1 April 1995

OPTICS COMMUNICATIONS

ELSEVIER

Optics Communications 115 (1995) 563-567

Study of two-wave coupling in Cu:KNSBN using red light

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Received 15 April 1994; revised version received 1 November 1994

Abstract

Two red-wave light mixing amplification in Cu:KNSBN is extensively studied through the gain versus the grating wavelength. The crystal has shown excellent response in the red region. The time evolution of the diffraction efficiency is also investigated.

1. Introduction

Photorefractive crystals have been extensively studied, because they show much promise in the fields of optical information storage, interconnection and information processing [1]. Among these crystals the tungsten bronze family has been shown to have the best structure, featuring the largest linear electro-optical coefficient, no phase transition at room temperature, easy processing and sensitivity to red light.

Two-wave mixing (2WM) has been studied systematically in SBN [1], but only recently in KNSBN [3,4], where most of the works has been focused on phase conjugation. In Ref. [4], experimental research of 2WM in Cu:KNSBN using 514.5 nm an Ar^+-laser was reported; in Ref. [3], Y. Tomita et al. reported obvious amplification in Ce:KNSBN for red light, but did not give the value of the gain.

In this paper, we report an experimental study of 2WM in a Cu:KNSBN crystal using 632.8 nm HeNe laser. Firstly, the gain is measured as a function of the grating wavelength using both 514.5 nm and 632.8 nm laser, then the two results are compared. Furthermore, the process of grating recording has been studied for large and small modulation cases.

2. Gain coefficient and diffraction efficiency

It is well known that steady-state 2WM gain can be expressed as:

$$\frac{I_{\text{with pump}}}{I_{\text{without pump}}} = \frac{(r+1)\exp(\Gamma L)}{1+r\exp(\Gamma L)}, \tag{1}$$

where r is the ratio of the input signal to the pump intensity, Γ is the gain coefficient and $L=l/\cos(\theta'/2)$, where l is the crystal thickness and θ' is the internal beam angle. When r is very small (it is satisfied in our experiment), ΓL becomes an exponential gain coefficient. Γ can be given by [2]

$$\Gamma = \frac{2\pi R\gamma_{\text{eff}}}{\lambda n}\tilde{E}, \tag{2}$$

where λ is the wavelength in vacuum, n is the index of refraction. R is the electron–hole competition factor, $\tilde{E}$ is the imaginary component of the saturation space-charge field, and γ_{eff} is the effective linear electrooptic coefficient. For the $42mm$ point group ($BaTiO_3$, SBN, KNSBN) γ_{eff} is given by

$$\gamma_{\text{eff}} = n_o^4\gamma_{13}\cos\theta' \tag{3}$$

for ordinary polarized light and

SSDI 0030-4018(94)00631-8

$$\gamma_{\rm eff}=\tfrac{1}{2}[n_o^4\gamma_{13}(\cos\theta'-\cos 2\beta')+4n_o^2n_e^2\gamma_{42}\sin^2\beta' +n_e^4\gamma_{33}(\cos\theta'+\cos 2\beta')]\cos\beta' \qquad (4)$$

for extraordinary polarized light. Here n_0 and n_e are the indices of refraction of o and e light respectively, β' is the internal angle between the grating wave vector and $\hat{c}$ axis. Without applied field, the space-charge field $\tilde{E}$, according to the diffusion model, is given by

$$\tilde{E}=\frac{E_d}{1+E_d/E_q}, \qquad (5)$$

where $E_d=k_BTk_g/q$ is the diffusion field and $E_q=qN_{\rm eff}/\epsilon_0\epsilon k_g$ is the maximum sustainable space-charge field. k_B is the Boltzmann's constant, T is the temperature, q is the electron charge, $\epsilon_0\epsilon$ is the susceptibility, $N_{\rm eff}=N_A(1-N_A/N_D)$ is the effective density of acceptor sites, $k_g=2\pi/\Lambda_g$, and Λ_g is the grating wavelength. Wood et al. have given an expression for Γ as a function of Λ_g [5]:

$$\frac{\lambda}{\Gamma\Lambda_g}=\frac{n\epsilon_0\epsilon}{qR\gamma_{\rm eff}N_{\rm eff}}\left(\frac{\lambda}{\Lambda_g}\right)^2+\frac{\lambda^2nq}{4\pi^2R\gamma_{\rm eff}k_BT}. \qquad (6)$$

The recording of the holographic grating is also a 2WM process in which r is larger than that of the amplifying experiment. The modulation index can be described by Kukhtarev's equations. For small modulation m ($m=2\sqrt{I_1I_2}/(I_1+I_2)$), without applied field, the evolution of the grating index can be described as an exponential increase during the recording or an exponential decrease during the erasure. Theoretically, the response time τ in both cases is equal to [2]

$$\tau=\frac{hc\epsilon_0\epsilon}{q\lambda\alpha I\mu\tau_R}, \qquad (7)$$

where h is the Planck's constant, c is the speed of light in vacuum, μ and τ_R are the carrier mobility and the lifetime respectively, and α is the absorption coefficient ($\alpha=s(N_D-N_A)\approx SN_D$). The time evolution of the grating index is given by

$$\Delta n(t)=\frac{R\gamma_{\rm eff}}{2n}m\tilde{E}[1-\exp(-t/\tau)] \qquad (8)$$

and that of the diffraction efficiency can be expressed as

$$\eta(t)=\sin^2\left(\frac{\pi l\Delta n(t)}{\lambda\cos\theta'/2}\right). \qquad (9)$$

For the large gain case, the energy exchange between the pump beam and the signal beam cannot be neglected, it causes both the time evolution of the diffraction and the maximum efficiency to be quite different from those of the small gain case thus making Eq. (9) no longer valid. Hong and Saxena [6] have given an expression including energy coupling between the two recording beams. When both the pump and the signal beam are extraordinary lights, we have

$$\eta(t)=\sin^2[\arctan(e^{\Gamma(t)L}\sqrt{r/2})-\arctan(\sqrt{r})]. \qquad (10)$$

In our theoretical analysis, the values of parameters for KNSBN are taken as: $\epsilon_{11}=588$, $\epsilon_{33}=500$, $\gamma_{13}=30$ pm/V, $\gamma_{33}=200$ pm/V, $\gamma_{42}=820$ pm/V, $n_0=2.35$, $n_e=2.27$, for both 514.5 nm and 632.8 nm, so that we have not considered the dispersion in this paper. $N_{\rm eff}$ is taken from our experimental data, it is quite different in the crystal because of the doping concentration.

3. Experimental

The Cu : KNSBN used in our experiment was grown at Shandong University, China. The crystal size is $4.5\times5\times6$ mm, the 6 mm side is along the $\hat{c}$ axis, and $l=5$ mm corresponds to the direction of propagation.

The experimental setup is shown in Fig. 1. Both 514.5 nm Ar^+ laser and 632.8 nm HeNe laser are expanded to a 3 mm diameter beam by two lenses to obtain a uniform intensity distribution. The expanded beam is split into the signal and pump beams by a splitter. The KNSBN crystal is placed with the $\hat{c}$ axis normal to the bisector of the two beams, so that in our experiment the largest electrooptic coefficient γ_{42} is not included. The signal beam is focused by a lens ($f=20$ cm) and covered completely by the pump beam. When θ is larger than 40 degrees, we adjust the two expanding lenses to make a larger pump beam, so that the covering condition is satisfied. The pump beam intensity is about 200 mW/cm^2, that of the signal beam is 10^{-3} weaker for o-light and 10^{-4}–10^{-5} for e-light. The signal beam transmission intensity with or without the pump is detected by a photomul-

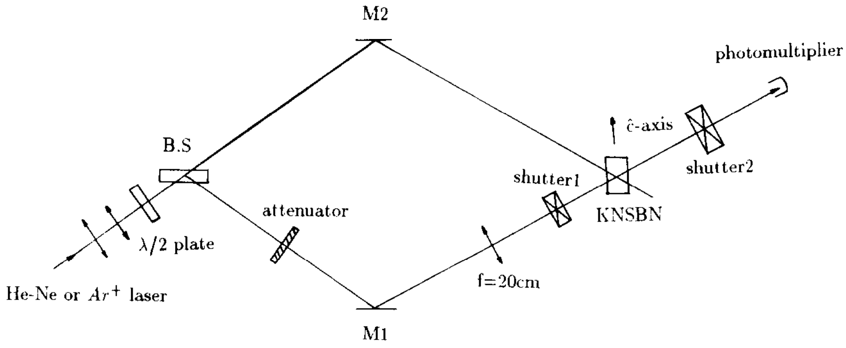

Fig. 1. Experimental setup for both gain and diffraction efficiency measurements.

tiplier. After each measurement, the crystal is illuminated by an intense light.

Firstly, we measured 2WM gain as a function of the grating wavelength (or θ) using both 514.5 nm and 632.8 nm laser (ordinary polarized light). The results are shown in Fig. 2 and Fig. 3. Fig. 2 is a plot of $\lambda/\Lambda_g\Gamma$ versus $(\lambda/\Lambda_g)^2$. $R\gamma_{\mathrm{eff}}$ and N_{eff} were obtained from the intercepts and slopes, respectively. For the 514.5 nm and 532.8 nm laser, R and N_{eff} were 0.78, 0.67 and 1.35×10^{23} m^{-3}, 1.25×10^{23} m^{-3}, respectively. From these results, we can see that $N_{\mathrm{eff}\,632.8}$ is slightly smaller than $N_{\mathrm{eff}\,514.5}$. That is to say: for the KNSBN crystal, the red light response is excellent. The smaller gain obtained with the 632.8 nm laser is consistent with the theoretical prediction, see the dependence on wavelength Eq. (2). Using these values, we give the results of the fitting of the gain coefficient in Fig. 3.

In addition, we set a $\lambda/2$ plate into the beam path

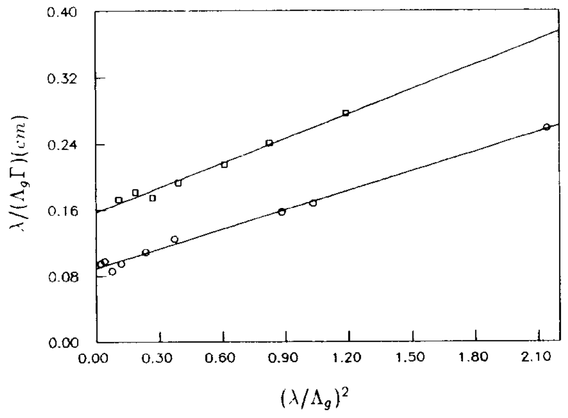

Fig. 2. Linearized plot of gain coefficient measurements with ordinary polarized light. ○ for 514.5 nm and □ for 632.8 nm.

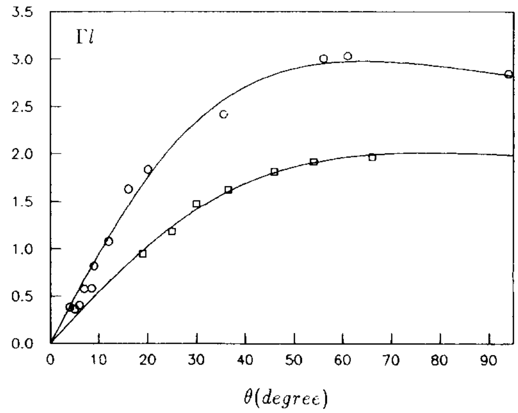

Fig. 3. Gain (ordinary polarized) ΓL versus θ. ○ for 514.5 nm and □ for 632.8 nm. Solid line is theoretical curve.

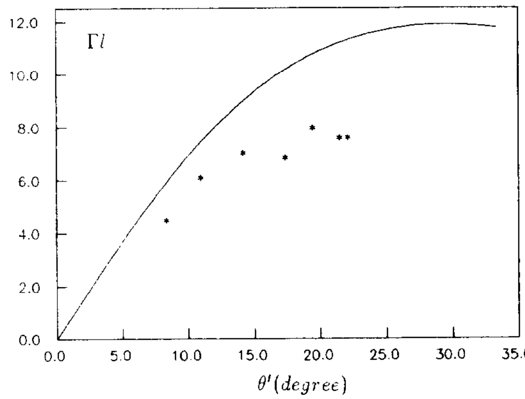

Fig. 4. Gain (extraordinary polarized) ΓL versus θ'. Theoretical curve (solid line) is based on the parameters obtained by the measurement on ordinary light.

to measure the gain for extraordinary polarized light using the 632.8 nm laser. The results are given in Fig. 4. The parameters used in the calculation were taken from the fitting of the ordinary case. The largest gain we obtained is about 16 cm^{-1} at 20 degrees, being higher than that reported previously for Cu:KNSBN using a 514.5 nm Ar^+ laser [4]. The gain increases smoothly to a saturation value in each measurement, whereas oscillation of the gain with time [3] was not observed. The discrepancies between theory and experiments are mainly caused by two reasons, (i) unavoidable self-fanning of beams present in the crystal. This effect became very serious when the beam angle θ increased leading to depletion of both signal and pump and, consequently, to the reduction of the gain, (ii) the pump beam reflected at the exit surface of the crystal, overlaps with the signal beam and reduces the modulation of the grating, as well as the gain coefficient. The two problems can be overcome by using a small spot beam, however, the large beam angle will prevent the pump beam from covering the signal completely, thus leading to an inaccurate knowledge of the coupling length. For this reason, in our experiment the maximum angle we measured is about 50 degrees (25 degrees inside the crystal). More complete and accurate results may be obtained by the so called varying interaction length method [7].

The time evolution of the diffraction efficiency was measured by using the same experimental setup shown in Fig. 1 except for two shutters set into the signal beam path before and behind the crystal. Both writing and reading beams were extraordinary polarized lights. The diffraction efficiency of the grating was measured by periodically interrupting the signal beam while recording the transmitted intensity of the diffraction beam. The grating period was 1.05 μm (θ=35 degrees), and (I_1+I_2) were 180 mW/cm^2. Two cases were performed, with modulation 0.75 and 0.1, respectively. The results are shown in Fig. 5, in which we used Eqs. (7), (8), and (10) to calculate the evolution of the grating index. The curves are quite similar except for the value of the efficiencies. The maximum experimental efficiencies are 66% and 50% for $m=0.75$ and 0.1 respectively, while the theoretical values are 78% and 69%. The energy losses due to the beam fanning are 7% and 11%. The response is much slower than that of the 514.5 nm laser.

In our experiment, we observed that the grating was not erased by the exact Bragger-angle reading beam after the maximum efficiency has been reached. It seemed to reach an equilibrium state. We believe that

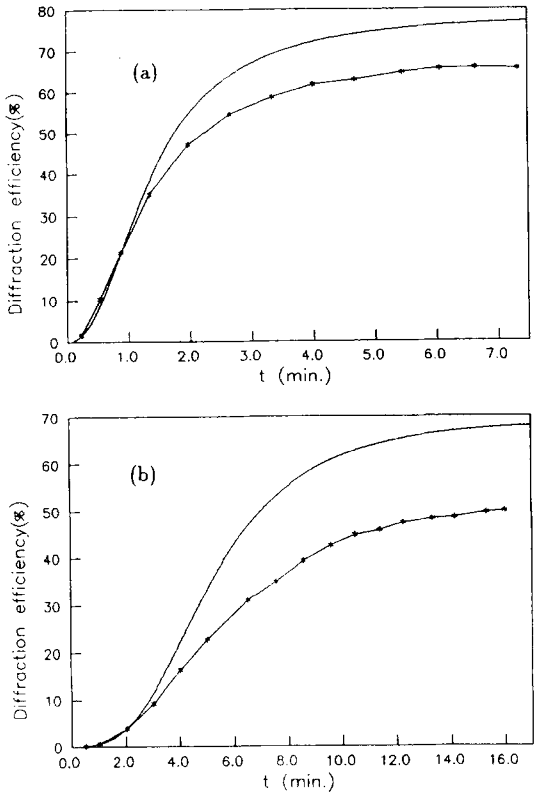

Fig. 5. Time evolution of recording diffraction efficiency. Λ= 1.05 μm, (a) $m=0.75$; (b) $m=0.1$.

it is a result of coupling effects. The detail study will be performed in the future.

3. Conclusions

We have experimentally investigated 2WM in a Cu:KNSBN crystal using a 632.8 nm laser. Comparison with the results obtained with the 514.5 nm laser shows an excellent response of the crystal in the red region. The maximum gain (16 cm^{-1}) we have measured is even larger than that reported previously using 514.5 nm [4].

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