter as the nonlinear medium reaches a value of 99%. The fidelity of ruby is also reported. Additionally the effect of the recording system on the value of the fidelity is discussed.

Measurement of the fidelity of optical phase conjugation (OPC) is important in the optimization of phase conjugate optics as well as in verifying the validity of the theory of OPC. Various experimental methods have been implemented in fidelity measurements which include the utilization of spatial filters,[1] diffraction gratings,[2] and phase conjugate interferometers.[3–5] The latter method was proposed first by Basov *et al.*[3,4] for measuring the fidelity of phase conjugation by stimulated Brillouin scattering. Recently Naylor *et al.*[5] measured the fidelity of OPC by degenerate four-wave mixing (DFWM) in $BaTiO_3$ using an interferometer which utilized one phase conjugate mirror. It was shown by these authors that the fidelity decreases as the ratio of the probe beam power over the pump beam power increases. The definition of fidelity used in Refs. 2, 3, and 5, as well in this letter, is: fidelity H is the power of the conjugate part of the reflected beam normalized with respect to the total power of the reflected beam:

$$H = P_c/(P_c + P_{nc}) = P_c/P_r. \tag{1}$$

This definition is suitable for the quantitative determination of the wave front reversal quality.

Recently semiconductor-doped glasses have been shown to be promising materials for use in nonlinear optical devices[6–10] owing to their high third-order susceptibility and short response time. Knowledge of all phase conjugation parameters of these composite materials is important in the evaluation of the materials and optical systems for potential applications.

In this letter we wish to report measurements of the fidelity of OPC by DFWM, utilizing a modified Twyman–Green interferometer in which the two conventional mirrors have been replaced by phase conjugate mirrors[11] consisting of semiconductor glass OG530 and ruby crystals.

The experimental results presented in this letter were obtained with the aid of the system shown in Fig. 1. It consists of a continuous wave mode-locked Nd:YAG laser frequency doubled to yield 532 nm pulses of approximately 75 ps duration. The 532 nm laser beam was split into the pump and probe beams. Both beams were directed through a dual frequency optical chopper (pump beam $F_1 = 667$ Hz, probe beam $F_2 = 800$ Hz) to the interferometer. At the interferometer input the mean pump and probe beam power was 180 and 110 mW, respectively. All beams were vertically polarized. The length of one of the arms of the interferometer was varied by means of a piezoelectric transducer. The phase conjugate mirrors PC1 and PC2 utilized DFWM in the retroreflection scheme.[12,13] The interference signal was detected by a photomultiplier tube, and fed into a lock-in amplifier, locked at one of the frequencies F_1, F_2, $F_1 + F_2$, or $F_1 - F_2$. The resulting signal was fed into a microcomputer which also controlled the piezoelectric transducer driver voltage. In the experiments where both arms utilized the same type of phase conjugate mirror a 3 mm semiconductor-doped glass (OG530 color filter with transmission 55% at 532 nm) was used initially as the nonlinear medium. Subsequently, a 5 mm ruby crystal, with axis c oriented along the beam and transmission 51%, replaced one of the color filters at PC1 (see Fig. 1) in order to measure the phase conjugate fidelity of ruby. Blocking either arm enabled us to measure the power of the reflected beam from each conjugator separately. The phase conjugate reflectivity for the arm with OG530 filter was approximately 10^{-5}. The interferometer was aligned using the interference of the retroreflected pump beams. This guaranteed the correct alignment of the conjugate beams in terms of the spatial and temporal overlap at the beamsplitter as well as collinear propagation past it (less than 0.1 mrad deviation from collinearity). An aberrator (glass plate) was inserted in the path of the pump beam in front of the beamsplitter in order to determine the effect of pump beam quality on fidelity. Similarly an aberrator consisting of a cylindrical lens in the probe beam path of one arm of the interferometer was used to measure the wave front reconstruction capability of the particular phase conjugator. The interference signal as a function of the mirror displacement with OG530 as the nonlinear medium in both arms of the interferometer is shown in Fig. 2(a). In addition the reflected signals ($P_{r,1}$,$P_{r,2}$) from either arm of the interferometer, with the second arm blocked, are shown also in Fig. 2(a). Figure 2(b) displays the interference signal when the OG530 color filter in one arm of the interferometer was replaced with a ruby crystal. The contrast ratios of the interfer-

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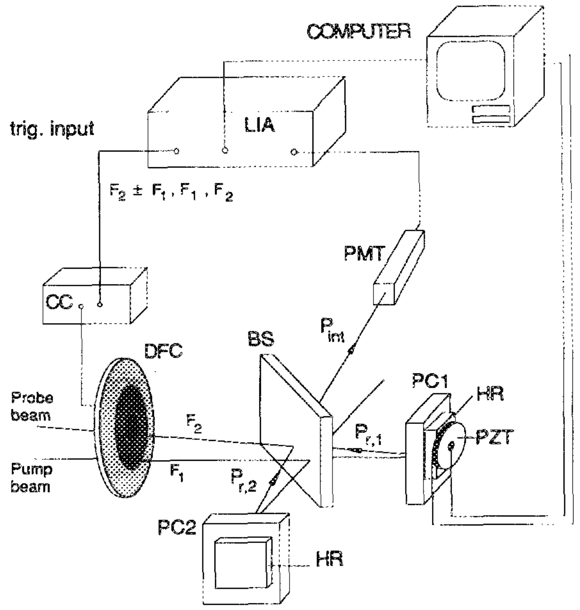

FIG. 1. Experimental system used for fidelity measurements of optical phase conjugation by DFWM. DFC: dual frequency optical chopper; CC: chopper controller; BS: beamsplitter; PC1, PC2: phase conjugators; HR: high reflecting mirrors; PZT: piezoelectric transducer; PMT: photomultiplier; LIA: lock-in amplifier.

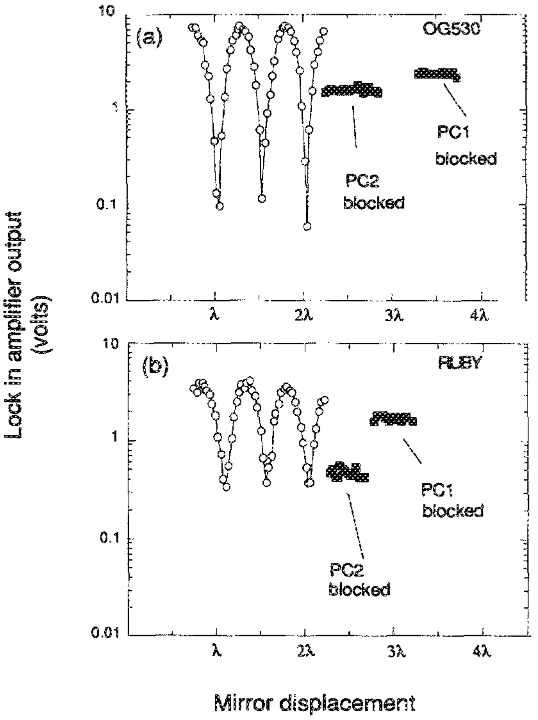

FIG. 2. Interferometer output signal as a function of the displacement of the mirror mounted on the PZT (○) and the reflected signals from each conjugator (▩): (a) when semiconductor-doped glass OG530 is used in both arms, and (b) when one of the OG530 filters is replaced by a ruby crystal.

ence traces are listed in Table I. The contrast ratios expected from the measured reflected signals $P_{r,1}$, $P_{r,2}$ are shown also in Table I. Provided that $P_{r,1}$ and $P_{r,2}$ are solely conjugate signals the calculated and measured contrast ratio values ought to be identical. In order to elucidate the effect of the experimental system on the recorded fidelity values we performed measurements with the lock-in amplifier locked on four different triggering frequencies F_1, F_2, $F_1 + F_2$, and $F_1 - F_2$. These results are included in Table I as well as the contrast ratios in the presence of an aberrator. It is thus noticed that in the presence of an abberrator the two contrast ratios differ substantially. The same is true in the case where the lock-in amplifier triggering frequency is equal to the pump or the probe chopping frequencies F_1, F_2.

In order to interpret the experimental data in terms of fidelity we derived an expression connecting the fidelity to the experimental parameters $P_{r,1}$, $P_{r,2}$ and the measured contrast ratio. The interference signal $P_{\rm int}$ is given by[6]

$$P_{\rm int} = P_{r,1} + P_{r,2} - 2\sqrt{P_{c,1}P_{c,2}}\cos\varphi, \tag{2}$$

where $P_{r,i} = P_{c,i} + P_{nc,i}$ $(i = 1,2)$ is the sum of the conjugate and nonconjugate parts of the reflected beam and φ is the phase difference of the two conjugate beams. The values of $P_{r,1}$ and $P_{r,2}$ are obtained by blocking the appropriate arm of the interferometer.

In the case where both nonlinear media are identical and have the same fidelity values we obtain

TABLE I. Fidelity values for semiconductor-doped glass (OG530 filter) and ruby crystal.

Material PC1	Lock-in amplifier triggering frequency	Aberrator	Contrast ratios $\dfrac{P_{\rm max} - P_{\rm min}}{P_{\rm max} + P_{\rm min}}$ [a]	Contrast ratios $\dfrac{2\sqrt{P_{r,1}P_{r,2}}}{P_{r,1} + P_{r,2}}$	Fidelity [a]
OG530	$F_2 - F_1$	No	0.98	0.99	0.99
OG530	F_1	No	0.92	0.97	0.95
OG530	F_2	No	0.91	0.98	0.93
OG530	$F_2 + F_1$	No	0.97	0.98	0.99
OG530	$F_2 - F_1$	In pump beam	0.87	0.96	0.90
OG530	$F_2 - F_1$	In probe beam	0.89	0.99	0.90
Ruby	$F_2 - F_1$	No	0.82	0.85	0.96

[a] Estimated error is ±2%.

$$H = Q\frac{(P_{r,1}/P_{r,2}+1)}{2\sqrt{P_{r,1}/P_{r,2}}}. \quad (3)$$

In Eq. (3), Q is the contrast ratio of the interference signal which is given by

$$Q = (P_{\max} - P_{\min})/(P_{\max} + P_{\min}).$$

The calculated fidelity values are included in Table I. It is important to notice that the fidelity values with the lock-in amplifier locked at the sum and difference frequencies of the optical chopper are 0.99. This verifies the fact that the nonconjugate reflected signal which depends on the product of the intensity of the probe and pump beams is negligible. In addition the high fidelity value indicates that scattered light is successfully rejected by the lock-in amplifier. In contrast, when the lock-in amplifier is locked on either the pump or probe beam frequencies the fidelity values are reduced owing to the presence of scattered light which amounts to 6–10% of the total reflected signal. The exact percentage was found to depend also on the size of the shielding diaphragms and varies from spot to spot on the semiconductor glass. We applied Eq. (3) in calculating the fidelity of ruby and the fidelity of OG530 in the presence of an aberrator in the probe beam path. The lower value of fidelity indicates imperfect wave front reconstruction and the fact that the two reflected beams are not identical.

In conclusion, the fidelity of semiconductor-doped glass OG530 and ruby is measured by means of a conjugate mirror interferometer. The observed lower value for the fidelity of ruby is attributed to a higher degree of inhomogeneities present in the crystal. This leads to wave front distortion of the pump beam which subsequently affects the quality of the conjugate beam. We also have shown that the fidelity values may vary with the optical and recording system used.

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