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On definition of acoustooptic figure of merit for interaction between surface acoustic and guided optical waves

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Introduction

The acoustooptic interaction between surface acoustic waves (SAWs) and guided optical waves (GOWs) is of a great importance for the purposes of an optical signal processing. A guided optical wave deflector controlled by the SAW has been demonstrated for the first time in Ref. 1. Since then, various acoustooptic devices including light modulators, beam deflectors, tunable filters etc. have been developed [2]. The choice of material for such devices is determined by requirements of the efficient generation of SAWs over a large bandwith, the ability to produce good–quality optical guiding layers, and the efficient acoustooptic interaction. The efficiency of the acoustooptic interaction is usually characterized by the acoustooptic figure of merit, M_2 . This parameter has been initially introduced to chararacterize the interaction in the bulk wave case (see e.g. [3]). When extending its application to the surface wave case, one meets some specific peculiarities which must be taken into account. The purpose of this paper is to consider the definition of the acoustooptic figure of merit in the case of guided optical wave diffraction by surface acoustic wave. These considerations are illustrated by an example of practical importance.

Regimes of acoustooptic diffraction

Two regimes of the acoustooptic diffraction are distinguished, depending on the value of characteristic parameter

$$Q = \lambda L / \Lambda^2 \ , \tag{1}$$

where λ and Λ are the optical and acoustic wavelengths in the interaction medium, respectively, and L is the acoustic beam width. When $Q > 1$, the Bragg diffraction takes place. In this case, there is a single diffraction maximum at the angle given by:

$$\sin\theta_B = \lambda / \Lambda \ . \tag{2}$$

The angle between the incident light direction and the normal to the acoustic wave poropagation direction must be $\theta_B / 2$. The diffraction efficiency can be expressed as

$$I_d / I_i = \sin^2(\xi / 2) \ , \tag{3}$$

where

$$\xi = \frac{2\pi L}{\lambda_0} \Delta n \ , \tag{4}$$

I_i and I_d are the intensities of the incident and diffracted light, respectively, λ_0 is the optical wavelength in a free space, and Δn is the amplitude of the refractive index perturbation induced by the acoustic wave.

When $Q << 1$, the Raman– Nath diffraction takes place. The light is diffracted into multiple orders and the angle of diffraction into the *j*–th order can be expressed as

$$\Theta_j = j\lambda / \Lambda \ . \tag{5}$$

Here the normal light incidence with respect to the acoustic wave propagation direction is assumed. The intensity of the light diffracted into the *j*– th order is given by:

$$I_j / I_i = J_j^2(\xi) \ , \tag{6}$$

where J_j is the *j*– th order Bessel function.

Definition of M_2 for bulk waves

From the practical point of view, it is convenient to relate the diffracted light intensity to the acoustic power. The acoustically induced refractive index change, Δn, introduced in Eq.4, arises due to the photoelastic effect. The expression describing this effect in the simplest scalar form can be written as:

$$\Delta n = \frac{1}{2} n^3 pS \ , \tag{7}$$

where n is the refractive index, p is the photoelastic coefficient, and S is the amplitude of the strain created by the acoustic wave. Both optical and acoustic waves here are assumed to be plane waves. The strain is related to the acoustic intensity, I_{ac} , by:

$$S = \left(\frac{2I_{ac}}{\rho V^3}\right)^{1/2} \ , \tag{8}$$

where ρ is the mass density of the propagation medium, and V is the acoustic velocity. Substitution of Eq. 8 into Eq. 7 yields

$$\Delta n = \left(\frac{1}{2} M_2 I_{ac}\right)^{1/2} \ , \tag{9}$$

where M_2 is the acoustooptic figure of merit defined as:

$$M_2 = \frac{n^6 p^2}{\rho V^3} \ . \tag{10}$$

Assuming the acoustic beam cross–section is rectangular with length L and height H, one can relate the acoustic intensity to the acoustic power, P, by:

$$I_{ac} = \frac{P_{ac}}{H L} . \tag{11}$$

By substituting Eqs. 9–11 into Eq. 4, the argument of Bessel function (or so called Raman–Nath parameter) is rewritten in the form:

$$\xi = \frac{\pi}{\lambda_0}\left(2 M_2 P_{ac} \frac{L}{H}\right)^{1/2} . \tag{12}$$

The advantage of using surface acoustic waves is that much higher values of ratio L/H as compared to those in the bulk wave case can be obtained.

Definition of M_2 for surface acoustic waves waves

In the case of interaction between guided optical waves and surface acoustic waves one must take into account the essential non–homogeneity of the both optical and acoustic wave field distributions. The Eq. 4 still holds, but Δn now is the change in the effective refractive index of guided mode and is further denoted as Δn_m . It can be expressed as a function of the overlap between the guided mode fields, $E_m(z)$, and the acoustically induced change of refractive index in the propagation medium, $\Delta n(z)$, where z is the coordinate along the normal directed from the surface into the substrate depth. When the incident and diffracted modes are the same, this expression becomes:

$$\Delta n_m = \frac{\int_0^\infty E_m^2(z) n(z) dz}{\int_{-\infty}^\infty E_m^2(z) dz} . \tag{13}$$

Rewrite the refractive index change in the form:

$$\Delta n(z) = \Delta n(0) f(z), \tag{14}$$

where $\Delta n(0)$ is the amplitude of the refractive index change induced by the SAW at the substrate surface, $z = 0$, and $f(z)$ is the index profile function normalized so that $f(0) = 1$. Evidently, $f(\infty) \to 0$. Define the overlap integral as

$$F = \frac{\int_0^\infty E_m^2(z) f(z) dz}{\int_{-\infty}^\infty E_m^2(z) dz} . \tag{14}$$

Then Eq. 13 is rewritten in the form:

$$\Delta n_m = \Delta n(0) F . \tag{15}$$

In general, the refractive index modulation by the SAW arises due to three different interaction mechanisms: the photoelastic effect, the electrooptic effect (in piezoelectric materials) and the surface corrugation. The index change can be calculated provided all the components of elastic displacements and electric fields of the SAW and photoelastic, electrooptic and dielectric permittivity tensors in the propagation medium are known.

The complete set of these data is not always available, especially when the optical waveguiding layers are formed at the substrate surface using technologies which may change the properties of an initial material. For practical purposes, it is convenient to relate the index change to the quantity which can be reliably measured. It is the amplitude of the normal component of the elastic displacement on the SAW propagation surface, $u_3(0)$, which can be directly measured by the acoustooptic laser probe [4]. Let us write the index change in the form analogous to Eq. 7:

$$\Delta n(0) = \frac{1}{2} n_m^3 \, p_{eff} \, S_{31}(0) , \tag{16}$$

where n_m is the effective refractiv index of given mode, the amplitude of the strain component at the surface

$$S_{31}(0) = \frac{\omega}{V} u_3(0), \tag{17}$$

ω is the cyclic frequency of the SAW, and photoelastic coefficient p_{eff} is an effective parameter containing the contributions from all the above mentioned mechanisms of acoustooptic interaction. Substitution of Eq. 17 into Eq. 16 yields:

$$\Delta n(0) = \frac{1}{2} n_m^3 \, p_{eff} \frac{\omega}{V} u_3(0). \tag{18}$$

On the other hand, the component $u_3(0)$ can be related to the total power P of the SAW. It is convenient to write this relation in the form given in Ref. 5:

$$u_3(0) = 10^{-6} A \left(\frac{P}{\omega L}\right)^{1/2} . \tag{19}$$

The values of coefficient A in $m^{1/2}$ $s/kg^{1/2}$ units for various types and orientations of crystals has been calculated and tabulated in Ref. 5. Our goal now is to rewrite Eq. 18 in the form similar to that of Eq. 9. By substituting Eq. 19 into Eq. 18 and after some simple transformations one obtains:

$$\Delta n(0) = \left(\frac{1}{2} M_2^{eff} \frac{P}{H_{eff} L}\right)^{1/2} , \tag{20}$$

where

$$M_2^{eff} = \frac{n_m^6 \, p_{eff}}{\rho V^3} \tag{21}$$

and

$$H_{eff} = \frac{10^{12}}{\pi \rho f V A^2} . \tag{22}$$

The effective SAW thickness, H_{eff}, can be understand as the thickness of acoustic beam with the homogenous displacement $u_3(0)$, which has the linear power density, P/L, equal to that of the surface acoustic wave.

Now, by substituting Eq. 20 into Eq. 15, the change of effective refractive index is expressed as

$$\Delta n_m = F\left(\frac{1}{2} M_2^{eff} \frac{P}{H_{eff} L}\right)^{1/2} \tag{23}$$

Finally, substitution of Eq. 23 into Eq. 4 yields the Raman– Nath parameter:

$$\xi = \frac{\pi}{\lambda_0} F\left(2M_2^{eff} P \frac{L}{H_{eff}}\right)^{1/2} \quad (24)$$

The expression obtained is the surface wave analogue of that for the bulk wave case (see Eq. 12). The efficiencies of the acoustooptic diffraction in Bragg and Raman-Nath regimes can be related to the SAW power using Eqs. 3 and 6.

Experimental example

Let us illustrate the considerations given above by determining the effective acoustooptic figure of merit for a real structure. We choose the structure consisting of GaN layer on sapphire substrate, which actually deserves much interest due to its great potential for appplications in blue and ultraviolet optical wavelength range. The experimental investigation of the guided optical wave diffraction by surface acoustic waves in GaN–sapphire structure has been reported in Ref. 6. Intensities of light diffracted into the zeroth and first Raman– Nath orders has been measured as functions of the SAW power both for TE and TM optical modes. Theoretical curves calculated from Eqs. (6) and (24) were fitted to these dependencies by choosing the value of the product $F^2 M_2^{eff}$. The values of other parameters necessary for calculation are given in Table 1.

Table 1

Parameter	Value
λ_0	0.6328 μm
ρ	$4 \cdot 10^3$ kg/m³
f	194 MHz
L	1.3 mm
V	4700 m/s
A	1.841 s (m/kg)$^{1/2}$
H_{eff}	25.8 μm

Measured and calculated dependencies I_0/I_i and I_1/I_i are shown in Fig. 1. The values of $F^2 M_2^{eff}$ obtained from the best fit are given in Table 2.

Table 2

Mode	Product $F^2 M_2^{eff}$, s³/kg
TE_0	$2.08 \cdot 10^{-15}$
TM_1	$1.64 \cdot 10^{-15}$

To determine the value of M_2^{eff}, one must calculate the overlap integral using Eq. 14. For this purpose, the profile of the refractive index change *f*(z) and the distribution of the electric field *E*(*z*) of guided mode must be known. The calculation of these functions is beyond the scope of the present paper. Anyway, for estimation purposes, a rough approximation, $F = 1$, seems to be suitable.

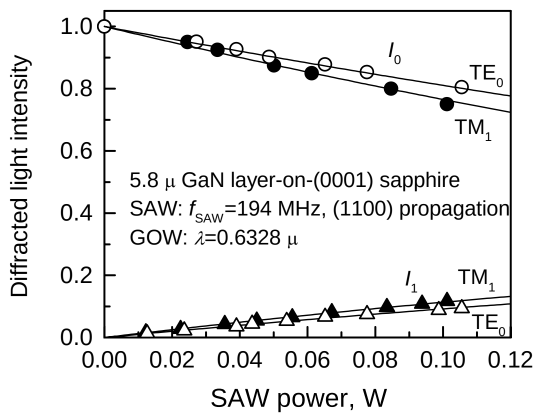

Fig. 1. **Dependencies of diffracted light intensity on SAW power. Dots, experiment; lines, theory.**

Since most practical devices operate in the Bragg regime, we use our results to estimate the SAW power necessary for the 100 % light beam deflection. It is found from Eq. 3 by requiring

$$\xi = \pi \, . \quad (25)$$

This condition yields

$$P_{100\%} = \frac{1}{2} \frac{H_{eff}}{L} \frac{\lambda_0^2}{F^2 M_2^{eff}} \, . \quad (25)$$

From Eq. 25 it follows that SAW powers 1.9 and 2.4 W are necessary to obtain the 100 % light beam deflection of TM and TE modes, respectively, for the conditions and parameters listed in Table 1. Most interesting applications of GaN– based structures are expected in the short optical wavelength range. For wavelength 0.38 μ with acoustic beam width 3 mm the considerably lower SAW powers, 0.3 W for TE and 0.38 W for TM, are expected.

Conclusions

When the acoustooptic interaction is realized in a layered structure using surface acoustic and guided optical waves, the spatial distribution of acoustic and optical fields is very important. The properties of material itself are estimated by the acoustooptic figure of merit which can be evaluated from the acoustooptic diffraction measurements. The values of the acoustooptic figure of merit for gallium nitride are evaluated and the potential possibilities of using this material for acoustooptic modulators in short– wavelength visible and ultraviolet range are demonstrated.

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Dėl paviršinių akustinių bangų ir optinių bangolaidžio modų sąveikos akustooptinės kokybės rodiklio apibrėžimo

Reziumė

Optinių bangolaidžio modų difrakcijos paviršinėmis akustinėmis bangomis efektyvumą, kaip ir tūrinių bangų atveju, apibūdina akustooptinės kokybės rodiklis M_2. Paviršinių bangų atveju reikia atsižvelgti į tai, kad optinių ir akustinių laukų pasiskirstymas erdvėje yra nevienalytis. Naudojant efektyvius parametrus, difraguotos šviesos intensyvumo priklausomybėms nuo paviršinių akustinių bangų galios galima suteikti tokį pat pavidalą kaip tūrinių bangų išraiškoms. Iš eksperimentinių duomenų apskaičiuota akustooptinės kokybės rodiklio vertė dariniui GaN sluoksnis– safyro padėklas.

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