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THEORY AND EXPERIMENT ANALYSIS OF TWO-DIMENSIONAL ACOUSTO-OPTIC INTERACTION*

/1047**

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ABSTRACT

The universal coupled wave equation of two dimensional acousto optic effect has been deduced and the solution of normal Raman-Hath acousto optic diffraction was derived from it. The theory was compared with the experimental results of a two dimensional acousto optic device consisting of two one dimensional modulators. The experiment results agree with the theory. Roman-Nath type.

A. INTRODUCTION

In 1976, Change etal(1) established the unified theory of acousto optic interaction by using the parameter interaction theory in non-linear optics. Their theory gives correct explanations for a series of phenomena in Raman-Nath type, Bragg type, normal and abnormal acousto optic interactions, as well as their applications. The previous work, however, was done in one-dimensional conditions. Acousto optic interaction can be multiple dimensional, namely, a simple light beam can interact with

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many ultrasonic waves from multiple directions simultaneously in the same acousto optic medium to produce acousto optic diffraction along multiple directions. A typical example is two dimensional acousto optic diffraction. Recent work(2,3) has demonstrated that two dimensional acousto optic interaction may be utilized to prepare multiple channel switches, space-division multiple use devices and space light modulators. Therefore, it has broad and promising application potential in such fields as optical computation, optical communication, optical information processing and optical exchange.

The two dimensional Raman-Nath acousto optic modulator that we prepared is a key device for optical space coherence double steady-state which will find important use in coherence measurement, picture coding and optical computation(4).

B. THE COUPLED WAVE FUNCTION OF TWO DIMENSIONAL ACOUSTO OPTIC INTERACTION

Let incident light be a monochromatic planar wave, the angle between its traveling direction and x-z plane is θ_o, the angle with X axis is θ_1, its circular frequency is W_o and wave vector is k_o then the mode of k_o is:

$$k_0 = \frac{2\pi n_0}{\lambda_0}, \tag{1}$$

where λ_o is the wavelength of the light in vacuum, n_o is the refractive index of medium to the incident light (generally speaking, n_o is related to the polarization and traveling direction of the incident light). Assuming circular frequencies and wave vectors of two beams of ultrasonic waves be ω_{1s}, K_{1s} and ω_{2s}, K_{2s}, respectively, and the modes of wave vectors K_{1s} and K_{2s} are (respectively):

$$K_{1s}=\frac{2\pi}{\lambda_1}=\frac{2\pi}{v_1}f_1, \quad K_{2s}=\frac{2\pi}{\lambda_2}=\frac{2\pi}{v_2}f_2, \tag{2}$$

where λ_1 and λ_2 are the ultrasonic wavelengths, f_1 and f_2 are the frequencies of ultrasonic waves, and v_1 and v_2 are acoustic velocities. As in general situations, let K_{1s} be in the x-y plane with the angle between its direction and x axis being θ_α; K_{2s} be in x-z plane with the angle between its direction and x axis being θ_β, as shown in Figure 1.

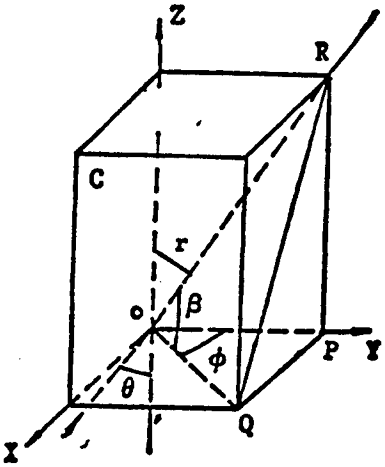


Fig. 1 Schematic diagram of acousto-optic interaction

According to the principle of parameter interaction, incident light wave couples with the ultrasonic waves in the medium to form a series of multiple frequency polarized waves and their circular frequency $\omega_{p,q}$ and wave vectors $K_{p,q}$ are (respectively):

$$\left.\begin{aligned} \omega_{p,q}&=\omega_0+p\omega_{1s}+q\omega_{2s}, \\ k_{p,q}&=k_0+pK_{1s}+qK_{2s}, \end{aligned}\right\} \tag{3}$$

where $p, q=0, \pm 1, \pm 2, \cdots$. These polarized waves in turn excite the light radiation of the same frequencies, namely, the corresponding diffracted light. Their total electric fields E(r,t) can be expressed as the following series:

$$\boldsymbol{E}(\boldsymbol{r}, t)=\sum_{p,q=-\infty}^{\infty} \boldsymbol{e}_{p,q} E_{p,q}(x) \exp[i(\omega_{p,q} t-\boldsymbol{k}_{p,q} \cdot \boldsymbol{r})], \tag{4}$$

where $e_{p,q}$ is the unit electric field vector of diffraction order (p,q). Assuming the ultrasonic wave is a single frequency planar wave, then the corresponding strain tensor and non-linear polarized vector are S(r,t) and P^{NL}, respectively. The free light wave vector of diffracted light of order (p,q) excited by the polarized wave is $k_{p,q}$. When the direction k_o of incident light is arbitrary, $k'_{p,q}$ is generally not equal to $k_{p,q}$. For this reason the momentum mismatching $\Delta \boldsymbol{K}_{p,q}=\boldsymbol{k}'_{p,q}-\boldsymbol{k}_{p,q}$. as shown in Figure 2 was introduced. In this equation $\Delta \boldsymbol{K}_{p,q}$ is limited to the direction along x-axis, thus the model of $k_{p,q}$ is $(n_{p,q}\omega_{p,q}/c)$ and its direction makes $\Delta \boldsymbol{K}_{p,q}$ orient along x axis. Therefore, $\Delta \boldsymbol{K}_{p,q} \doteq [(k_{p,q}^2-k_{p,q}^{\prime 2})/2k'_{q,q}]$ Let:

$$\left.\begin{aligned} x_{1p,q} &= -n_{p,q}^2 n_{p-1,q}^2 P_1, \\ x_{2p,q} &= -n_{p,q}^2 n_{p,q}^2 P_2, \end{aligned}\right\} \tag{5}$$

where p_1 and p_2 are efficient acousto optic coefficients along the corresponding directions. Because $[dE_{p,q}(x)/\ dx] \ll k'_{p,q}$, we omit item $[d^2E_{p,q}(x)/dx^2]$ in the parameter interaction equation$^{(5)}$ and consider the above-mentioned conditions to obtain:

$$\begin{aligned} \frac{dE_{p,q}(x)}{dx}-i\Delta K_{p,q}E_{p,q}(x) = \frac{k_{p,q}^2}{4k'_{p,q}}[&n_{p+1,q}^2 P_1 S_1 E_{p+1,q}(x)-n_{p-1,q}^2 P_1 S_1 E_{p-1,q}(x) \\ &+n_{p,q+1}^2 P_2 S_2 E_{p,q+1}(x)-n_{p,q-1}^2 P_2 S_2 E_{p,q-1}(x)], \end{aligned} \tag{6}$$

The above equation is the coupled wave equation of two dimensional acousto optic interaction. Thus the following conclusions can be drawn:

(1) When the length of acousto optic interaction L is short, decrease of light intensity of each diffracted light due to momentum mismatching is not obvious. Therefore diffracted light of multiple orders can be obtained, namely, Raman-Nath diffraction.

(2) When the length of acousto optic interaction L is long, all diffracted light which is $\Delta K_{p,q} \neq 0$ becomes weak. The incident light forms zero-order light which can not couple with the most close neighbor that is different from it by four orders. Therefore, strong diffracted light can be obtained only when the direction of incident light is adjusted to make one of $\Delta K(\pm 1, 0)$ and $\Delta K(0, \pm 1)$ equal to zero, namely, the Bragg diffraction. it can be seen that two dimensional Bragg diffraction gives the same results as one dimensional Bragg diffraction, namely, only certain second order diffracted light which includes order (0,0) can be obtained.

C. THE SOLUTION OF THE COUPLED WAVE EQUATION OF RAMAN-NATH DIFFRACTION

In the case of normal acousto-optic interaction, $\Delta n = -n^3 PS/2\, e_{p,q}$ are all in the same direction and $n_{p,q} = n_0$. Normally, $\theta_a = \theta_\beta = (\pi/2)$, Define:

$$\xi_1 = -\frac{2\pi \Delta n_1 L}{\lambda_0 \cos\theta_1}, \quad \xi_2 = -\frac{2\pi \Delta n_0 L}{\lambda_0 \cos\theta_1}, \tag{7}$$

where ξ_1 and ξ_2 represent the phase shift caused by acousto optic interaction K_{1s} and K_{2s}, respectively. Considering the arbitrary and independent nature of values p and q, the diffracted light efficiency of each order for Raman-Nath diffraction of vertical incidence can be derived by using the progressive relationship of the Bessel function:

$$\eta_{p,q} = J_p^2(\xi_1) J_q^2(\xi_2)\text{。} \tag{8}$$

From ultrasonic power $P_s = \frac{1}{2}\rho v^2 |S|^2 HL$ (where ρ is density of the medium, υ is the velocity of sound, S is strain and H is the width of energy converter) the relationship between diffraction efficiency and ultrasonic power is further obtained:

$$\eta_{p,q} = J_p^2(M_1\sqrt{P_{s1}}) J_q^2(M_2\sqrt{P_{s2}}), \tag{9}$$

Where M_1 and M_2 are a parameter related to the acousto optic modulator.

D. EXPERIMENTAL CONTENT AND RESULTS

The two-dimensional Raman-Nath type acousto-optic modulator used in this work was home-made by binding together two one-dimensional Raman-Nath type acousto-optic modulators whose acoustic field directions are perpendicular to each other. The crystal material was $PbMoO_4$, acoustic field frequency $f_{1s}=26\,\mathrm{MHz}$, $f_{2s}=28\,\mathrm{MHz}$ and incident light wave $\lambda_0=6328\,\text{Å}$. The experimental apparatus is shown in Figure 3.

The diffraction efficiencies under several situations were determined in the experiments and the results are shown in Table 1. The space diffraction patterns were calculated by computer according to the experimental results and are shown in Figure 4, where peak height represents relative light intensity.

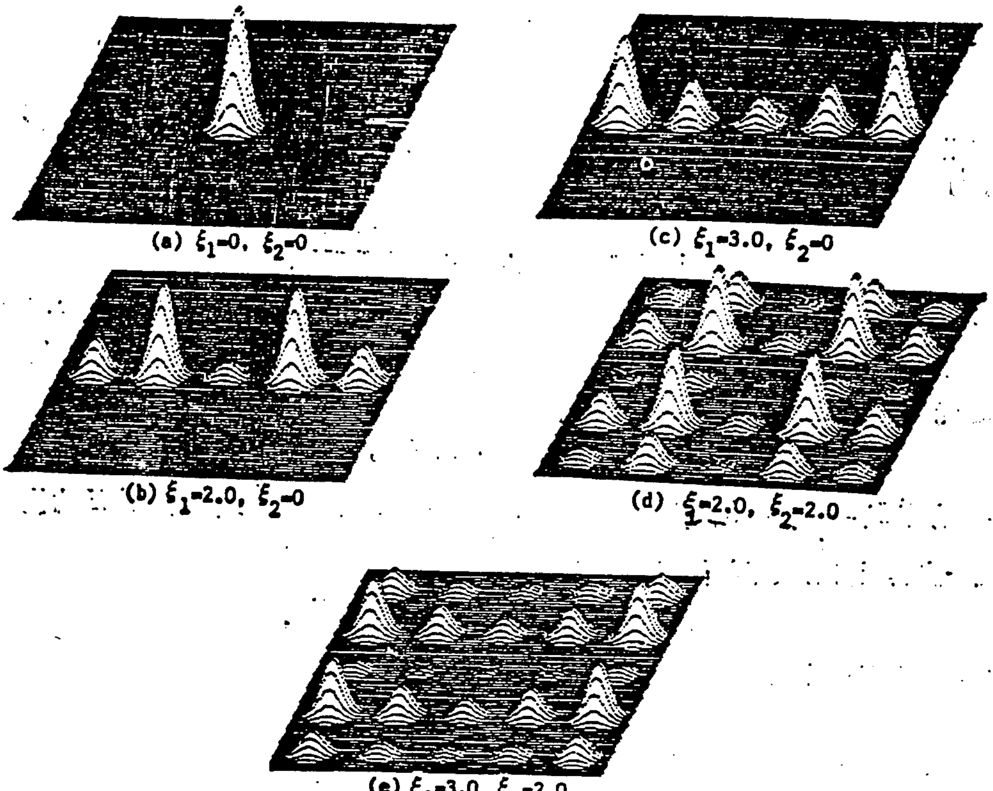
Calculations using Equation (8) have shown that the experiments agree well with the theory. The minor difference between the theoretical diffraction efficiency and the experimental results is due to the difference in diffraction efficiency η of the device of this type of structure. The diffraction efficiency of this type of device is:

$$\eta_p = J_p^2\left[\xi_1 \frac{\sin\left(\frac{1}{2}\,\alpha_0\theta_1\right)}{\frac{1}{2}\,\alpha_0\theta_1}\right], \quad \eta_q = J_q^2\left[\xi_2 \frac{\sin\left(\frac{1}{2}\,\alpha_p\theta_2\right)}{\frac{1}{2}\,\alpha_p\theta_2}\right], \tag{10}$$

In this equation it is assumed that the light first acts on the device of $\xi=\xi_1$. Because the action of diffracted light from the first acousto-optic device on the second device is not vertical incidence, its incident angle changes with the variation of order P. When the incidence is perpendicular to y-z plane, namely, $\alpha_0=0$, the diffraction efficiency is:

$$\eta_{p,q} = J_p^2[\xi_1]\,J_q^2\left[\xi_2 \frac{\sin\left(\frac{1}{2}\,\alpha_p\theta_2\right)}{\frac{1}{2}\,\alpha_p\theta_2}\right], \tag{11}$$

Note that $[\sin(\alpha_p\theta_2/2)/(\alpha_p\theta_2/2)]<1$, thus $\eta_{p,q}$ changes slowly with P_{52} and the slowness varies with the different diffraction orders from the first acousto-optic modulator.



(a) $\xi_1=0$, $\xi_2=0$

(b) $\xi_1=2.0$, $\xi_2=0$

(c) $\xi_1=3.0$, $\xi_2=0$

(d) $\xi_1=2.0$, $\xi_2=2.0$

(e) $\xi_1=3.0$, $\xi_2=2.0$

Fig. 3 Acousto-Optic diffraction patterns

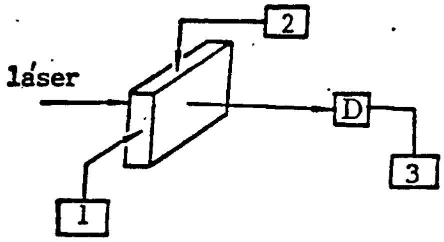


Fig. 4 Experimental setup

1, 2 AO power source;

3 laser power dynamometer

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