Signal-to-pump ratio dependence of buildup and decay rates in photorefractive nonlinear two-beam coupling

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The buildup and the decay of photorefractive two-beam coupling are experimentally demonstrated to be strongly dependent on the intensity ratio of the two beams (signal-to-pump ratio). The experiment, done with a $BaTiO_3$ crystal, shows good agreement with the theory of two-beam coupling in the depleted-pump regime. The deviation of the response behavior from the small-signal regime is seen for ratios as small as $\sim 10^{-5}$. These results are significant for applications of two-beam coupling as gain media, especially for the elimination of amplified noise (fanning).

Two-beam coupling is a basic process in photorefractive optics. It is used as a tool for understanding and studying material parameters and processes and as a building block for more-complex optical configurations, such as four-wave mixing for phase conjugation. It is also attractive on the application side because of the possibility of obtaining high gains for laser beams with pictorial information. Amplification factors of $\sim 10^4$ and higher can be obtained[1] with photorefractive $BaTiO_3$ or strontium barium niobate crystals. One interesting example, out of many suggested applications with photorefractive wave mixing in image processing, is the novelty filter. It is an all-optical processor that is based on the response of two-wave mixing[2] (or four-wave mixing[3]). It is obvious that the temporal dynamics of the wave-mixing process is essential. However, such an analysis has been done only in a limited fashion, mainly in the undepleted-pump approximation, because of the difficulty in obtaining explicit analytical solutions of the overall photorefractive nonlinear wave-mixing dynamics. Understanding the dynamics can be beneficial even for steady-state applications. For example, it is known that the steady-state high gain in two-wave mixing is accompanied by intense noise originating from amplified scattering from imperfections in the crystal. This is the fanning effect in photorefractive crystals. Rajbenbach *et al.*[4] succeeded in eliminating this noise by rotating the mixing crystal. This procedure caused a selective erasure of gratings, which is explained below.

Here we present an experimental study of buildup and erasure behavior for two-beam coupling with a strong signal beam, and we compare our results with those of an analysis that accounts for pump depletion.[5] Our main result is the experimental verification of the strong dependence of the buildup and the erasure rates on the signal-to-pump ratio. We show that the deviation of the response behavior from the small-signal regime is significant even for low signal-to-pump ratios of 10^{-5}. These results have implications for the use of two-wave mixing as an amplifying medium. They explain, for example, the slow buildup of noise (fanning) compared with the signal and the reason for its suppression when the mixing crystal is rotated.[4]

The coupling equations for two-wave mixing in photorefractive media are[6-8]

$$\frac{\partial A_1(z,t)}{\partial z} = -\frac{\gamma}{G} E_{sc}(z,t) A_4(x,t), \tag{1}$$

$$\frac{\partial A_4{}^*(z,t)}{\partial z} = \frac{\gamma}{G} E_{sc}(z,t) A_1{}^*(z,t), \tag{2}$$

$$\frac{\partial E_{sc}(z,t)}{\partial t} + \frac{E_{sc}(z,t)}{\tau} = \frac{G}{\tau} \frac{A_1(z,t) A_4{}^*(z,t)}{I_0}, \tag{3}$$

where G and τ are constants, γ is the photorefractive coupling constant, E_{sc} is the internal space-charge electric field that is developed in the material, and A_1 and A_4 are the pump and the signal amplitudes, respectively. (τ depends on the total beam intensity, which was kept constant in our experiments.) These equations were solved[5-8] in the undepleted-pump approximation. An interesting result was the dependence of the buildup and the erasure of the gratings on the coupling constant γ. As γ [and the steady-state amplification factor $\exp(\gamma l)$, where l is the interaction length in the photorefractive crystal] increases, the normalized response becomes slower or the frequency bandwidth of the amplifier decreases.[5,8] This behavior resembles other amplifiers and can be explained by the fact that at high amplifications the signal energy in the interaction zone of the crystal is drawn mostly from the diffraction of the pump beam by the grating inside the material. Because the grating is not altered at the moment the input signal is turned off, the signal inside the crystal initially remains strong, and therefore the output signal drops off slowly. Our purpose here is to study the cases in which the signal intensity is nonnegligible. For comparison with the experimental data, the solution of Eqs. (1)–(3) was obtained numerically, as was done in Ref. 5.

The experiment setup is similar to the regular two-wave mixing configuration, shown in Fig. 1. The two beams with the 514.5-nm line of an argon-ion laser illuminated the photorefractive medium, a poled 7 mm × 6 mm × 3 mm $BaTiO_3$ crystal with the c axis along the 7-mm side. The spot sizes of the beams in the interaction zone in the

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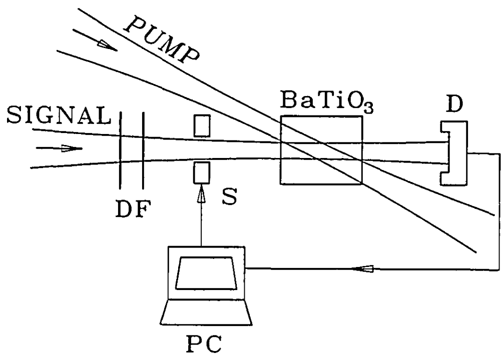

Fig. 1. Schematic of the experimental setup. DF, neutral-density filter; S, shutter; PC, personal computer; D, detector. The pump and the signal beams are denoted as 1 and 4, respectively, in the text.

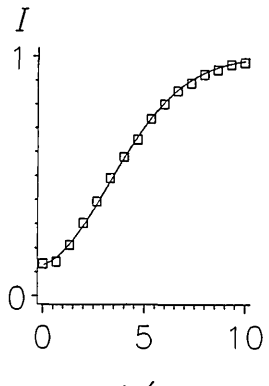

Fig. 2. Experimental data and a theoretical fit of the (normalized) signal output buildup for the small-signal regime, with a signal-to-pump ratio of $I_4/I_1 = 9.7 \times 10^{-6}$. The estimation from the data here together with that from Fig. 3 gives $\gamma l = 3.6$ and $\tau = 1.5$. In this graph, with the relatively small signal, the amplified noise (fanning) is significant, and therefore we preferred to include it in the experimental data; hence, the recorded signal does not start from a zero value. This background was added to the theoretical curve.

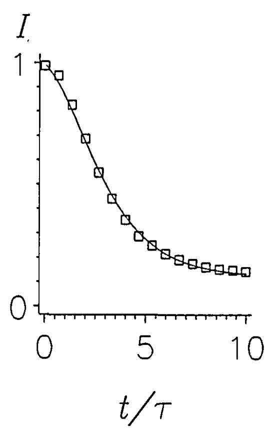

Fig. 3. Experimental data and a theoretical fit of the (normalized) signal output decay for the small-signal regime with a signal-to-pump ratio of $I_4/I_1 = 9.7 \times 10^{-6}$. As for Fig. 2, the signal includes the fanning and does not decay to a zero value.

crystal were ~1 mm. The input was to the surface normal to the c axis, and the angles between the beams and the c-axis direction were 15° and 38° (outside the crystal). Different coupling coefficients (γl) can be obtained by changing the angles of the beams and the crystal orientation.[5] In the experiment, which was controlled by a personal computer, we measured the response of the amplifier for various signal-to-pump ratios after the input signal was turned on and off.

In the comparison of the experimental and theoretical results, we start with the undepleted-pump regime. This allows us to estimate the parameters γ and τ, as was done in Ref. 5. Figures 2 and 3 give the experimental and theoretical curves for the buildup and decay of a small signal. This gives $\gamma l = 3.6$ and $\tau = 1.5$ s. The fitting is based on common values of τ and γl for the buildup and the erasure processes together. Here the signal-to-pump ratio was 9.7×10^{-6}. The pump beam had a power of 10 mW in all experiments. The use of moderate powers was found to be important for obtaining nonerratic data; the data can be highly sensitive to thermal effects, as is discussed below.

We next compare the experimental results with those of the theory[5] in the depleted-pump regime. Figures 4 and 5 show the experimental results for the normalized signal output buildup and decay with various signal-to-pump ratios. We can see that the behavior of the time response strongly deviates from the small-signal regime for signal-to-pump ratios, I_4/I_1, as small as $\sim 10^{-5}$. (The pump

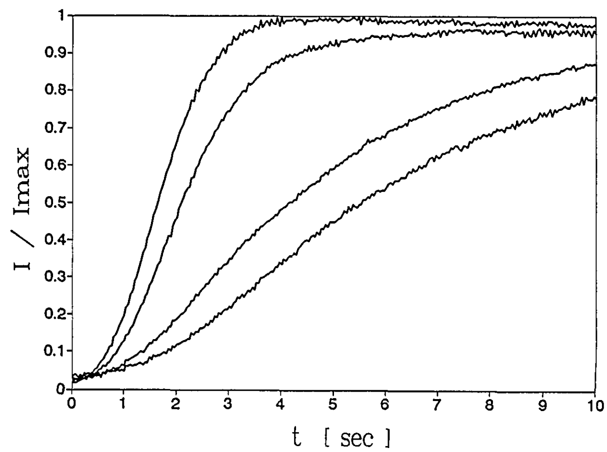

Fig. 4. Experimental results of the (normalized) signal output buildup for various signal-to-pump ratios I_4/I_1: 2×10^{-5}, 4×10^{-5}, 1.5×10^{-4}, and 3×10^{-4}. Curves with quicker buildups correspond to higher ratios.

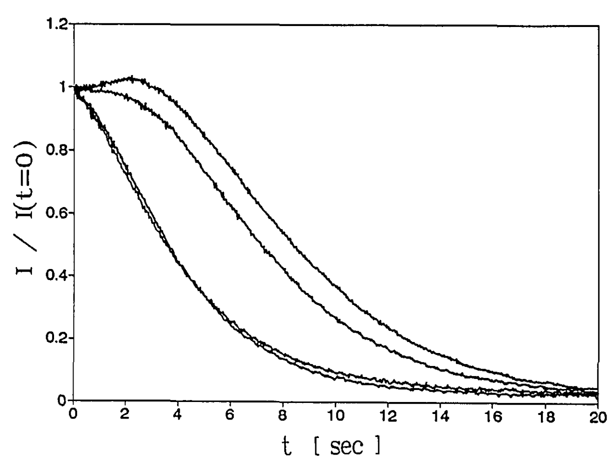

Fig. 5. Experimental results of the (normalized) signal output decay when the input signal is turned off, for various signal-to-pump ratios I_4/I_1: 2×10^{-5}, 4×10^{-5}, 1.5×10^{-4}, and 3×10^{-4}. Curves with slower decays correspond to higher ratios.

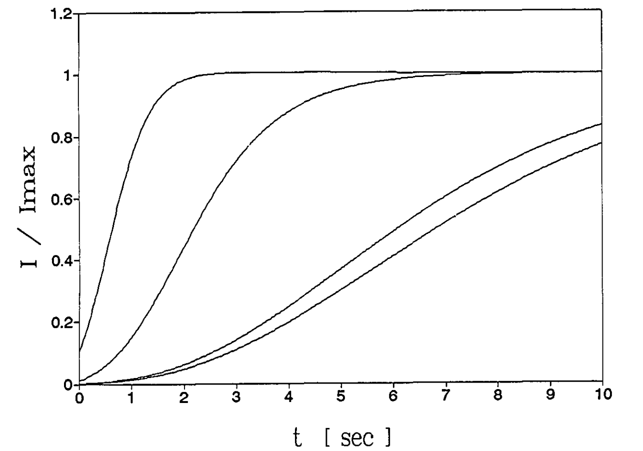

Fig. 6. Theoretical results of the (normalized) signal output buildup for various signal-to-pump ratios I_4/I_1: 2.5×10^{-5}, 2.8×10^{-4}, 1/100, and 1/9. The coupling constant used in these curves is the estimated $\gamma l = 3.6$ from the small-signal experimental curves of buildup and erasure (Figs. 2 and 3). Curves with quicker buildups correspond to higher ratios.

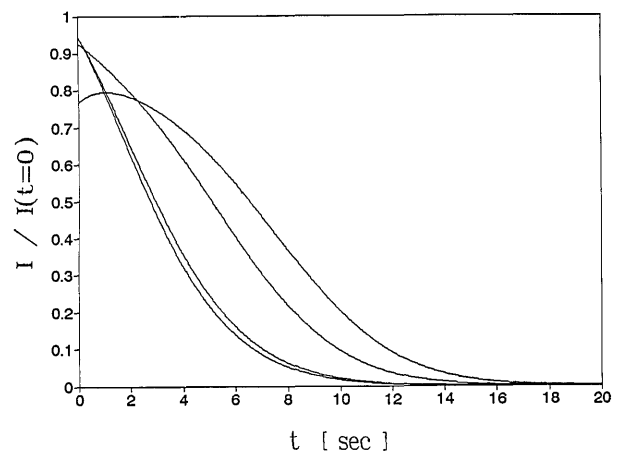

Fig. 7. Theoretical results of the (normalized) signal output decay when the input signal is turned off for various signal-to-pump ratios I_4/I_1: 2.5×10^{-5}, 2.8×10^{-4}, 1/100, and 1/9. The coupling constant used in these curves is the estimated $\gamma l = 3.6$ from the small-signal experimental curves of buildup and erasure (Figs. 2 and 3). Curves with slower decays correspond to higher ratios.

beam had a power of 10 mW.) In Fig. 4, for the buildup process, curves with quicker responses correspond to higher signal-to-pump ratios. In the erasure process, Fig. 5, curves with slower decays correspond to higher ratios. Figures 6 and 7 show the results of the numerical solution of Eqs. (1)–(3). The figures depict the buildup and the decay of the signal for several signal-to-pump ratios with the parameters estimated from the experiments represented in Figs. 2 and 3. (The experimental geometry was the same for all experiments.) We can see good qualitative agreement between the theoretical and the experimental results. It is not a complete quantitative fit because of the inherent amplified noise, the fanning, in the experiments. This noise, which has not been taken into account in the model, causes a significant depletion of the pump beam. The signal beam is not greatly affected in such a process because of its different angular orientation, which results in lower coupling constants (γ) and lower amplification for the relevant noise components. Another reason for a stronger depletion of the pump is that its fanning occurs along its whole path. The signal interaction length is effectively shorter because of its a gradual buildup. Therefore the effective beam signal-to-pump ratio is lower than the input values indicated in the figures. We elaborate on this effect below.

Figure 4 shows that the stronger the input signal, the faster is the buildup of the output signal, as is predicted by the numerical solutions (Fig. 6). The reason is the limited possible gain for a strong signal because of pump depletion. Figures 5 and 7 show that the time needed to erase the grating becomes longer as the signal becomes stronger. The reason is that, even after the signal is turned off, the grating and the pump diffraction continue to generate the signal and sustain the grating. The stronger the modulation depth, the stronger the grating amplitude, and the erasure becomes slower. In the experimental graphs of the decay process for strong signals we also see a rise in the output before it starts to decay, as is predicted by the theory. This phenomenon stems from the fact that, after the signal is turned off, there is an increase in the pump intensity. Hence, because of the pump depletion, the grating is developed in regions in which it could not develop previously. The new grating causes an increase of the scattering efficiency of the pump with a resultant rise in the strength of the output signal.

There are several factors that limit the agreement between the theoretical model and the experimental results. We have mentioned the amplified noise scattering (fanning effect). This effect causes a depletion of the pump and also of the signal itself. Since the noise components have lower intensities than the two beams, the time scale of this depletion is longer than the signal amplification buildup, as can be seen in Fig. 8. Another discrepancy is the instantaneous drop of the calculated output in Fig. 7 after the input signal is turned off. The theory predicts an immediate drop in the output signal because of the loss of the part of the input that is eliminated.[5] In our experimental measurements (Fig. 5) we did not see a significant drop. We can eliminate the drop in the calculations by making γ complex and introducing a phase shift of 17° (for small signals) in the complex plane.[9] This means that the regular 90° phase shift between the interference pattern and the

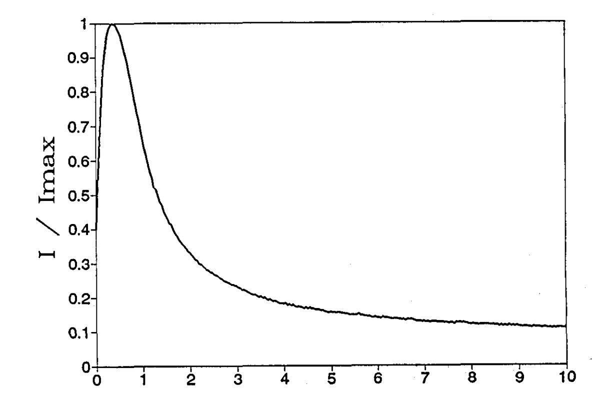

Fig. 8. Experimental results showing the long-term buildup of the signal, taken for high signal-to-pump ratios of 1/10. (The intensity I is in arbitrary units). Here we see the strong depletion of the signal beam caused by the fanning (amplified noise) buildup, which has a slower response.

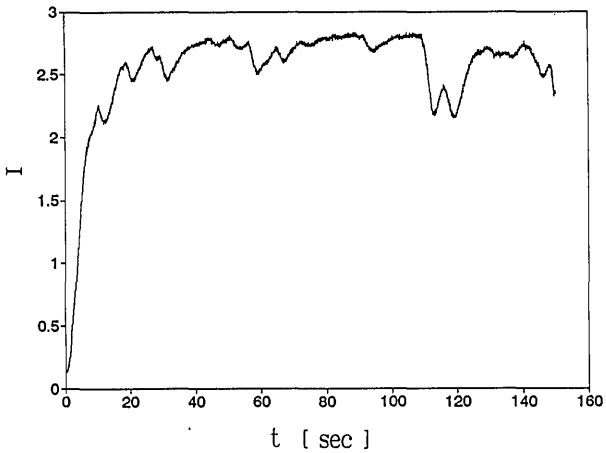

Fig. 9. Experimental data for the signal output buildup for strong input beams, showing the fluctuations that are due to thermal changes in the crystal. Here the pump power was 50 mW, compared with 10 mW in all other experiments.

grating is reduced by that amount. This shift can arise from dc electric fields in the crystal of ~0.4 kV/cm. In fact, several studies reported such internal fields (of photovoltaic or other origin) in $BaTiO_3$.[9,10]

We also observed strong fluctuations and an oscillatory behavior of the output signal when the power was increased. Figure 9 shows this behavior in the buildup process, seen for a moderate power increase of the pump beam to 50 mW, compared with 10 mW in the former experiments. This is probably caused by thermal changes, which were found to have a strong effect in strontium barium niobate and $BaTiO_3$ crystals,[11] or by other mechanisms.[12]

Our results explain the experiment of Rajbenbach *et al.*,[4] who have found that the amplified scattered noise (the fanning) has a long time constant compared with the signal in a two-wave mixing experiment. They used this effect to reduce the noise by rotating the crystal at a rate that was fast for the noise and slow for the signal buildup (and vice versa for the erasure). Then the fanning does not have the time to build significantly (and the small part that is sustained is easily erased). The difference in the time constants is a simple result of the fact that the strength of the scattered light that gives rise to the fanning is much less than the strength of the input signal in the crystal.

In conclusion, we have presented experimental results showing a dependence of the buildup and erasure rates in photorefractive two-wave mixing on the signal-to-pump ratio. The experiment was done with a $BaTiO_3$ crystal. The results were compared with numerical calculations of the coupled equations for strong signals in the undepleted-pump regime and were found to give a good fit. Our results explain the experimental method in which amplified noise is eliminated by rotating the mixing crystal, and the method can be useful in other dynamic photorefractive devices, such as novelty filters.

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