Conversion of unpolarized light to polarized light with greater than 50% efficiency by photorefractive two-beam coupling

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All known polarizers operate through a separation of orthogonal electric field components, one of which is subsequently discarded. As a result, 50% of the unpolarized incident light is wasted in the process of conversion to polarized light. We demonstrate a new method by which we use the optical power in the ordinarily discarded component as the pump to amplify the retained component through photorefractive two-beam coupling to achieve greater than 50% throughput. © 2000 Optical Society of America

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Unpolarized light is a superposition of light of two orthogonal states of polarization, with a relative phase that fluctuates randomly. Standard linear polarizers function by transmission of one polarization component and rejection of the other and thus have a maximum of 50% efficiency for converting unpolarized light to linearly polarized light. In this Letter we describe a new method for converting unpolarized light to polarized light with, in principle, unit efficiency. Our method takes advantage of the phase-insensitive nature of photorefractive two-beam coupling to amplify one polarization component of a light beam, using the orthogonal component as a pump beam. In some respects our technique is similar to the known technique of beam cleanup, in which light that is ordinarily rejected by a spatial filter is used to amplify the clean zero-order spatial frequency component.[1]

The photorefractive effect[2] occurs in certain nonlinear materials in which the redistribution of optically excited charge carriers leads to a modification of the refractive index. Let us assume that two optical waves interact within a photorefractive material so that the field within the material can be described by

$$E(\mathbf{r},t) = [A_p(z)\exp(i\mathbf{k}_p\cdot\mathbf{r}) + A_s(z)\exp(i\mathbf{k}_s\cdot\mathbf{r})]\exp(-i\omega t) + \text{c.c.} \quad (1)$$

The standard mathematical models[3] of the photorefractive effect show that a refractive-index distribution (i.e., a grating) described by

$$n = n_0 + \left(\frac{1}{2}\, i{n_0}^3 r_{\text{eff}} E_m \frac{{A_s}^* A_p}{|A_p|^2 + |A_s|^2} + \text{c.c.}\right) \quad (2)$$

is established within the material. Here r_{eff} is the electro-optic coefficient that is relevant to the polarization direction of the interacting waves and E_m is a material- and geometry-dependent parameter with the dimensions of a field strength that characterizes the maximum space-charge field that can be established in the material. The refractive-index distribution is shifted spatially in phase with respect to the optical intensity distribution by $\pm\pi/2$ rad, depending on the sign of r_{eff}, which is determined by the crystal orientation. This phase shift allows one diffracted beam to interfere constructively with the zero-order component of the other, thus providing gain, while the other pair of diffracted and zero-order beams interferes destructively, attenuating the other beam. Energy transfer is thus unidirectional, depending on the crystal orientation and, most importantly, independent of the phase difference between the two input beams.

Depolarized beams possess statistically random spatial and temporal variations in the phase difference between orthogonal electric field components. The spatial and temporal bandwidths associated with these random differences yield a measure of the spatial and temporal degree of depolarization for the field. A depolarized beam can be separated into two linearly polarized beams by use of a polarization-dependent beam splitter; however, the phase-shift difference between the beams remains a randomly varying function of space and time. Photorefractive two-beam coupling is insensitive to sufficiently slowly varying random phase differences between the interacting beams and transfers power unidirectionally by dynamically adjusting the grating phase. Furthermore, experiments have confirmed that two-beam coupling is possible even with light of limited spatiotemporal coherence.[4] Thus, this coupling process can in principle be used to transfer all the optical power from one polarization component emerging from a polarizing beam splitter to the other, producing a beam containing nearly all the optical power in a single polarization state. The initial polarization inhomogeneity will, of course, be imprinted in the form of an intensity inhomogeneity for each of the split-off beams. However, for sufficient gain and interaction length this effect will not result in significant nonuniformity of the intensity of the output beam. The finite spatial and temporal bandwidths of the photorefractive response ultimately impose corresponding limits on the extent of the spatial and temporal degree of depolarization of a beam that can be corrected with near-unit efficiency. For barium titanate,[5] the spatial resolution is of the order of 1–5 μm, and the temporal

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response time is approximately 0.5 s at a light intensity of 1 W/cm^2.

To demonstrate this technique we employed the setup shown in Fig. 1(a). Passing a linearly polarized, collimated Gaussian laser beam at 514 nm through a birefringent spatial depolarizer scrambles the polarization state of the beam in the transverse spatial plane. A polarizing beam splitter then splits the beam into orthogonal linear components. A half-wave plate then rotates the rejected vertical component by 90°, copolarizing both beams. An external crossing angle of 10° is employed. We refer to the beam that is amplified as the signal beam (S) and to the beam that is attenuated as the pump beam (P). A conventional polarization analyzer is used to determine that the amplified signal beam remains linearly polarized. In Fig. 2 we plot the measured power of the exiting signal beam as a function of analyzer angle for two cases. In the first case we block the pump beam before it enters the barium titanate so that no power transfer can occur. The data show that the signal beam is linearly polarized, because the intensity of the light transmitted through the analyzer obeys the $\cos^2\theta$ dependence of the law of Malus. When we repeat the experiment with the pump beam applied, we measure a nearly twofold increase in transmitted signal power. The $\cos^2\theta$ dependence of signal power on analyzer angle (Fig. 2) shows that the amplified signal beam remains linearly polarized.

We quantitatively determined how efficiently we can transfer optical power between orthogonal polarization states. These experiments were performed at 633 nm at which the photorefractive sensitivity of barium titanate is lower than 514 nm. We found that we were able to suppress unwanted competing processes (such as linear absorption and self-pumped phase conjugation) more readily at this longer wavelength. We employed the setup shown in Fig. 1(b), which is similar to that of the first experiment, shown in Fig. 1(a), except that before it enters the polarizing beam splitter the light is deterministically linearly polarized and rotated to some arbitrary angle by a half-wave plate, thus producing two orthogonally projected components. Here we varied the input polarization angle and measured the time evolution of the power transfer by use of two-beam coupling for various input angles. Figure 3(a) shows the measured power of the pump and the signal beams as functions of time for an input polarization angle of 40°. Initially, as can be seen, the signal beam is amplified, whereas the pump beam is depleted. After a fraction of a second, however, the signal-beam power reaches a maximum value, after which both beams are attenuated owing to the growth of beam fanning. A third beam, which we call the fan-suppression beam, at a different wavelength of 514 nm is then directed to overlap the common volume of the signal and the pump beams. At high intensities, the third beam nearly completely washes out the gratings formed by the signal and the pump beams, and beam fanning as well as two-beam coupling is nearly completely eliminated. However, when the third beam has an intensity that is comparable with that of the signal and the pump beams, it suppresses the undesired beam fanning without significantly degrading the desired two-beam coupling process.[6] The optimum intensity for eliminating beam fanning while preserving two-beam coupling was found to be 0.24 W/cm^2, which was 70% of the combined intensity of the signal and the pump beams. The experiment was then repeated with the inclusion of this third fan-suppression beam, and the results are plotted in Fig. 3(b). As can be seen, the signal beam experiences monotonic amplification until virtually all the pump beam is depleted, and subsequently its power remains nearly constant. Temporal evolution traces were taken for input polarization angles ranging from 0° to 90°, and we took the saturating maximum value from each trace to produce the plot shown in Fig. 4. In the figure the measured transmitted signal-beam power is plotted as a function of input polarization angle, and the results are compared (taking reflection losses into account) with the $\cos^2\theta$

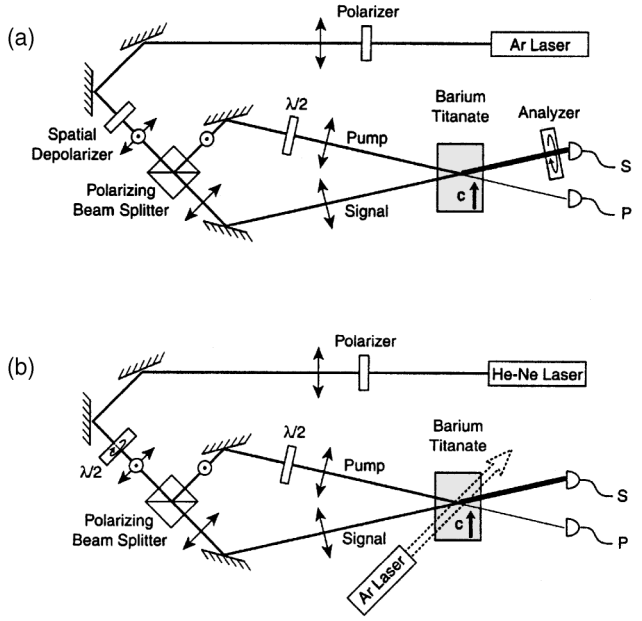

Fig. 1. (a) Experimental setup used to demonstrate the possibility of converting depolarized light to linearly polarized light with greater than 50% efficiency. (b) Experimental setup used to measure quantitatively the extent to which optical power can be transferred between orthogonal polarization states. $\lambda/2$'s, half-wave plates.

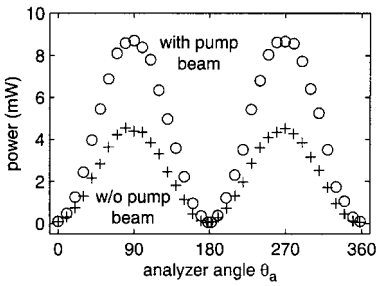

Fig. 2. Power of the 514-nm signal beam measured as a function of the angle of the polarization analyzer of Fig. 1(a). Note that the signal beam has been amplified approximately twofold by the pump beam while maintaining its initial linear polarization.

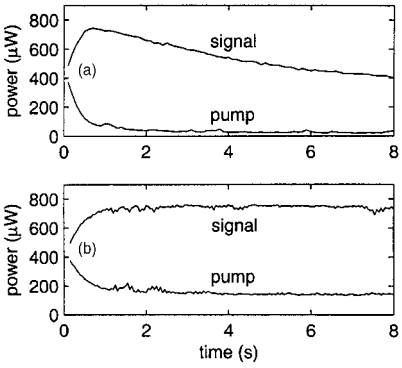

Fig. 3. Temporal evolution of the signal and the pump beams, illustrating power transfer to the signal beam by use of the setup shown in Fig. 1(b). In the absence of the fan-suppression beam (a), the signal beam is initially amplified at the expense of the pump beam. On further evolution, however, both beams are attenuated owing to the growth of beam fanning. By application of the fan-suppression beam (b), beam-fanning losses are minimized, and the amplified signal beam saturates at maximum gain.

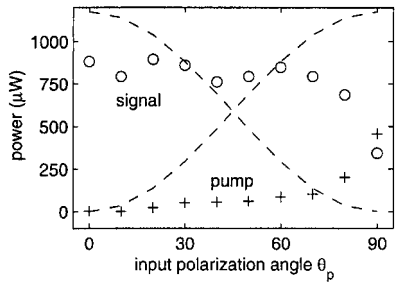

Fig. 4. Measured transmitted power of the signal and the pump beams as a fraction of the input polarization direction. For comparison, the predicted transmittance of an ordinary linear polarizer is also shown (dashed curves). The transmitted signal power is nearly constant for a wide range of input polarizations and exceeds the value predicted by the law of Malus for $\theta_p > 30°$. The data were collected at 632.8 nm with the setup shown in Fig. 1(b).

dependence of the law of Malus, which would be expected for an ordinary polarizer. The transmitted signal beam is linearly polarized and nearly constant in optical power for a wide range of input polarization angles. An ideal photorefractive polarizer, with complete two-beam coupling energy transfer and unit internal transmission, would give 100% transmitted intensity for all polarizer orientations except $\theta_p = 90°$, where there is no signal to be amplified. Owing to the high photorefractive gain coefficient and imperfections in our polarizing beam splitter, the data point at $\theta_p = 90°$ for the signal beam is not at zero. Nonetheless, the device is able to exceed the predicted law of Malus for a significant range of input polarization angles. The maximum internal efficiency is 73%, as opposed to 50% for a conventional polarizer.

With the photorefractive materials that are available at present, this technique is limited to temporally coherent light. However, as photorefractive materials continue to improve in speed and sensitivity, we envisage future application of this technique to broadband or faint signals. Other two-beam coupling processes, such as Brillouin coupling[7] or two-wave mixing after imparting a frequency shift to one beam in strongly driven atomic systems,[8] could be used as a nonlinear mechanism for our scheme. Our device would then improve the effectiveness of very sensitive detection schemes that require polarized inputs, such as certain astronomical observations and night-vision applications.

From a certain perspective our results seem surprising, because the randomness or entropy of the polarization state of the light[9] has decreased as a result of the nonlinear optical interaction. In this regard our system bears some analogy to Bennett's Maxwell demon.[10] Presumably this decrease in entropy is compensated for by an increase in the entropy associated with other degrees of freedom of the overall system, such as the intensity of the transmitted light field, the phase of the space-charge grating in the crystal, and the thermalization of energy within the crystal following the decay of the space-charge grating.

In summary, we have presented the design of a new polarizer that can turn unpolarized light into polarized light with essentially unit efficiency. We have constructed a device that converts spatially unpolarized light to polarized light with greater than 73% internal efficiency. We have also presented experimental results that quantify how efficient the energy transfer of the photorefractive coupling scheme can be.

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