NAIC-ID(RS)T-0368-94

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by

Zuoqing Wang, Chenghao Wang

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HUMAN TRANSLATION

NAIC-ID(RS)T-0368-94 3 January 1995

MICROFICHE NR: 95C000010

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English pages: 15

Source: Shengxue Xuebao, Vol. 14, Nr. 1, January 1989;
pp. 51-57

Country of origin: China
Translated by: SCITRAN
F33657-84-D-0165
Requester: NAIC/TATA/J.M. Finley

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ACTA ACUSTICA, Vol. 14, No. 1, January 1989

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THE ANGULAR SPREAD OF THE DEFLECTED ACOUSTIC BEAM DIFFRACTED BY A BRAGG GRATING OUT OF A SURFACE ACOUSTIC WAVE

Zuoqing Wang and Chenghao Wang[1]

Abstract In this paper, basing on the equations of the deflection angle and of the deflection efficiency, the relation between the angular spread of the deflected SAW beam on the Bragg grating denoted by $\delta\theta_1$, and the parameters of the grating is analyzed. A parameter referred to as "Bragg width of the angular spectrum" of the acoustic grating is defined and it is designated with $\delta\theta_B$. The meaning of the parameter $\delta\theta_B$ for distinguishing the angular spread range of the deflection beam is discussed as well. It is concluded from the analysis that if the spread angle of the incident beam (labelled with $\delta\theta_{im}$) is larger than the "Bragg width of the angular spectrum" of the grating, the spread angle of the deflection beam $\delta\theta_1$ will equal to $\delta\theta_B$; On the contrary, if the angular divergency of the incident beam is less than $\delta\theta_B$, then, $\delta\theta_1=\delta\theta_{im}$.

Experimentally, 4 kinds of samples with different configuration patterns, 2 of which correspond to the regime of $\delta\theta_{im}\gg\delta\theta_B$, and the others correspond to the regime of $\delta\theta_{im}\ll\delta\theta_B$, are investigated by optical method. The width of the angular spread for incident beam and that for deflected beam are estimated by measuring the width of the acousto-optical diffraction point patterns. It is demonstrated that experimental results agree with theoretically expected results.

1. INTRODUCTION

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By applying the Bragg diffraction effect of an acoustic grating to a surface acoustic wave (SAW), one can produce large angular deflection-scanning[1], and thus one can build a purely acoustic spectrometer[2], for the emitted spectra of an acoustic "SAW-acoustic grating" type. One of the basic functions of such devices is to resolve the number of

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* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

[1] Chinese Institute of Acoustics, Academia Sinica. Received on February 5, 1986

points. Just like in the cases of any acoustic-optic deflectors, the capability of the acoustic beam deflector of a SAW-acoustic grating type which can distinguish the number of points can be used to determine deflection scanning-angle $\Delta\Theta_1$ and the angular spread $\delta\Theta_1$ of the deflected acoustic beam.

In the cases of an acoustic-optic deflector, because the angular spread of an incident optic ray is much smaller than that[3], of an acoustic beam, the spread angle of the deflected optic ray is equal to the spread angle of the incident ray. In the cases of a SAW-acoustic grating deflector, usually the deflection scanning could be made to be rather large, e.g. 0.5 rad, but the angular spread of the incident acoustic beam can also be large. In order to increase resolvable point-patterns, one can choose the right kind of acoustic diffractions for the incident acoustic spectra to make the angular spread of the deflected acoustic beam small; that is, one can utilize the property of the so-called "space angular spectral filtering" to improve the resolution power. It clarifies the relation between the angular spread $\delta\Theta_1$ of the deflected acoustic beam and various parameters of an acoustic grating, which is a very important problem in designing acoustic beam deflectors of the "SAW-acoustic grating" type and RF spectrometer of a "SAW-acoustic grating" type.

This paper proceeds in 2 directions of the theory and experiment, to present the research results on the relation between the angular spread of the deflected acoustic beam and various parameters of the acoustic graing, under the situation of an acoustic Bragg diffraction. In section 2, the relevant theory is analyzed, in section 3 the experimental facts are introduced to compare with the theoretical analyses. And finally there will be a brief concluding remark.

2. ANALYSIS OF THE RELATION BETWEEN THE ANGULAR SPREAD OF A DEFLECTED ACOUSTIC BEAM AND VARIOUS PARAMETERS OF THE ACOUSTIC GRATING

Under any strong Bragg condition, usually there is only the zeroth order acoustic beam (namely the direct beam) or the 1st order acoustic beam (a deflected acoustic beam) in the projection field of an acoustic grating. The approximate expression of the deflection angle Θd of a deflected acoustic beam[1] is

$$\theta_d = \theta_1 - \theta_{inc} \simeq -2\theta_B \simeq -\Lambda/\Lambda_g. \tag{1}$$

where Θ_{inc} is the incident angle, Θ_1 the diffraction angle of the 1st order acoustic beam (the intersectional angle between the wave-vector of the deflected acoustic beam and the acoustic grating line), Λg is the period of the acoustic grating, Λ is the wavelength of the sound wave and Θ_B is the Bragg angle. As it is clear from Eqn.(1), if the incident angle is around the vicinity of the Bragg angle, then the deflection angle is approximately 2 times the Bragg angle. In other words, if the angular spectrum of the incident acoustic beam does not spread out too widely, or if in a different way of speaking the central spectrum satisfies the Bragg condition, then the deflection angles of all the angular spectral components of the incident beam are all 2 times the Bragg angle.

The strength of any angular spectral component of a deflected beam[1] is

$$I_1(g) = \frac{I_{inc}}{g^2+1} \cdot \sin(\beta\sqrt{g^2+1}), \tag{2}$$

In Eqn.(2), I_{inc} is the strength of the corresponding angular spectrum of the incident beam, 2β is the so-called the phase modulation rate of an acoustic grating, and β is defined by the following expression:

$$\beta = \frac{\pi}{2} \cdot (\Delta v/\bar{v}_0) \cdot L_g/\Lambda \cos\theta_B. \tag{3}$$

Lg is the thickness of the acoustic grating, and $\Delta v/\bar{v}_0$ is the sound speed modulated amplitude of the grating region. And g shows the extent of the deflection of the Bragg angle, whose formula is as follows:

$$g = \frac{1}{\frac{1}{2}(\Delta v/\bar{v}_0)} \cdot \frac{\Lambda}{\Lambda_g} \cdot \left(\sin\theta_{inc} - \frac{1}{2}\frac{\Lambda}{\Lambda_g}\right). \tag{4}$$

One can see from Eqn.(2) that if $\beta \ll \pi/2$, then for $g = 0$ the deflection effect is the greatest[4]. And $g = 0$ is nothing but the Bragg condition, that is,

$$\sin\theta_{inc} = \frac{1}{2}\frac{\Lambda}{\Lambda_g} = \sin\theta_B. \tag{5}$$

In an actual situation, an incident acoustic beam has a constant angular spectral width. When frequency is constant, only a certain angular spectral component rigidly satisfies Eqn.(5), while for other angular spectral components Eqn.(5) is not satisfied and thus $g \neq 0$. From Eqn.(2) one can see that as the absolute value of g increases, the deflection effect declines. When the deflection effect goes down to one-half of its maximum value, g becomes g_c; that is,

$$I_1(g_c) = \frac{1}{2} I_1(0). \tag{6}$$

From Eqn.(6) one can find g_c, and by putting g_c into Eqn.(4) and expressing it in terms of the corresponding angular spectral components, one gets: $\Theta_{inc} = \Theta_B \pm \delta\Theta_B/2$, where we call $\delta\Theta_B$ the "Bragg angular spectral width" of an acoustic grating. On the other hand, IDT is always only active within the range of a certain constant frequency-band width, while in speaking in terms of some definite angular spectral component, only in a specific frequency f_o, Eqn.(5) holds, but in other frequencies Eqn.(5) is not satisfied as to give $g \neq 0$. Furthermore as the absolute value of g increases, the deflection effect goes down. In the same fashion, when the deflection effect goes down to one-half, the g value is called g_c, and from Eqn.(4) one can find the corresponding peripheral frequency f_c, and then the corresponding deflection effect is one-half of that for f_o. When one wants to express it in terms of the above-mentioned frequency: $f_c = f_o \pm \Delta f_B/2$, then such Δf_B is called the "Bragg frequency band-width" of an acoustic grating. Below we shall discuss these 2 quantities separately, with their relevant parameters.

1. <u>"Bragg frequency band-width" formula</u>

From Eqns. (2) - (4) and (6), one can get

$$\Delta f_B/f_0 \simeq 4(\beta_c g_c/\pi) \cdot (\Lambda_g^2 \cdot \cos\theta_B / L_g \Lambda_c). \qquad (7)$$

where βc and Λc are the values for the peripheral frequency of the corresponding "Bragg frequency band-width". However, if the coefficient

$$(\beta_c g_c/\pi) = 0.45,$$

These formulas are equivalent to the corresponding formulas in the acoustic-optic diffraction cases[3]. For this coefficient, more will come in the following discussions.

2. The "Bragg angular spectral width" and its physical significance

From Eqn.(4), to consider the component of $\theta_{inc} = \theta_B \pm \delta\theta_B/2$ and Eqn.(3), one finds the formula for the "Bragg angular spectral width" to be

$$\delta\theta_B \simeq 2(\beta g_c/\pi)(\Lambda_g/L_g). \tag{8}$$

As will be proved below, the value of coefficient $(\beta g_c/\pi)$ becomes 0.44 in a constant condition, while in Eqn.(6) for a -4dB width (not quite half-way down), the number (expressed as $\beta g_o/\pi$) is 0.5. Thus the acoustic grating "Bragg angular spectral width" corresponds to the principal lobe width of the acoustic beam for aperture of L_g and wavelength Λ_g, but the grating lines of the acoustic grating must be straight and equal lengths, and they themselves do not scatter.

From the above discussions one can see that the meaning of the "Bragg angular spectral width" of an acoustic grating is as follows: If the angular spectral width of the incident acoustic beam (usually defined as -3dB and expressed by $\delta\Theta_{inc}$) is an appropriate width, when it undergoes an acoustic grating diffraction, its angular spectral components, which exist within

$$(\theta_B - \delta\theta_B/2) \leqslant \theta_{inc} \leqslant (\theta_B + \delta\theta_B/2)$$

can be effectively deflected. In the technical expression, the "Bragg angular spectral width" of an acoustic grating $\delta\Theta_B$ is -3dB band-width of the space angular spectral width of the Bragg acoustic grating for the incident acoustic beam. In terms of angles, as $\delta\Theta_B$ gets smaller, the better becomes the selectivity of the space frequency.

3. The value of coefficient $(\beta g_c/\pi)\pi$) and $(\beta_c g_c/\pi)\pi$)

By inserting Eqn.(2) into Eqn.(6), one can get

$$\sin^2(\beta\sqrt{g_c^2+1})/(g_c^2+1) = \frac{1}{2}\sin^2\beta, \tag{9}$$

Thus the g_c value which satisfies the above relationship formula is related to β. When β picked its value from 0.001 π tp 0.5 π, we computed the corresponding g_c, and then we obtained the related curve between the $(\beta g_c/\pi)$ value and β within the given β values, as shown in Fig. 1, indicated as curve-a. The curve-b is from the values for -4dB. From Eqn.(2) one can see that if $\beta << \pi/2$, the maximum value exists when the Bragg condition[4] is satisfied. Thus the upper limit of the β value is at $\pi/2$. One can see from the curves that for $\beta < 0.2\ \pi$, $(\beta g_c/\pi) \approx 0.44$.

The relevant coefficient $(\beta\ g_c/\pi)$. If βc is the value for the central frequency f_o, the β values at both sides of the equality sign in Eqn. (6) are not identical, thus the relationship becomes a little complicated. From Eqn.(2) to Eqn.(6), one gets

$$\sin^2(\beta_c\sqrt{g_c^2+1})/(g_c^2+1) = \frac{1}{2}\sin^2[\beta_c/(1+4\beta_c g_c/Q)]. \tag{10}$$

where

$$Q = 2\pi\Lambda_c L_g/(\Lambda_g^2\cos\theta_B), \tag{11}$$

which is the characteristic parameter[1] of an acoustic grating. By comparing Eqn.(10) with Eqn.(9), the difference appears to be the quantity of this characteristic parameter Q. In a strong Bragg condition $Q \geq 10$, so we choose in our calculations for the Q value to be : 10, 15, 20, 50, 100 and infinity. The values of βc in each curve are between 0.001 π to $\pi/2$. The calculated results are shown in Fig.2. Thus if Q is infinity it corresponds to Curve-a of Fig.1, which can also be observed from Eqn.(10). From Fig. 2 one can see that if $\beta_c < 0.1\ \pi$, the $(\beta_c g_c/\pi)$ values for various above Q values are as follows: 0.69, 0.63, 0.59, 0.51, 0.475 and 0.44.

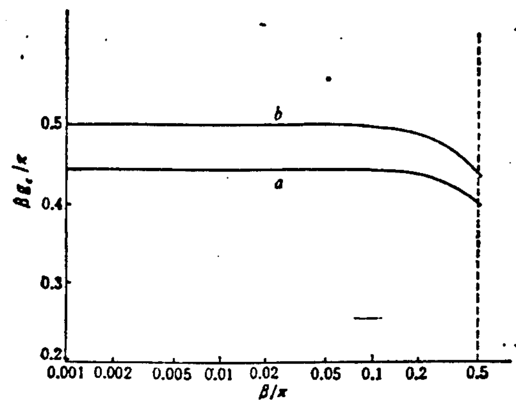

Fig. 1 The relationship obtained from calculation of the coefficient $(\beta g_c/\pi)\sim\beta$

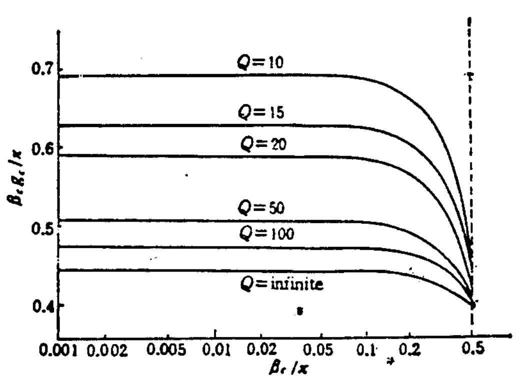

Fig. 2 The relationship curve of $(\beta_c g_c/\pi)\sim\beta_c$

As a suggestion, in the cases of acoustic-optic deflection, because the β-value is not related to the acoustic frequency[3], thus the coefficient of the "Bragg band-width" formula can be determined by Eqn. (9). Consequently as β gets smaller, this coefficient takes a value of 0.44. I. C. Chang picked 0.45[3], but the approximation was fairly good.

4. The "Bragg angular spectral width" of Valley-Peak-Valley

The keypoint of this paper is to investigate the effect of the "Bragg angular spectral width" on the functions of the instruments. However in experiments, what one measures are the valley-peak-valley width of the principal lobe, and it is not -3dB width. Thus in order to make a comparison with the experimental values, the following simple discussion on the valley-peak-valley total width of the "Bragg angular spectral width" of an acoustic grating, expressed by $\delta\Theta_I$, is called for. From Eqn.(2)

$$I_1(g_0) = 0, \tag{12}$$

one can find the corresponding g_o as the 1st zero-value. The corresponding Eqn. (8) becomes

$$\delta\theta_T \simeq 2(\beta g_0/\pi)(\Lambda_g/L_g). \tag{13}$$

The coefficient $(\beta g_o/\pi)$ can be worked out in the same fashion as before to come up with a curve, and the results are shown in Curve-b of Fig. 1. One can see that for $\beta \leq 0.3\,\pi$, $(\beta g_o/\pi) \approx 1$. Also $\delta\Theta_T \approx 2\,(\Lambda_g/L_g)$. The physical significance of such results has already been discussed above.

It became clear from the results of the above calculations for the $(\beta g_c/\pi)$ coefficient that the deflection effect formula given by Eqn.(2) is not always in the shape of a standard "Sinker function", but when β is rather small, i.e. smaller than $0.1\ \pi$, its distribution is pretty close to the shape of a "sinker function".

It is clear from the above results that the effects of various coefficients of an acoustic grating all concentrate on the "Bragg angular spectral width" $\delta\Theta_B$. If the angular spectral width of the incident beam $\delta\Theta_{inc}$ is greater $\delta\Theta_B$, then due to the selective action of the acoustic grating on the angular spectra, the angular spectral width of the deflected beam is $\delta\Theta_1 = \delta\Theta_B$; on the contrary if the angular spectral width of the incident beam $\delta\Theta_{inc}$ is smaller than $\delta\Theta_B$, all angular spectral components effectively received deflections, and thus the width of the principal lobe of deflection is equivalent to that of the incident beam, namely: $\delta\Theta_1 = \delta\Theta_{inc}$.

Simply speaking, one can say that the spreading angle $\delta\theta_1$ of the deflected beam is

$$\delta\theta_1 = \begin{cases} \delta\theta_B, & 若\ \delta\theta_{inc} > \delta\theta_B; \\ \delta\theta_{inc}, & 若\ \delta\theta_{inc} < \delta\theta_B. \end{cases} \tag{14}$$

Eqn.(14) is thus this paper's most important expression obtained from its theoretical analyses.

3. EXPERIMENTAL RESULTS

By use of the optical method, pictures were taken on the acoustic-optic diffraction patterns[1,5] of the samples which are being measured and whose zeroth order spot was taken as the origin, and the distribution of the optic diffraction patterns was matched up one-to-one with the corresponding space frequency (direction and intensity) distribution of the sample to be measured. Because the principal lobe of the zeroth order acoustic beam of the irradiated field is equivalent to the principal lobe of the incident beam[1], and because experimentally we took pictures of the irradiated fields for the entire acoustic-optic diffraction patterns, we could measure the valley-peak-valley width of the zeroth order and 1st order principal lobes and then investigated the relationships between coefficients of Eqn.(8) and Eqn.(13), to calculate the values of $\delta\Theta_{inc}$ and $\delta\Theta_1$.

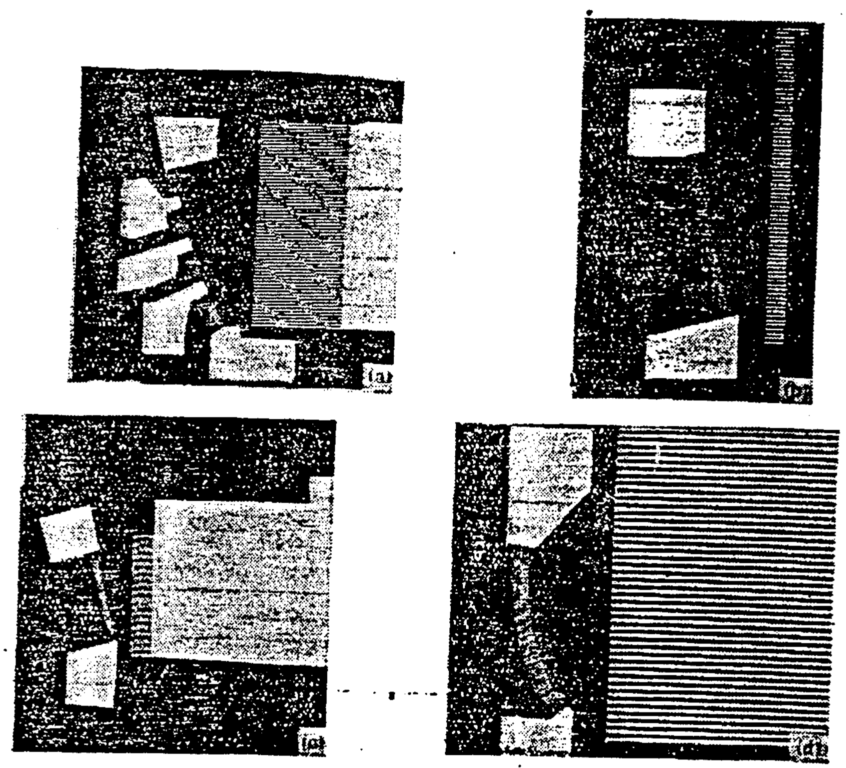

Fig.3 The structural diagrams of the 4 different kinds of samples

To test the relationships described in Eqn.(4), we designed and measured 4 samples of different structures. Their structures are shown in Fig. 3. And the parameters of each sample are shown in Table 1. 4 IDT's of No.1 sample all have different central frequencies and different apertures W, but their acoustic gratings were all arranged in the same fashion; the IDT's of No. 2 sample were all alike, but they were of 2 different kinds of acoustic grating thicknesses L_g; No. 3 sample had flat and straight IDT's but they were arc-shaped (the extending angles were 0.18 rad); No. 4 sample was also an arc-shaped IDT (the aperture angle was 0.4 rad) but its acoustic grating is flat and straight. As can be seen from the parameters of Table 1, No. 1 and No.4 samples are of the $\delta\Theta_{inc} >> \delta\Theta_B$ condition, while No. 2 and No. 3 samples corresponded to the case of

paste 1

In Table 1, Λ_0 is the period of IDT and the numerical figures in the $\delta\theta_{inc}$ column are the values of central frequencies.

TABLE 1. THE DESIGN PARAMETERS OF 4 KINDS OF EXPERIMENTAL SAMPLES

No.	1 IDT 的参数			2 声栅参数			3 备注
	Λ_0(mm)	W(mm)	$\delta\theta_{inc}$ (rad)	Λ_g (mm)	L_g (mm)	$\delta\theta_B$ (rad)	
1	0.25	2.0	0.113	0.25	7.28	0.034	$\delta\theta_{inc} \gg \delta\theta_B$
	0.20	1.6	0.113				
	0.16	1.4	0.103				
	0.13	1.2	0.097				
2	0.175	14	0.0113	0.35	1.4	0.22	$\delta\theta_{inc} \ll \delta\theta_B$
				0.35	3.5	0.09	
3	0.06	4	0.014	4 弧形声栅		0.18	$\delta\theta_{inc} \ll \delta\theta_B$
4	5 弧形 IDT		0.4	0.12	12	0.009	$\delta\theta_{inc} \gg \delta\theta_B$

Key:
(1) IDT Parameter (2) acoustic grating parameters (3) Ref.
(4) arc-shaped acoustic gratings (5) Arc-shaped IDT's

TABLE 2 COMPARISON OF THE MEASURED RESULTS WITH THE THEORETICAL ESTIMATED RESULTS

No.	中心频率时的 $\delta\theta_{inc}$ (rad) 1		$\delta\theta_B$(rad)	$\delta\theta_1$(rad)	2 类 别	3 结 果
	4 计算值	5 测量值	4 计算值	5 测量值		
1	0.113		0.034	0.027	$\delta\theta_{inc} \gg \delta\theta_B$	$\delta\theta_1 \simeq \delta\theta_B$
	0.113	0.11				
	0.103	0.10				
	0.097	0.09				
2	0.013	0.022	0.22	0.02	$\delta\theta_{inc} \ll \delta\theta_B$	$\delta\theta_1 \simeq \delta\theta_{inc}$
			0.09	0.02		
3	0.014	0.015	0.18	0.015	$\delta\theta_{inc} \ll \delta\theta_B$	$\delta\theta_1 \simeq \delta\theta_{inc}$
4	0.40	0.40	0.008	0.013	$\delta\theta_{inc} \gg \delta\theta_B$	$\delta\theta_1 \simeq \delta\theta_B$

Key: (1) $\delta\Theta$inc for central frequencies (rad)
(2) Types (3) results (4) calculated values
(5) experimental values

For the above 4 kinds of samples, the measured results of $\delta\Theta_{inc}$ and $\delta\Theta_1$ by use of the optical method are shown in Table 2. For the convenience of comparison, in Table 2 the theoretically estimated values of $\delta\Theta_{inc}$ and $\delta\Theta_1$ are listed together (the same for the values of Table 1). For the flat straight acoustic grating, $\delta\Theta_B$ was calculated with Eqn.(8). Among them, for No. 1 and No. 2 samples, because $\beta < 0.2\ \pi$, the coefficient ($\beta g_c/\pi$) was taken as 0.45, while for No.4 sample because $\beta \approx 0.5\ \pi$, the coefficient was taken as 0.4; for the flat straight IDT, it was taken as $\delta\Theta_{inc} \approx 0.9\ \Lambda/W$; for the arc-shaped IDT's their corresponding aperture angles were taken to be either $\delta\Theta_B$ or $\delta\Theta_{inc}$.

The results of Table 2 confirm that: For $\delta\Theta_{inc} > \delta\Theta_B$ (in the cases of No.1 and No. 4 samples), $\delta\Theta_1 \approx \delta\Theta_B$; while for $\delta\Theta_{inc} < \delta\Theta_B$ (belonging to No.2 and No. 3 samples), $\delta\Theta_1 \approx$

$\delta\Theta_{inc}$, to agree with the theoretically estimated results. From the numerical figures of Table 2 one can see that the comparison of the experimental results and the theoretically estimated results concurs a general agreement, especially in the results from No. 4 sample. When we were making designs, parameters were chosen such that $\delta\Theta_{inc} >> \delta\Theta_B$, or by reversing it to make it "much smaller". Going through such a procedure is due to the reason that first, we hope that the application of acoustic grating space to choose frequencies can clearly improve resolution power, namely in the case of $\delta\Theta_{inc} >> \delta\Theta_B$; secondly, because the precision of the experimental method itself is not good enough. Furthermore, the numerical figures from measurements on the samples seemed to be divergent and the main reason was that the surfaces of the samples were not smooth enough, and thus the imprinted patterns of the acoustic-optic diffraction were deformed, as to affect the final outcomes of the measurements.

4. BRIEF CONCLUSION

This paper started out with the deflection formula of Bragg diffraction and the deflection effect formula, to discuss the relation between the spread angle of deflected acoustic beam $\delta\Theta_1$ and the acoustic graing parameters. The results shows that the effect on the spread angle of an acoustic beam due to the acoustic grating parameters can be established by "Bragg angular spectral width" $\delta\Theta_B$ of the acoustic grating. If one defines -3dB of the principal lobe of an acoustic beam angular spectra as the spread angle, then as long as the usual phase-modulation rate is not too large, $\delta\Theta_B \approx 0.88\ \Lambda_g/L_g$. This means that for the spread angles of a rectangular wave-flux of any ordinary aperture L_g and wavelength Λ_g, the space angular spectra of such acoustic grating vector itself do not have any spread. The results also shows that if the spread angle of the incident beam $\delta\Theta inc$ is greater than $\delta\Theta_B$, then $\delta\Theta_1 \approx \delta\Theta_B$; on the contrary, if the spread angle of the incident beam $\delta\Theta_{inc}$ is smaller than $\delta\Theta_B$, then $\delta\Theta_1 \approx \delta\Theta_{inc}$. This explains that a Bragg acoustic grating has a filtering effect of space angular spectrum of the incident acoustic beam, and acts like a "band filtering device" of the usual band-width $\delta\Theta_B$.

Experimentally, by use of the method of observing and measuring the widths of acoustic-optic diffraction patterns, 4 kinds of samples of different structures -- 2 kinds corresponding to the cases of $\delta\Theta_{inc} >> \delta\Theta_B$, while other 2 kinds corresponding to the cases of $\delta\Theta_{inc} << \delta\Theta_B$ -- were measured for $\delta\Theta_{inc}$ and $\delta\Theta_1$. The results show that the above-mentioned results of theoretical analyses agree with the results of the experimental measurements.

The experimental samples used in this paper were prepared by Comrade Gyejun Chang and special gratitude is thus expressed here.

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