Double-color-pumped photorefractive oscillator and image color conversion

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Can two laser beams of different colors interact with each other to initiate a photorefractive oscillation *in a slowly responding (~1 sec) crystal?* We report on the operation of this new nondegenerate four-wave mixing device, in which two other beams and the gratings are efficiently self-generated. An application for image color conversion is demonstrated. In an experiment, we used for the two pumps combinations of the lines of an argon-ion laser (514.5, 496.5, 488, 476.5, and 457.9 nm) and a He–Ne laser (632.8 nm). The mixing crystal was $BaTiO_3$ with a photorefractive time constant of the order of 1 sec.

We describe and demonstrate a new photorefractive oscillation by dynamic four-wave mixing (4WM) that is induced and pumped by two input beams of different colors. Despite their difference in wavelength, these beams interact with each other to cause the self-generation of a common grating and two oscillation beams of different colors. Efficient wave mixing occurs even in a slowly responding photorefractive crystal such as $BaTiO_3$ (used in our experiments), which has a time constant of about 1 sec. Since this process is self-produced, it finds the solution with highest gain, which corresponds to automatic Bragg matching. This device, which we call the double-color-pumped oscillator (DCPO), is an outgrowth of the double phase-conjugate mirror[1,2] (DPCM), in which two input beams that may be mutually incoherent but of the same wavelength are simultaneously phase conjugated. In the DCPO, this frequency-degeneracy constraint is relaxed. Spatially modulated beams of different colors can exchange their spatial information through the wave mixing, resulting in image color conversion. We demonstrate this effect here; another important application for beam steering, which is free of Bragg restrictions, is presented elsewhere.[3]

The DCPO is shown in Fig. 1. Two input beams 4 and 2, with different wavelengths λ and λ', respectively, are directed into opposite faces of a photorefractive crystal. An oscillation buildup occurs, in which a coherent grating is generated in conjunction with two output beams 1 and 3, with wavelengths λ and λ', respectively. These self-generated beams emerge from the interaction region at an angular offset θ with respect to the input beams 2 and 4. This phenomenon is fundamentally different from other multicolor operations of phase-conjugate mirrors[4] and four-wave mixing.[5]

The physical mechanism behind this peculiar oscillation pumped by two beams of different colors is similar to that of the DPCM.[1,2] That is, the grating is induced by each of the pump beams 4 and 2 with its own self-generated mate 1 and 3, respectively. Beams 4 and 1 with wavelength λ together with beams 2 and 3 at wavelength λ' mutually build a common set of gratings. In the **k** vector picture,[3] the self-generated beams (the directions of $\mathbf{k}_1$ and $\mathbf{k}_3$), and their common grating $\mathbf{k}_g = \mathbf{k}_4 - \mathbf{k}_1 = \mathbf{k}_2 - \mathbf{k}_3$, are self-chosen to fulfill the **k** conservation or Bragg condition. This is in contrast to conventional holography or 4WM,[5] in which the grating is externally determined by writing beams, which in turn imposes the Bragg condition. Unlike the DPCM, the DCPO is inherently not a phase-conjugating device, which is manifested in the angular offset of output beams 1 and 3 for nondegenerate frequencies. However, the detailed pictorial information carried on an input beam is still transferred to the reflected output. As in holography, the pictorial input (on beam 4 in Fig. 1) is transferred to beam 3 (at a different color) with magnified or reduced scale. The transferred image quality in beam 3 for λ and λ' far apart will deteriorate. The need to Bragg match all the spatial components of the grating simultaneously puts an upper limit on the number of resolution elements that can be processed for $\lambda \neq \lambda'$.[5]

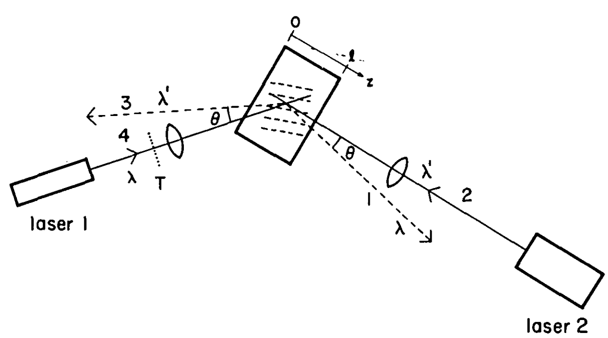

Fig. 1. Schematic of the DCPO with two input beams 4 and 2 of different colors λ and λ', respectively. The spatial modulation T (resolution chart) carried by beam 4, at wavelength λ, into the crystal emerges on an oscillation beam 3 at wavelength λ'. Note the angular deviation θ of the output beams, which automatically optimizes Bragg matching for all values of λ and λ'.

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Image transfer in the DCPO is closely related to the lack of image cross talk in the DPCM, which we have discussed elsewhere.[2] In that device, the buildup of image-bearing phase-conjugate beams occurs without the presence of cross talk between the two images. This is due to the oscillatory nature of the device, in which both the gratings and output beams 1 and 3 build up as an oscillation. The phase-conjugate solution gives the highest gain and fulfills the phase-matching condition. The DCPO, which is a generalization to nondegenerate wavelengths, fulfills the phase-matching without the phase-conjugation condition. We have noticed, in both the DCPO and the DPCM, that spatially modulated input pumps improve the oscillation quality. They eliminate the conical diffraction in the direction perpendicular to the plane defined by inputs $\mathbf{k}_4$ and $\mathbf{k}_2$. This results from the reduction in degrees of freedom for the oscillation vectors $\mathbf{k}_1$ and $\mathbf{k}_3$, which must satisfy the gratings' overlap and Bragg condition for every spatial frequency of the pumps. For the DCPO with different input wavelengths and angular detuning, this requirement seems to permit extensive spatial modulation of one input pump beam. The use for real-time color conversion of images is clear.

In an experimental demonstration of the DCPO, shown in Fig. 1, we used a single-domain $BaTiO_3$ crystal with geometry and orientation similar to that reported earlier for the DPCM.[1] We pumped the crystal with two beams 4 and 2, each of a different color, chosen from the extraordinarily polarized spectrally separated output lines of an argon-ion laser operating on its five strong lines: 514.5, 496.5, 488, 476.5, and 457.9 nm, as well as the 632.8-nm line of a He–Ne laser. Oscillation and efficient self-generation of beams 1 and 3 was achieved with every combination of two lines. To demonstrate image color conversion, one of the pumps (beam 4) with wavelength $\lambda = 488$ nm was spatially modulated by a resolution chart and then focused ($f = 10$ cm) into the crystal face $z = 0$. Each of the argon laser's five lines was alternately used as beam 2, which was focused ($f = 20$ cm) through the crystal face $z = l$ and crossed beam 4 in the crystal with the same angular configuration used for each line. The angle between beams 4 and 2 in the crystal was about 173° (as in the DPCM), and the crystal's midplane $z = l/2$ was approximately the common focal plane of both lenses. In this experiment the c axis is parallel to the z axis in the figure. The image transferred from beam 4 to beam 3, with the color of pump beam 2, is shown in the series of pictures of Fig. 2. Each picture corresponds to a different wavelength of beam 2 (and 3). The intensity of output beam 3, accounting for Fresnel reflections, varied from 30 to 60% of the intensity of input pump 2 over the whole spectral range used. When the He–Ne laser was used for pump beam 2, reconstruction of small, select portions of the image were obtained on beam 3 (not shown in Fig. 2). In this case, the transmission efficiency of the DCPO was about 6% (in Ref. 3 our reported higher efficiencies also compensated for crystal absorption). Besides the decrease in resolution, another important factor is the difference in crystal efficiency for the two input wavelengths. This efficiency is a function of wavelength-dependent material parameters and the input pumps' intensity ratio, as is shown below.

The DCPO operated even when one or both input pumps consisted of the complete (unseparated) all-lines output of the argon laser. In particular, when input beam 4 contained all lines and was spatially modulated, inputting beam 2 at any wavelength λ' within the argon spectrum resulted in efficient oscillations and a spatially modulated output beam 3. In this case, output beam 1 was seen to contain mainly the two strongest argon lines at 488 and 514.5 nm.

An analysis of the DCPO can be carried out in a

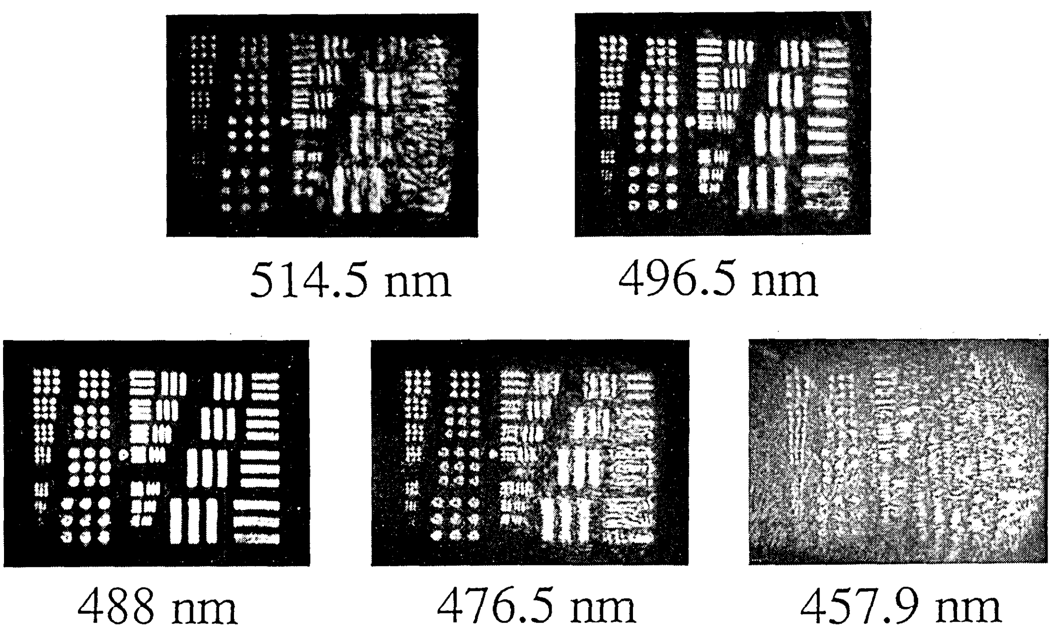

Fig. 2. Photographs of output beam 3 for five values of λ', with λ of beam 4 kept constant at 488 nm. $\lambda' = 488$ nm is the output in the degenerate case and corresponds to a DPCM.

fashion similar to that for the DPCM, in the nondepleted pumps approximation.[2] The coupled-wave equations for the four mixing beams' amplitudes A_i (for beam i) are given by an extension of the degenerate-frequency case (in the slowly varying wave approximation with transmission gratings[6]):

$$\frac{dA_1}{dz} = \frac{-\gamma}{I_0}(A_4A_4^*)A_1 - \frac{u\gamma}{I_0}(A_2^*A_4)A_3, \qquad (1)$$

$$\frac{dA_3}{dz} = \frac{v\gamma}{I_0}(A_2A_4^*)A_1 + \frac{(uv)\gamma}{I_0}(A_2A_2^*)A_3, \qquad (2)$$

where $I_0 = |A_2|^2 + |A_4|^2$ and $\gamma = i/2(2\pi/\lambda)[n_I \exp(-i\zeta_I)/\cos\alpha]$ is the coupling constant for wavelength λ and angle α between beam 1 and the crystal surface ($z = 0$) normal. It incorporates an effective index refractivity n_I, which is a function of various material parameters.[6] ζ_I is the phase shift between the index grating and the fringe pattern and is equal to $\pi/2$ in crystals in which diffusion current dominates.

The difference in the grating writing (or refractivity) with wavelength λ' (beams 2 and 3) compared with λ (of 4 and 1) is manifested in the second terms of Eqs. (1) and (2), through u, where

$$u = \left[\frac{n_I(\lambda')}{n_I(\lambda)}\right]\left\{\frac{\exp[i\zeta_I(\lambda')]}{\exp[-i\zeta_I(\lambda)]}\right\}.$$

This difference is due to the different values of trap density and other material properties for different wavelengths.

The wavelength nondegeneracy in the gratings' reading stage is expressed in the extra factor v in Eq. (2):

$$v = (\lambda/\lambda')(\cos\alpha/\cos\alpha'),$$

where α' is the angle between beam 3 and the crystal's surface ($z = l$) normal (α and α' are not shown in Fig. 1).

From the solution for A_1 and A_3, where the pumps A_2 and A_4 are taken to be constants (nondepleted approximation), we find ρ and t, where

$$\rho \equiv A_3(0)/A_1(0) = \frac{-1}{u}\left(\frac{A_4}{A_2}\right)^* \frac{e^{p\gamma l} - 1}{e^{p\gamma l} - q/(uv)},$$

$$t \equiv A_1(l)/A_1(0) = \frac{e^{p\gamma l}[1 - q/(uv)]}{e^{p\gamma l} - q/(uv)}, \qquad (3)$$

$A_i(0)$ and $A_i(l)$ are the amplitude values of beam i at $z = 0$ and l, respectively, $q \equiv |A_4/A_2|^2$ is the input pumps' intensity ratio, and $p \equiv (uv - q)/(1 + q)$. For an operating DCPO, ρ and t are infinite, since zero beam amplitudes for $A_1(0)$ and $A_3(l)$ grow into nonzero $A_1(l)$ and $A_3(0)$ output beams. At this operating point [from Eqs. (3)],

$$\gamma l = (1/p)\ln[(q/uv)]. \qquad (4)$$

We can derive the threshold value for γl, which is the lowest operatable value, from Eq. (4). This occurs at

$$|(\gamma l)_{\text{th}}| = 1 + 1/(uv) \quad \text{for } q = uv. \qquad (5)$$

Note that for the DPCM (the degenerate case), $uv = 1$ and the correct values are obtained,[1,2] i.e., $|(\gamma l)_{\text{th}}| = 2$ for $q = 1$. As for the DPCM, a calculation that takes the pump depletion into account should predict oscillation in a range of q values for any γl above threshold.[2] Our crystal exhibited $|\gamma l| \approx 3$–4 in a two-wave mixing configuration.

These equations show that there are no basic restrictions on the operation of the DCPO with any two input frequencies λ and λ'. The only requirement is that the corresponding (γl)'s not be less than the $(\gamma l)_{\text{th}}$ derived above. In $BaTiO_3$, (γl) is sufficiently high throughout the visible spectrum including the near infrared.[7] Thus the DCPO using $BaTiO_3$ should be useful in this range and, in particular, from infrared to visible image color conversion.

In conclusion, we have analyzed and demonstrated a new photorefractive 4WM device that is induced and pumped with two beams of different colors. The gratings and the two output beams are efficiently self-generated. This device relaxes the frequency-degeneracy requirements of the DPCM. We have demonstrated image color conversion, in which spatial modulation on an input beam of one color is copied onto the output beam of another color.

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