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Beam couplings and phase conjugate effects in reflection and transmission in $BaTiO_3$

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Abstract. The details of experiments showing the effects of self-pumped phase conjugation on reflection and on transmission in barium titanate crystal are given. The specular reflection and the second-surface reflection of an extraordinary polarized beam, incident on the face of the crystal parallel to its *c*-axis, get reduced in intensity as the phase conjugation develops. It has been found that parts of the self-pumped phase conjugate beam emerge out of the crystal as additional transmission beams. They grow in intensity as the phase conjugation develops. Other measurements which combine coherent or incoherent coupling beams are presented and used to explain the observations.

Keywords. Phase conjugate effect; self-pumping; specular reflection; second surface reflection.

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1. Introduction

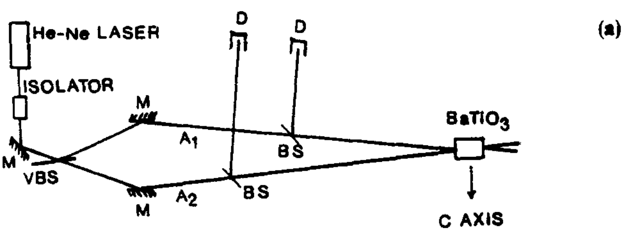
We have reported earlier at recent conferences (Venkateswarlu *et al* 1989a, b, c), our preliminary results on beam couplings and on the effects of phase conjugation in transmission and reflection in $BaTiO_3$. Pepper (1989) has reported his observation of the decrease in specular reflectivity from phase conjugate mirrors with the increase in phase conjugate reflectivity. Lindsay and Dainty (1986) reported cancellation/partial cancellation of specular reflection at a plane mirror in the presence of a phase-conjugate mirror, while Lindsay (1987) later discussed its cancellation and enhancement. The experimental results were in agreement with the theoretical predictions of Friberg and Drummond (1983), Drummond and Friberg (1983) and Nazarathy (1983). While the work described in the earlier papers of Lindsay and Dainty (1986) and Lindsay (1987) dealt with effect of phase conjugate beam on specular reflection at a separate mirror different from the phase conjugator, the present work like that of Pepper (1989) deals with the effect of phase conjugation on specular reflection from the phase conjugate mirror itself.

Further we have observed that not only the specular reflection but also the subsequent second-surface reflection of an extraordinary polarized beam, incident on the face of a $BaTiO_3$ crystal parallel to its *c*-axis, gets reduced in intensity, though for a different reason, as the self-pumped phase conjugation develops. We noticed also that parts of the self-pumped phase conjugate beam go out of the crystal as additional transmitted beams which grow in intensity as the phase conjugation develops. The details of this work and the results obtained will be presented. Other measurements which combine coherent or incoherent coupling beams with the self-pumping beams are also presented and used to explain the observations. Very recently Zhang *et al* (1990) reported self-pumped phase conjugation in suitably cut $KNbO_3$:Fe crystal and a simultaneous reduction in specular reflection and also in a corresponding reflection from the ring cavity.

2. Experiment and results

We used the experimental configurations shown in figures 1(a) and 1(b) to study the effects of phase conjugation and beam couplings on transmission and reflection in $BaTiO_3$ crystal 5·7 × 7·4 × 7·6 mm^3) using a He–Ne laser (6328 Å). Two horizontally polarized coherent beams A_1 and A_2 meet in the crystal as shown in figure 1(a). The crossing angle is 5°, with A_1 making 73° with the *c*-axis in horizontal plane. Figure 1(b) shows the experimental arrangement where two separate He–Ne lasers are used for incoherent beam excitation. Here the beam crossing angle is 11° while the two horizontally polarized beams A_1 and A_2 make 73° and 84° with the *c*-axis respectively. The point of entry in figures 1(a) and 1(b) is about 2 mm from the edge nearest to A_1 and the spot size about 1.5 sq.mm. Under individual pumping, one sees at the detectors D_1 and D_2 the self-pumped phase conjugate beams A^*_{1i} and A^*_{2i} of A_1 and A_2 respectively (figure 2a). The letter *i* in the subscript is used to signify that the phase conjugates correspond to those obtained under individual pumping. A_1T and A_2T are the main transmitted beams of A_1 and A_2 respectively. They decrease in intensity as their phase conjugates develop under individual pumping. The reflected beams (A_1R_1, A_1R_2) and (A_2R_1, A_2R_2) in figure 2a are seen even when the self-pumping is not developed, while additional transmitted beams (A_1T_1, A_1T_2) and (A_2T_1, A_2T_2) appear as the corresponding self-pumped phase conjugates of A_1 and A_2 develop.

Figure 2a shows the different reflected and transmitted beams of A_1 and A_2 while



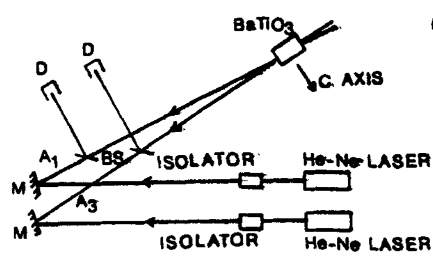


Figure 1. Experimental arrangement. M: Mirrors, BS: Beam splitters, VBS: Variable beam splitter, D: Detectors (a) A_1 and A_2 are coherent beams from a He–Ne laser. (b) A_1 and A_3 are from two separate He–Ne lasers and are incoherent.

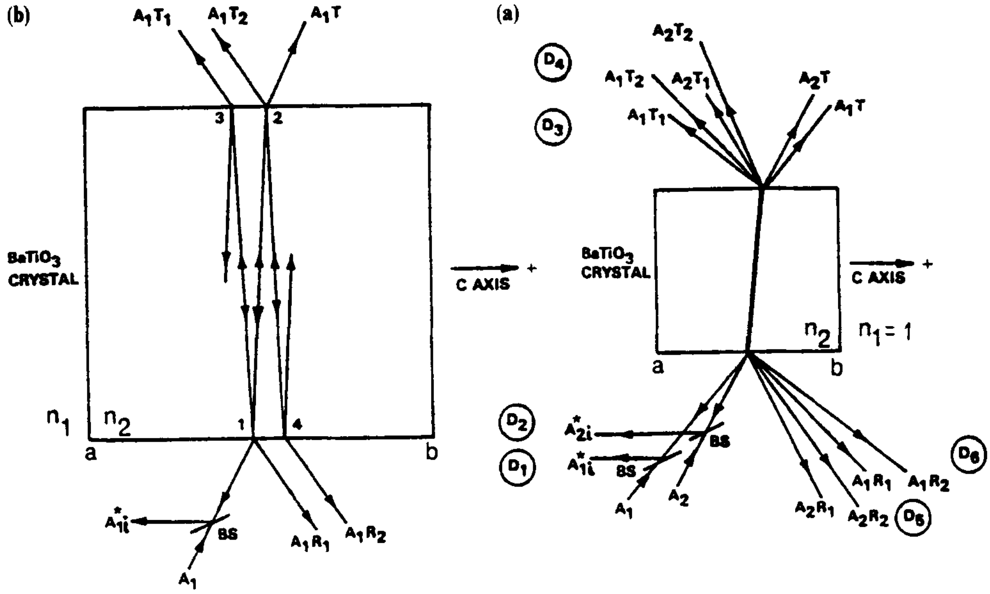


Figure 2a. Reflection, transmission and phase conjugate signals: A_{1i}^*, A_{2i}^* are phase conjugates of A_1 and A_2. (A_1R_1 and A_1R_2) and (A_2R_1 and A_2R_2) are reflected beams of A_1 and A_2 respectively. (A_1T_1 and A_1T_2) and (A_2T_1 and A_2T_2) are phase conjugate transmissions of A_1 and A_2 after internal reflection. A_1T and A_2T are main transmissions of A_1 and A_2 respectively. n_1 and n_2 are the refractive indices of the media. D: Detectors, BS: Beam splitters. $n_1 = 1$ for air.

Figure 2b. Development of A_1R_1 the specular reflection, A_1R_2 the second surface reflection from the back, and A_1T the main transmission of A_1. The phase conjugate signal A_{1i}^* and the transmitted signals A_1T_1 and A_1T_2 are dependent on self-pumped phase conjugation. A_1T_1 and A_1T_2, if retroreflected will travel in the directions of A_1R_1 and A_1R_2 respectively. The development of the reflected and transmitted beams of A_2 will be similar to those of A_1. n_1 and n_2 are the refractive indices of the media.

figure 2b shows the development of the transmitted beams, and the reflected beams corresponding only to the beam A_1 under consideration. It is seen that, if A_1R_1 is retroreflected by a mirror, it goes out along A_1T_1 and similarly A_1R_2 gets retroreflected along A_1T_2. Retroreflections of A_1T_1 and A_1T_2 will similarly emerge out along A_1R_1 and A_1R_2 respectively. These are more separated than expected because of the slight deviation of the front and back surfaces of the crystal from parallelism. It is seen that instead of running parallel, A_1R_1 and A_1R_2 diverge while A_1T_1 and A_1T_2 first come together and cross very near the surface of the crystal and then diverge. This feature is not shown in the figure. The transmitted beams A_1T_1 and A_1T_2 arise essentially from the self-pumped beam as seen in the figure 2b. Under simultaneous pumping, A_1 and A_2 are mutually Bragg-diffracted (Eason and Smout 1987; Smout and Eason 1987; Ewbank 1988) partially at the gratings formed due to fanning, and emerge in the directions of A_2 and A_1 respectively. Further, the fannings of these beams help one another to increase their individual self-pumped phase conjugation (Feinberg 1983). It is seen from the present experiments that, under simultaneous pumping, A_1 and A_2 get cross coupled also in transmission and reflection in the same manner as in self-pumped beams.

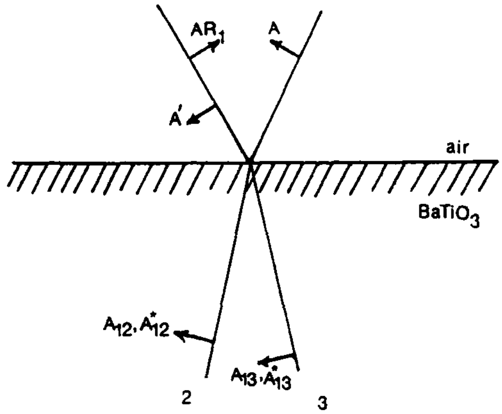


Figure 3. Polarization directions at interface. A: Input Polarization. AR_1: Reflection of A. A_{12}: Transmission of A. A_{12}^*: PC of A_{12}. A_{13}: Reflection of A_{12}^*. A_{13}^*: PC of A_{13}. A′: Transmission of A_{13}^*.

The development of the signals A_{1i}^*, A_1R_1, A_1T_1, A_1R_2 and A_1T_2 (figure 2b) are recorded in different sets of experiments. When A_1 is turned on, the specular reflection A_1R_1 and the subsequent second surface reflection A_1R_2 shoot up immediately, and A_{1i}^*, A_1T_1, A_1T_2 grow with time and stabilize, while A_1R_1 and A_1R_2 decrease in intensity and stabilize.

The beam A_1 is horizontally polarized and is parallel to the plane of incidence. A part of the phase conjugate of A_1 gets reflected at the point 1 (figure 2b), goes in the direction $1 \rightarrow 3$ and partly gets phase conjugated to return to the point 1 along the direction $3 \rightarrow 1$, and then emerges in the direction A_1R_1. Thus this emerging beam which has undergone phase conjugation two times is in phase with A_1, and therefore its amplitude has the same sign as A_1 but opposite in sign to that of A_1R_1 for the angles of incidence used (Rossi 1957), explaining partly the decrease in intensity of the specular reflection as the self-pumped phase conjugate increases. This can be seen clearly from figure 3 which shows the polarization directions at interface of the various rays involved. Our observation concerning the decrease of intensity of specular reflection is in agreement with Pepper's (1989) observation as well as with that of the earlier workers (Lindsay and Dainty 1986; Lindsay 1987; Drumond and Friberg 1983). Pepper (1989) showed how the intensity of the specular reflection decreases as the phase conjugation increases.

The beam A_1 after refraction gets internally reflected at point 2 (figure 2b) and comes to point 4 and then emerges as A_1R_2. However, a part of the internally reflected beam $2 \rightarrow 4$ gets self-pumped, reverses its direction and emerges in the direction of A_1T_2. This process appears to be partly responsible for the decrease in intensity of A_1R_2, as the self-pumped phase conjugation A_{1i}^* and the related A_1T_2 develop. The effects of fanning, the build up of A_{1i}^* and other related factors on the decrease of A_1R_2 are to be looked into.

In one of the experiments (figure 1a), the powers in the coherent beams A_1 and A_2 are kept at 3·0 mW and 3·5 mW respectively. The self-pumped signal A_{1i}^*, the transmitted signal A_1T_2 and the reflected signal A_1R_2 as recorded at the detectors D_1, D_4 and D_6 (figure 2a) respectively, when only the beam A_1 is turned on, are shown in figure 4. One can see that A_1R_2 decreases while A_1T_2 grows up with A_{1i}^*.

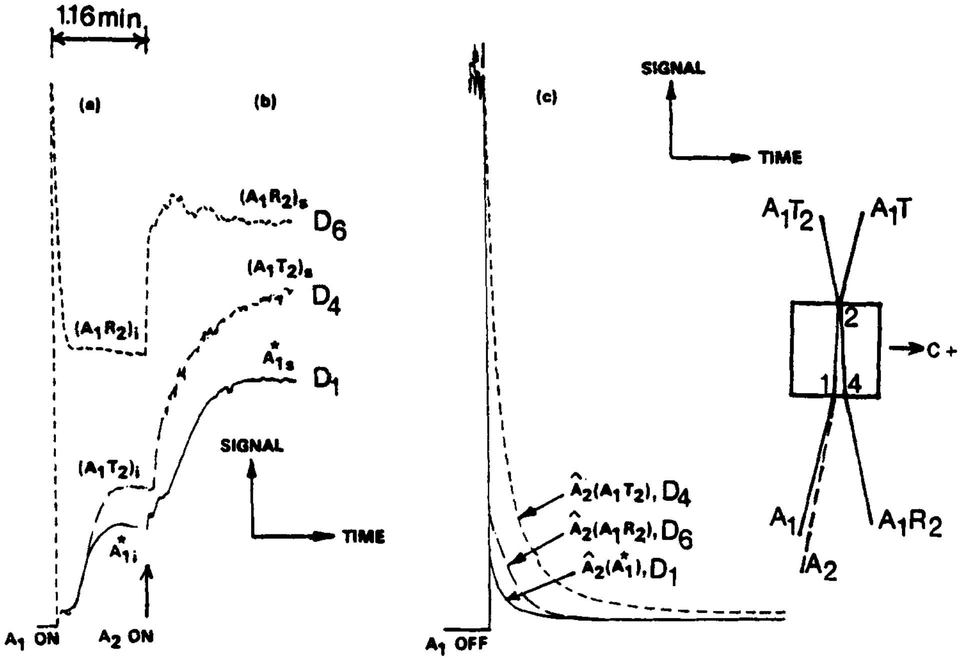


Figure 4. (a) reflected beam $(A_1R_2)_i$, transmitted beam $(A_1T_2)_i$ and self-pumped phase conjugate beam A_{1i} under individual pumping by the beam A_1 at the detectors D_6, D_4 and D_1 respectively shown in figure 2a. (b) $(A_1R_2)_s$, $(A_1T_2)_s$ and A^*_{1s} represent their reflected, transmitted and self-pumped phase conjugate beams under simultaneous pumping by the coherent beams $(A_1 + A_2)$. (c) Decay of the signals in (b) when A_1 is turned off. $\hat{A}_2(A_1R_2)$, $\hat{A}_2(A_1T_2)$ and $\hat{A}_2(A^*_1)$ represent the signals at the detectors D_6, D_4 and D_1 respectively due to the cross coupling from the beam A_2. The time period for figure 3a, b (together) is 2·5 min and that for 3c is also 2·5 min. Insert represents experimental arrangement in brief. The amplification factors of D_6, D_4 and D_1 in figure 3(a, b) are 10^5, 10^6 and 10^5 respectively while their ranges are 2·2 V, 700 mV and 2·0 V respectively. In figure 3c, their amplifications are 10^6, 10^6 and 10^5 while their ranges are 240 mV, 2·2 and 2·3 V respectively. To get the relative magnitudes of these signals the *y*-axis values are to be multiplied by 0·24, 2·2 and 23 respectively.

$(A_1T_2)_i$, $(A_1R_2)_i$ and A^*_{1i} represent the stabilized values at the detectors D_4, D_6 and D_1 respectively under individual pumping by A_1 alone. When A_2 is also turned on, all the three signals increase in intensity, but when A_1 is turned off they all decay, instead of abruptly coming to zero, indicating that the decay is of the cross coupled components of beam A_2 in all three signals [figure 4 (c)]. The stabilized values of the signals at D_4 D_6 and D_1, under simultaneous pumping by A_1 and A_2, are represented in figure 4 by $(A_1T_2)_s$ and $(A_1R_2)_s$ and A^*_{1s} respectively. The increase in these values under simultaneous pumping over those under individual pumping suggests that the positive cross-coupling effects are larger in this experiment than the erasure effects of A_2.

In the second experiment (figure 1b), the power in the beam A_1 was 7·4 mW. A beam A_3 (9·4 mW) from a second He–Ne laser was used to study the effects of incoherent beams in reflection and transmission. Figure 5 shows that the specular reflection A_1R_1 at the detector D_5, which is steady for a while, begins to decrease and stabilize at a lower intensity level as the self-pumped phase conjugate A^*_{1i} and the beam A_1T_1 develop, and stabilize. These developments in A_1R_1 and A_1T_1 are

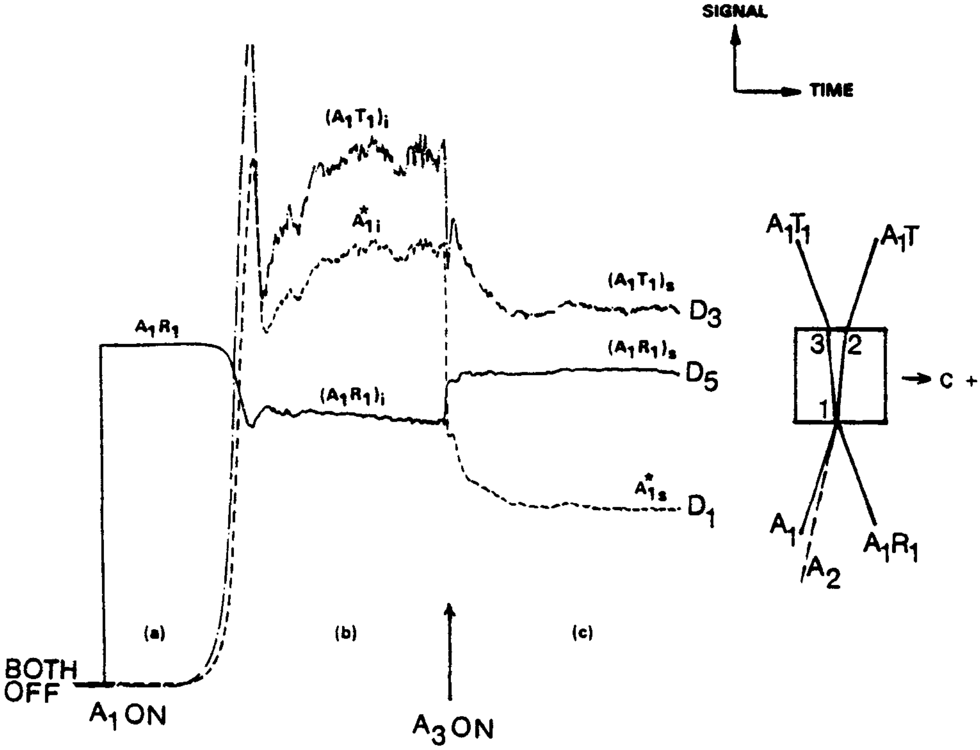


Figure 5. (a) Specular reflection A_1R_1. (b) the stabilized specular reflection $(A_1R_1)_i$, self-pumped phase conjugate A^*_{1i} and the transmission $(A_1T_1)_i$ under individual pumping by A_1, as observed at the detectors D_5, D_1 and D_3 respectively shown in figure 2a. (c) $(A_1R_1)_s$, $(A_1T_1)_s$ and A^*_{1s} represent the reflected, transmitted and the self-pumped phase conjugate beams under simultaneous pumping by the incoherent beams $(A_1 + A_3)$. The total time period is 10 min. Insert shows experimental arrangement in brief. The amplifications of D_3, D_5 and D_1 are all 10^5 while their ranges are 350 mV, 3·5 V and 1·0 V respectively. To get the relative magnitudes of these signals, the y-axis values are to be multiplied by 0·34, 3·5 and 1·0 respectively.

similar to those in A_1R_2 and A_1T_2 shown in figure 4. Under simultaneous pumping of A_1 and the incoherent beam A_3, the specular reflection A_1R_1 at the detector D_5 increases while the signals A_1T_1 at the detector D_3 and the phase conjugate signal A^*_1 at D_1 decrease. When A_1 is turned off, small effects of the cross-couplings from A_3 are seen in A^*_1 and A_1R_1 at D_1 and D_5 respectively, but no such effects are seen in A_1T_1 at D_3 as it goes down to zero abruptly while the signals at D_1 and D_5 do not. These decay curves are not shown in the figure. As the beam coupling effects between the incoherent beams A_1 and A_3 are very small, the changes in the signals at the detectors D_1, D_3 and D_5 in figure 5c under simultaneous pumping are probably mainly due to the erasure effects of A_3 on the grating responsible for phase conjugation. This results in an increase of the signal A_1R_1 and decrease in A^*_{1i} and A_1T_1.

In a third experiment with the same parameters as in figure 1b, it is found that when only A_1 is on, A_1R_2 first stabilizes at a low level, unlike in figure 4, even before the phase conjugation develops, and it then decays and stabilizes at a lower value,

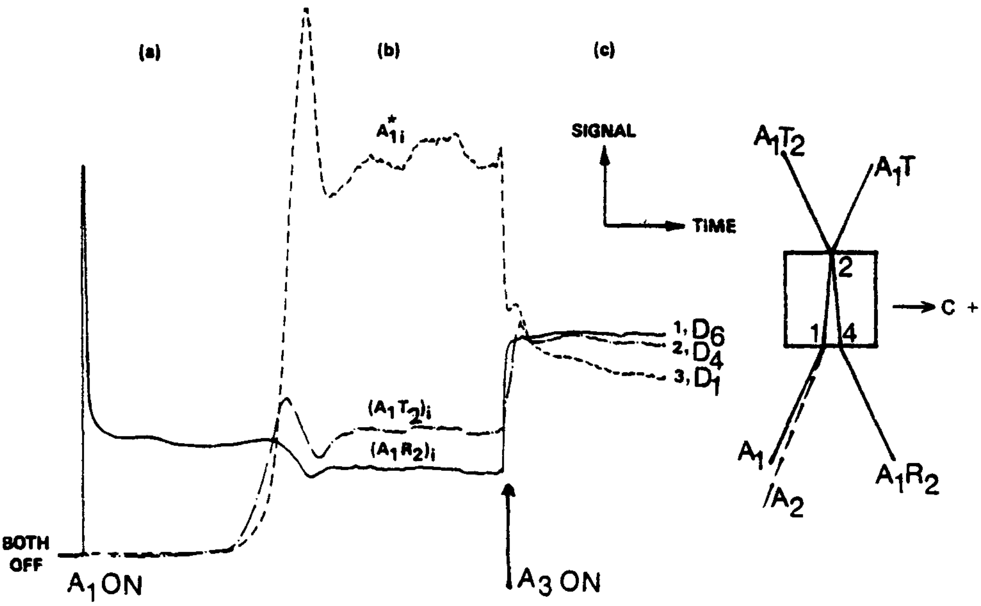


Figure 6. (**a**) The second surface reflection A_1R_2 from the back before phase conjugation develops. (**b**) The stabilized back reflection $(A_1R_2)_i$, self-pumped phase conjugate A^*_{1i} and the transmission $(A_1T_2)_i$ under individual pumping by A_1 as observed at the detectors D_6, D_1 and D_4 respectively shown in figure 2a. (**c**) The curves marked 1, 2 and 3 represent the reflected, transmitted and self-pumped phase conjugate beams $(A_1R_2)_s$, $(A_1T_2)_s$ and A^*_{1s} respectively at the detectors D_6, D_4 and D_1 under simultaneous pumping by the incoherent beams (A_1+A_3). The total time period is 7 min while that for 5 (a and b) is 5 min. Insert shows experimental arrangement in brief. The amplifications of D_6, D_4 and D_1 are all 10^5 while their ranges are 2·0 V, 200 mV and 1·0 V respectively. To get the relative magnitudes of these signals, the y-axis values are to be multipied by 2·0, 0·2 and 1·0 respectively.

as the phase conjugate signals A^*_{1i} and A_1T_2 develop and stabilize (see figure 6a, b). It may be noted here that the time scales are different in the two cases. It took longer time in figure 6 for the phase conjugation to develop fully than in figure 4. There is also an over shoot in the phase conjugate signal of figure 6 which is not present in figure 4. It is not yet clear whether the differences in behaviour in figure 6a, b from those in figure 4a are because of the higher power (7·4 mW) of the beam A_1 in figure 6a than that (3·4 mW) in figure 4. When the incoherent beam A_3 is also turned on, the phase conjugate beam A^*_1 decreases in intensity while the beams A_1T_2 and A_1R_2 increase in intensity in figure 6. The grating erasure in the region $1\rightarrow 2$ causes a stronger reflected beam (A_1) at point 2 and this would increase both A_1R_2 and A_1T_2. Like in the earlier experiment small effects of cross-coupling of A_3 are seen in A^*_1 and A_1R_2 (see figure 7) at the detectors D_1 and D_6 respectively, if the crystal is first simultaneously pumped by A_1 and A_3, and then A_1 is turned off. The signals at the detectors D_1 and D_6 did not fall down to zero abruptly when A_1 is turned off. However no effect of the coupling is seen in A_1T_2 at the detector D_4.

Experiments have been carried out to see the effect of angle of incidence ϑ_i of the incident laser beam on the self-pumped phase conjugate reflection and on the percentage of decrease in specular reflection and second surface reflection. The angle

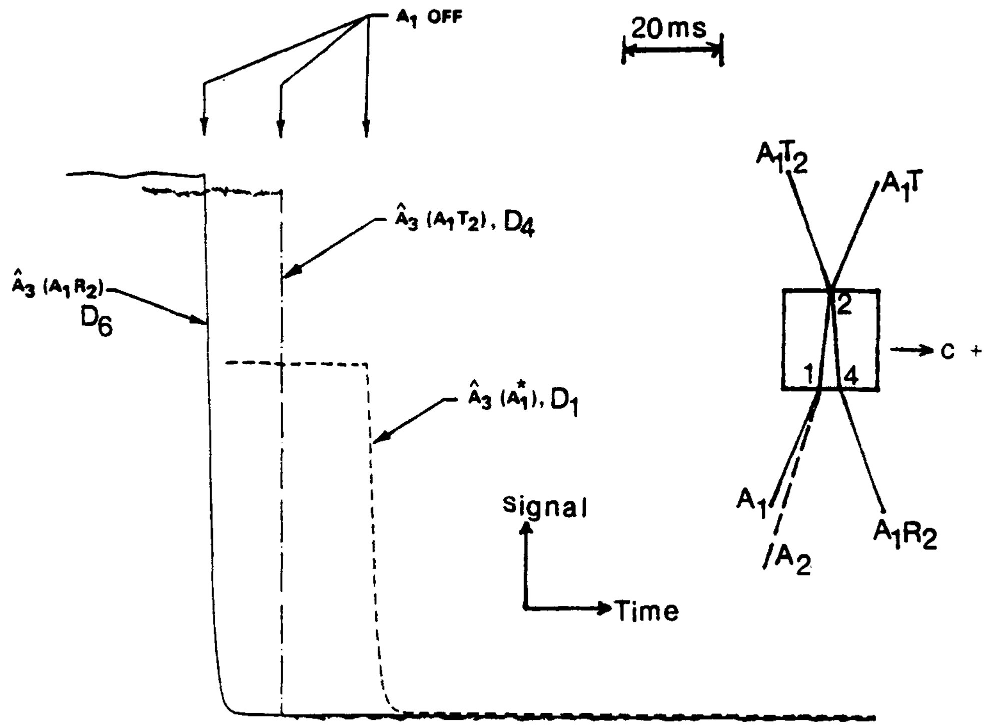


Figure 7. Decay of the signals in figure 5c when the beam A_1 is turned off. $\hat{A}_3(A_1R_2)$, $\hat{A}_3(A_1^*)$ and $\hat{A}_3(A_1T_2)$ represent the signals at the detectors D_6, D_1 and D_4 respectively shown in figure 2a. Small cross coupling from A_3 is noticeable in $\hat{A}_1$ and A_1R_1 but not in A_1T_2 which abruptly goes to zero. The curves are shifted with respect to one another along horizontal for clarity. Insert shows experimental arrangement in brief. The amplifications of D_6, D_4 and D_1 are 10^6, 10^4 and 10^4 respectively while their ranges are 200 mV, 50 mV and 400 mV respectively. To get the relative magnitudes of these signals, the y-axis values are to be multiplied by 0·2, 5·0 and 40 respectively.

of incidence used varied from 5° to 45°. It has been found that the phase conjugate reflectivity increased with the angle of incidence ϑ_i in the range 5°–24° and accordingly the specular reflection and the second surface reflection decreased with the increase in the angle of incidence. There was not much change in the intensity of the phase conjugate when ϑ_i was increased from $\vartheta_i = 24°$ to $\vartheta_i = 45°$ and therefore not much change in the reduction of the intensities of reflections have been noticed.

Experiments have also been carried out on the effect of the point of entry of the laser beam on the crystal surface containing the crystal axis in the horizontal plane keeping the angle of incidence at 7°. The length of the edge ab of the crystal (figure 1b) is 7·6 mm. For the points of entry up to 1·5 mm from the point a, there was no self-pumping and beyond 1·5 mm the self-pumping showed up and increased. It was maximum in the range 2·5 to 4 mm beyond which it decreased and beyond 6 mm there was no self-pumping. The intensity of the incident beam has an effect on the self-pumped phase conjugate reflectivity. The self-pumped phase conjugate reflectivity increases with the intensity of the incident beam, but beyond, say about 15 mW, it decreased slightly because of self erasure.

3. Discussion

The behaviour seen in figures 4–6, that A_1R_1 and A_1R_2 decrease in intensity as the phase conjugate A_1^* develops while A_1T_1 and A_1T_2 increase, is as expected according to the discussion presented earlier.

It may be noted that beam fanning might be a possible cause for the initial decrease in intensity of $(A_1R_2)_i$ in figures 4 and 6 even before phase conjugation develops. The effect of the additional fanning and the beam coupling, in A_1^*, A_1T_1 and A_1T_2 when a second beam is turned on appears to be different in the three experiments. In figure 4 the phase conjugate signal at the detector D_1 under simultaneous pumping is larger than that under individual pumping, while it is smaller in figures 5 and 6. As indicated above and as reported by us (Venkateswarlu *et al* 1988a, b) and by Moghbel (1989) earlier, the stabilized signal A_{1s}^* at the detector D_1 under simultaneous pumping of two beams may probably be represented by

$$A_{1s}^* \approx A_{1i}^* + \hat{A}_2 - \Delta_1 \tag{3}$$

where A_{1i}^* represents the self-pumped phase conjugate of A_1 at the detector D_1 under individual pumping by A_1, $\hat{A}_2$ represents the increase in the signal at D_1 due to the mutual fanning effects and cross coupling, and Δ_1 represents the erasure effects of A_2 on the grating responsible for generating A_{1i}^*. There are two parts in $\hat{A}_2$. One is because A_1 and A_2 are mutually Bragg diffracted partially at the gratings formed due to fanning, and emerge as $\hat{A}_{1s}$ and $\hat{A}_{2s}$ in the directions of A_2 and A_1 respectively (Eason and Smout 1987; Smout and Eason 1987; Ewbank 1988). Further the fanning of these beams mutually help one another to increase the individual phase conjugations (Feinberg 1983) which may be represented by δA_{1s}^* and δA_{2s}^* respectively, and thus $\hat{A}_2 \approx (\hat{A}_{2s} + \delta A_{1s}^*)$.

If $\hat{A}_2$ is larger than Δ_1, the signal A_{1s}^* at D_1 from the relation (1) comes out to be more than the signal A_{1i}^* under individual pumping. On the other hand if $\hat{A}_2$ is less than Δ_1, A_{1s}^* at D_1 will be less than A_{1i}^*. Thus in the first experiment (figure 4) the increase of the signal under simultaneous pumping by A_2 and A_1 suggests that the erasing effect Δ_1 by A_2 is smaller than its contribution to increase the signal through its fanning and cross coupling. The reverse is the case in figures 5 and 6.

The increase or decrease of A_1T_1, A_1T_2 and A_1R_2 under simultaneous pumping may probably be understood on the same basis as those of A_1^* at D_1. It is however not essential that they behave exactly in the same manner, as the beam couplings take place in different parts of the crystal with different relative orientations with respect to the crystal. The beam A_1R_2 in figure 6c increased in strength to a higher value than what it was in figure 6a before the phase conjugation developed. This additional increase may be due to the significant effects of fanning from A_3R_2 on A_1R_2 and also similar effects from A_3 and A_3T_2. A small beam coupling from A_3 in A_1R_2 is noticed in this experiment but not as much as it was of A_2 in figure 4b where coherent beams were used. This might be partly because the crossing angle between the coherent beam A_1 and A_2 (figure 1a) is 5° while that between the incoherent beams (figure 1b) is 11°. Further the effect of beam couplings and fanning may be expected to depend also on whether the two beams that interact are coherent to one another, or are incoherent (Venkateswarlu *et al* 1988b). One expects that when A_1T_2 increases, A_1R_2 decreases which is as observed in individual pumping. However as both increase in figure 6c, when A_3 also is turned on, it appears that the positive effects of fanning due to A_3, A_3T_2 and A_3R_2 are very significant in increasing the signals A_1T_1 and A_1R_2 here.

4. Conclusions

The effects of phase conjugation on reflection have been shown to lead to decrease in intensity of specular reflection as well as the second-surface reflection. The origin of these results as well as the appearance of the components of the phase conjugate beam as two additional beams in transmission from the back surface is discussed. These effects appear to play an effective role in beam couplings.

The decrease and a possible cancellation of the specular reflection and the second-surface reflection at suitable angles of incidence may find applications in the fabrication of optical components like lenses and prisms with suitable photorefractive materials without the necessity of anti-reflection coating.

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