Self Bragg matched beam steering using the double color pumped photorefractive oscillator

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(Received 5 March 1987; accepted for publication 12 May 1987)

A new method for steering light beams with automatic (self-aligning) Bragg matching is presented. This device enables, in principle, a large beam deflection range which is not limited by the Bragg condition. It is based on a double color pumped photorefractive oscillator. Two input beams of different colors induce and pump a dynamic four-wave mixing process in a photorefractive $BaTiO_3$ crystal in which two other beams and a common set of gratings are self-generated. Steering is achieved by wavelength tuning of one of the pump beams. A deflection range of about 1.7°, with an efficiency ranging from 50 to 90%, is measured for a wavelength difference $\Delta\lambda$ of ± 30 nm for the two pumps (using argon ion laser lines). A deflection of 4.7° with an efficiency of 10% is seen for $\Delta\lambda = 144.8$ nm (corresponding to pumps at 488 and 632.8 nm).

A predominant class of electro-optic techniques for light beam steering is based on the use of tunable volume gratings via acousto-optic[1] or photorefractive effects.[2] These methods share the same basic limitation posed by the Bragg condition, which puts an upper limit on the deflecting range. This limit can be improved by using, for example, precorrection gratings.[2]

Here we present a new method for achieving efficient beam steering in which the Bragg condition is automatically satisfied, and therefore does not present a limitation, over any desired deflection range. This is based on the double color pumped oscillator (DCPO), a novel photorefractive oscillator which we have recently demonstrated[3] and applied for image color conversion.

The DCPO is shown in Fig. 1. Two pump beams 4 and 2, with arbitrary wavelengths λ and λ', respectively, are the inputs into opposite sides of a photorefractive crystal, where they overlap. Even in a slowly responding photorefractive mixer such as $BaTiO_3$ (with a time constant of about 1 s), the input beams interact with each other through a dynamic four wave mixing (4WM) process in which two other beams 1 (with wavelength λ) and 3 (with wavelength λ') are self-generated. This is accompanied by the buildup of gratings written by each pump beam together with its self-diffracted mate. That is, a common grating is simultaneously written by beam couples [4,1] and [2,3]. The $\bar{k}$ vector diagram for this process is shown in Fig. 2. The directions of self-generated beams $\bar{k}_1$ and $\bar{k}_3$ and the direction and magnitude of the grating $\bar{k}_g$ are self-chosen so as to fulfill the Bragg condition for both input colors simultaneously. This results in an angular offset θ (shown in Fig. 1) between the output and input beams for the nondegenerate input wavelengths. The DCPO relaxes the spectral constraints of the double phase conjugate mirror[4] (DPCM) which produces phase conjugate outputs in the frequency degenerate case.

The beam deflection capability of the DCPO is due to the dependence of θ on the wavelengths λ and λ'. For increasing deviations of λ' from λ, this deflection angle increases. Since this process is self-generated, it finds the most efficient angular configuration, that is, automatic Bragg matching occurs.

An analysis of this dependence can be done using Fig. 2, which describes the geometry of the beams inside the crystal. The input parameters are the wave vectors of the pumps $\bar{k}_4$ and $\bar{k}_2$ and the angle Ψ between them. In addition, we know the vector magnitudes $k_1 = k_4 \equiv k = 2\pi/\lambda$ and $k_3 = k_2 \equiv k' = 2\pi/\lambda'$. The directions of the wave vectors of the self-generated beams $\bar{k}_1$ and $\bar{k}_3$ are self-chosen through the oscillation such that a common grating $\bar{k}_g = \bar{k}_4 - \bar{k}_1 = \bar{k}_2 - \bar{k}_3$ is produced. Thus,

$$k_g = 2k \sin(\phi/2) = 2k' \sin(\phi'/2). \tag{1}$$

Furthermore, we see that

$$\phi + \phi' + 2\Psi = 360° \tag{2}$$

by inspection of the diagram. This results in the following expression for the beam deflection θ inside the crystal:

$$\theta = \frac{\phi - \phi'}{2} = \tan^{-1}\left(\frac{\sin\Psi}{(\lambda'/\lambda) - \cos\Psi}\right) - \tan^{-1}\left(\frac{\sin\Psi}{(\lambda/\lambda') - \cos\Psi}\right). \tag{3}$$

For small changes of λ' around λ, this gives

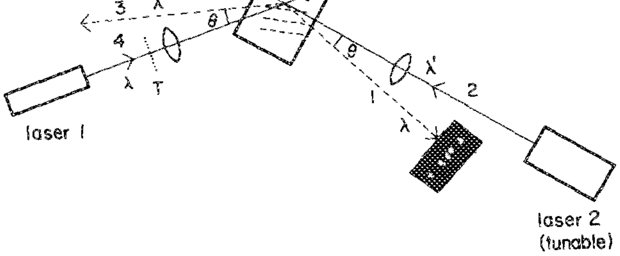

FIG. 1. Schematic of the beam steering experiment with the double color pumped oscillator (DCPO).

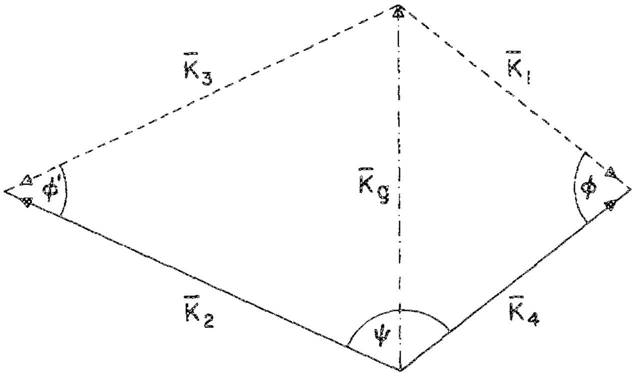

FIG. 2. $\bar{k}$ vector diagram of the beams and gratings. $|k_1| = |k_4| = 2\pi/\lambda$ and $|k_3| = |k_2| = 2\pi/\lambda'$.

$$d\theta = -\sin\Psi\left(\frac{d\lambda}{\lambda}\right). \tag{4}$$

In our experiments $\Psi \simeq 173°$, hence $d\theta \simeq 0.12(d\lambda/\lambda)$ in radians. Outside the crystal this angle is magnified due to refraction by a factor on the order of the crystal's refractive index (~ 2.4). An increase of about one order of magnitude may be achieved for Ψ close to 90° (or large k_g).

We carried out an experimental demonstration of the beam deflection. Two extraordinarily polarized input beams 4 and 2 simultaneously pumped a photorefractive $BaTiO_3$ crystal, as shown in Fig. 1. The c axis is parallel to the z axis in the figure. The input configuration was similar to that described in Refs. 3 and 4. Beam 4 was the $\lambda = 488$ nm line of an argon ion laser operating at all lines. Each of the laser's five strong lines (514.5, 496.5, 488, 476.5, and 457.9 nm) and the HeNe laser line (632.8 nm) took turns being pump beam 2. Efficient wave mixing developed for each value of λ'. Figure 3 shows the deflected output beam 1 and corresponding θ values outside the crystal, for each color of beam 2. The deflection range in this experiment was about 5.7° for a λ' tuning range of 174.9 nm. This value agrees with Eqs. (3) and (4) after accounting for refraction outside the crystal and can be significantly increased in a geometry where Ψ is closer to 90°, and by using a wider range of λ'. High diffraction efficiencies for beam 1 were observed, varying from 50 to 90% for λ' within the argon lines and about 10% for $\lambda' = 632.8$ nm. The coupling efficiency of the DCPO is a function of the input pumps' intensity ratio and material parameters. An analysis[3] of this device reveals that there are no basic restrictions on the range of λ and λ', as long as the photorefractive coupling constant is above some threshold value. In $BaTiO_3$, for example, the whole visible and near infrared spectrum should be appropriate. A continuous deflection can be achieved using a tunable laser, such as a dye or semiconductor lasers. Practical devices would also display fast switching times, unlike the slow response time of our $BaTiO_3$ sample (~ 0.01–1 s). The deflection rate is faster than the photorefractive gratings buildup since the deflection involves small changes in the grating structure and not a new buildup.

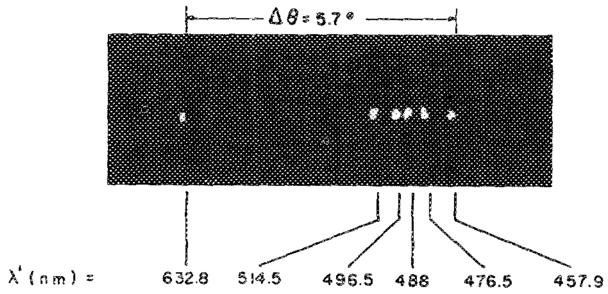

FIG. 3. Deflected output beam 1 (with $\lambda = 488$ nm) for various values of λ'.

The operation of the DCPO improves when spatial information modulates one of the pump beams. This was done in our experiment with a resolution chart T in the path of beam 4, as shown in Fig. 1. It helps force a collapse to an oscillation, by eliminating degrees of freedom for the generated beams 1 and 3.[3,4] Removing this modulation can result in unwanted diffractions, especially out of the plane defined by the input pumps.

In conventional beam steering devices, little control can be exercised in modifying the beams' spatial profile. In some applications, it may be important to spatially modulate as well as deflect a beam. The DCPO is unique in that it integrates these two characteristics while it automatically optimizes the efficiency, as explained earlier. Referring to Fig. 1, output beam 3 at λ', derived from pump 2, takes on the spatial information of pump 4 at λ as it is deflected. Varying λ in this case will change the deflection angle of this modulated output beam. We have demonstrated image color conversion with the DCPO elsewhere.[3]

In conclusion, we have analyzed and demonstrated a new method for steering light beams, using a dynamic photorefractive 4WM oscillation pumped by two beams of different colors. Despite their difference in wavelength they induce the efficient self-generation of a common grating and two deflected output beams of different colors, while automatically satisfying the Bragg condition for arbitrary input wavelengths. Thus, the DCPO presents a solution that overcomes the Bragg restriction of conventional devices without the need for external control. In addition, the spatial profile of the deflected beam can be controlled.

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