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Effect of temperature variation in photorefractive devices

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Abstract

The steady state coupling constant of photorefractive $BaTiO_3$ can be significantly enhanced by cooling it towards its tetragonal to orthorhombic phase transition at 5°C. This enhances the operation of devices such as passive and externally pumped passive phase conjugate mirrors and photorefractive optical limiters.

Introduction

High diffraction efficiency real-time holography in photorefractive barium titanate and its use in coherent beam amplification has made possible many novel nonlinear optical devices including passive (self-pumped) phase conjugate mirrors[1] (PPCM's), optical limiters,[2] unidirectional ring resonators[3] and interferometers.[4,5] In this paper, we describe the use of temperature control to increase the relevant electrooptic coefficient and hence the diffraction efficiency of photorefractive holograms in barium titanate near the tetragonal to orthorhombic phase transition. This enables the operation of devices such as infrared phase conjugate resonators which otherwise would have been below threshold.

Theory

In this section, we consider the theoretical temperature dependence of the coupling constant describing nonlinear photorefractive beam coupling effects. We begin by reviewing the standard theory of two beam coupling.[6] A pair of laser beams interfering in a photorefractive crystal writes a hologram which diffracts each beam into the other, usually causing one beam

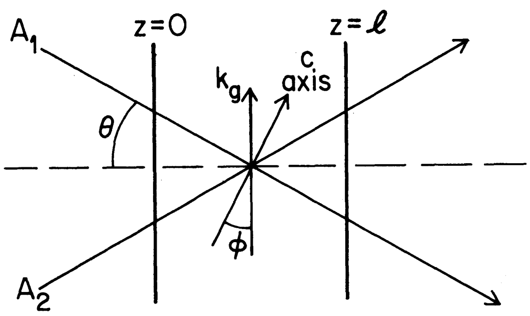

Figure 1. Two beam coupling geometry

to be coherently amplified at the expense of the other. Figure 1 is a diagram of this two beam coupling situation. Let the electric field amplitude associated with beam j be

$$\mathbf{E}_j(\mathbf{r},t) = A_j(\mathbf{r})\exp[i(\mathbf{k}_j\cdot\mathbf{r}-\omega t)] + c.c. \tag{1}$$

The standard coupled wave equations, using the slowly varying field approximation are

$$\frac{dA_1}{dz} = - \frac{\gamma}{I_0} A_1 |A_2|^2 \quad (2a)$$

$$\frac{dA_2^*}{dz} = + \frac{\gamma}{I_0} A_2^* |A_1|^2 \quad (2b)$$

where $I_0 = |A_1|^2 + |A_2|^2$ and the coupling constant γ is given by[7]

$$\gamma = - \frac{\omega}{2c \cos\theta} n_e n_o^2 r_{42} \sin^2\phi \cos\phi \; \frac{k_B T k}{e} \; \frac{1}{1 + (k_B T k^2 / e^2 N_d)\varepsilon} \quad (3)$$

where θ is the beams' angle of incidence, ϕ is the angle between the grating wavevector and the crystal axis, k_B is Boltzmann's constant, k is the grating wavevector, N_d is the trap density ($\approx 10^{16}/cm^3$) and ε is the low frequency dielectric constant ($\varepsilon^{-1} = \varepsilon_a^{-1} \sin^2\phi + \varepsilon_c^{-1} \cos^2\phi$). In our case, ε is of the order[8] of 10^{-8} F/m and the grating wavevector is of the order of 10^6 m^{-1}. There are two terms in the expression for γ given in Eq (3) which show strong temperature dependence near the tetragonal to orthorhombic phase transition,[9] the electrooptic coefficient r_{42} and the low frequency dielectric constant ε_a. These quantities are related to each other independently of temperature between 10°C and 110°C: $r_{42}/(\varepsilon_a - \varepsilon_0) = 0.045\ m^2/C$. That is, r_{42} and ε_a are approximately proportional to each other. At 40°C r_{42} is 1200×10^{-12} m/V, at 20°C it is 1800×10^{-12} m/V and at 10°C it is 3200×10^{-12} m/V. The form of Eq. (3) for γ shows that with the parameters for barium titanate, the tendency for γ to increase with increasing r_{42} far outweighs the tendency for γ to decrease with increasing ε. Thus, by cooling the crystal towards its tetragonal to orthorhombic phase transition, we can expect a large increase in coupling strength.

In $Sr_{1-x}Ba_xNb_2O_6$, another high diffraction efficiency photorefractive crystal, the large electrooptic coefficient is r_{33} which becomes larger towards the tetragonal to cubic phase transition.[10] We can expect to enhance the coupling strength of this crystal by heating it.

Experimental Demonstrations

To demonstrate the effectiveness of operation of barium titanate photorefractive devices near the 5°C phase transition, we examined the effects of temperature variation in several photorefractive devices. In each case, temperature control was achieved by immersing the crystal in an oil filled cuvette mounted on a thermoelectrically cooled copper block.

Fanning optical limiter

When an extraordinarily polarized laser beam passes through a crystal of barium titanate two beam coupling causes light scattered from crystal defects to be amplified into a broad fan of light.[11] This effect is so strong in barium titanate that it can be used as an optical limiting mechanism.[2] Figure 2 is a plot versus temperature of the power T transmitted through the optical limiter at steady state normalized by the power transmitted before the buildup of any holographic gratings. Also shown as a function of temperature is the intensity normalized response time t_r. The angle between the incident beam and the crystal c-axis was 49° measured outside the crystal. We see that between 10°C and 60°C the transmissivity increases from 3% to 11.5% while the response time decreases slightly.

Figure 3 is a plot of steady state transmissivity versus temperature for $10^{18}/cm^3$ cerium doped $Sr_{0.6}Ba_{0.4}Nb_2O_6$. As expected, the efficiency of the limiter becomes larger as the temperature is increased towards the tetragonal to cubic phase transition. However the efficiency increase, as well as the overall efficiency, is much smaller than for barium titanate.

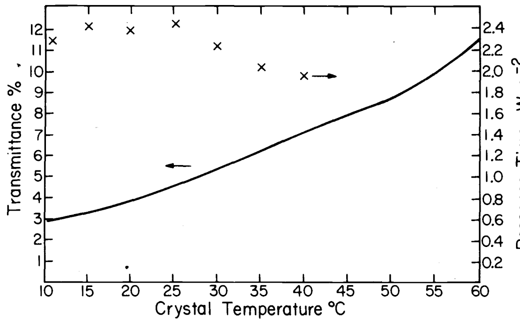

Figure 2. Temperature dependence and speed of response of the fanning limiter in barium titanate.

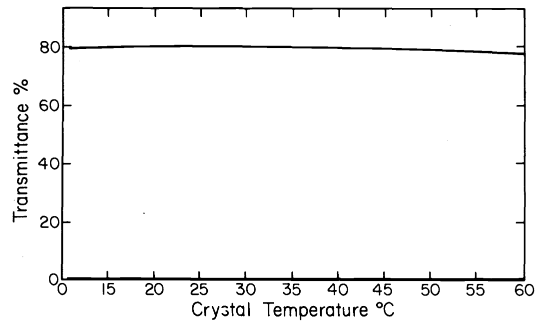

Figure 3. Temperature dependence of transmittance of fanning limiter in strontium barium niobate.

Passive (self-pumped) phase conjugate mirror and optical limiter

The photorefractive gain available in barium titanate is sufficient to enable the operation of oscillator devices which act as passive phase conjugate mirrors (PPCM's), self-inducing their pumps as oscillation beams. These phase conjugate mirrors also act as optical limiters by diverting light from the incident beam into oscillation beams and the phase conjugate reflection. Figure 4 depicts the two interaction region region PPCM which provides feedback for its oscillation beams by total internal reflection from the crystal surfaces.[12] The phase conjugate reflection is generated as beam 1, and beam 2 is limited by diversion of its power into oscillation beams 3,4,3' and 4'. Figure 5 shows the phase conjugate reflectivity and optical limiter efficiency as a function of temperature. At 10°C the phase conjugate reflectivity is 53%, and the normalized limiter transmissivity is 9.3%. At 56°C where the device is at threshold, the reflectivity is 16%, and the limiter transmissivity is 75%.

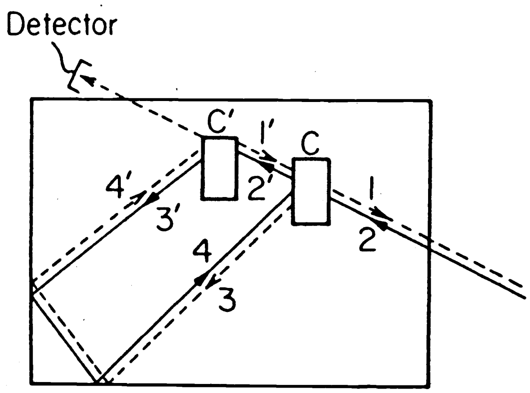

Figure 4. Two interaction region barium titanate passive phase conjugate mirror barium titanate.

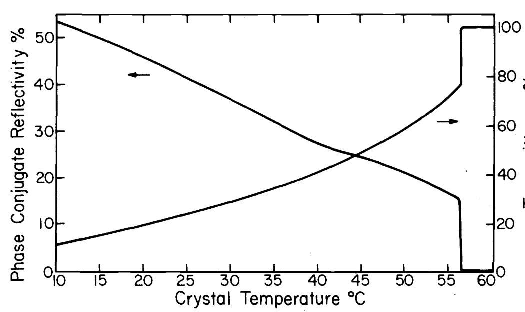

Figure 5. Temperature dependence of reflectivity of two interaction region PPCM and its transmissivity as an optical limiter.

Infrared phase conjugate resonator

The ring PPCM has a relatively low coupling strength threshold: $\gamma \ell = 1$ where ℓ is the length of the interaction region.[1] This enabled its demonstration with GaAlAs laser radiation at 0.85μm and at the 1.06μm line of the argon ion laser.[13] We report here the use of reduced temperature to realize, for the first time, a photorefractive phase conjugate mirror with gain pumped by a GaAlAs laser. The threshold for this device under optimum pumping conditions[1] is $\gamma \ell = 2\ln(1 + \sqrt{2}) \approx 1.76$. Figure 6 depicts a phase conjugate resonator using this phase conjugate mirror. The ordinary mirror (M_2) of this resonator is a high reflectivity dielectric plane mirror. Figure 7 gives the temperature dependence of the power in the oscillation beam normalized by the power of the GaAlAs buried heterostructure window laser[14] measured after the collimating lens. The oscillation intensity is approximately independent of temperature between 10°C and 13°C. Above 18°C the resonator is below threshold.

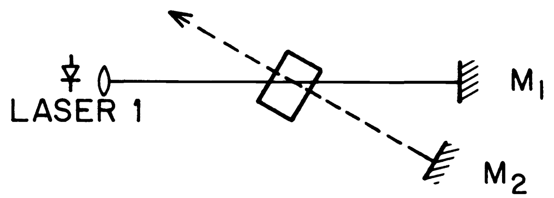

Figure 6. Barium titanate phase conjugate resonator pumped by GaAlAs diode laserr barium titanate.

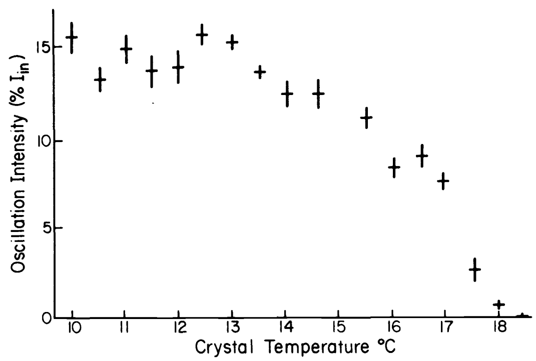

Figure 7. Temperature dependence of normalized oscillation intensity in laser diode pumped phase conjugate resonator.

Conclusion

We have shown that the photorefractive coupling strength in barium titanate may be appreciably increased by cooling the crystal towards its tetragonal to orthorhombic phase transition. The effectiveness of optical limiters and the reflectivity of passive phase conjugate mirrors may be enhanced, and devices such as infrared phase conjugate resonators which would not operate at room temperature may be realized at reduced temperatures.

Acknowledgement

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