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UTILIZATION OF SAW FOR STUDYING THE PROPERTIES OF OPTICAL WAVEGUIDES[1)]

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A short review of recent developments in the utilization of surface acoustic waves (SAW) for studying the properties of optical waveguides based on planar acoustooptic (AO) interactions in presented. In the particular case of the collinear resonant guided mode scattering by SAW into the radiative light mode it demonstrates a series of new precise measurements of the waveguide parameters in Ti-$LiNbO_3$, PE-$LiNbO_3$ and Cu-$LiNbO_3$.

I. INTRODUCTION

It is now well established that the investigations of SAW propagation in condensed matter are very informative when we study the related media properties or the ambient physical fields. On this basis there were also developed many widespread applications for different types of sensors, signal processors and an acoustical testing of the materials (see, for example, reviews [1-3]). The main features of SAW, which are ordinarily used, are the sensitivity of its phase velocity to the elastic properties of media and the frequency dependent penetration depth in the substrate (which means a locality of the testing).

This paper deals with SAW in testing the planar optical waveguides, when we can use the definite (or stable) elastic structure, but optical properties should be investigated. Recently this kind of SAW measurements is remarkably improved due to the application of the special type of AO interaction under collinear propagation of SAW and optical guided modes in the planar waveguide. We shall briefly review the main theoretical basis and the recent experimental results in the different kinds of waveguides in $LiNbO_3$.

II. COLLINEAR AO INTERACTION SAW AND GUIDED MODES IN PLANAR WAVEGUIDE

In any case of the resonant AO interactions we have to satisfy two quantum mechanical conservation laws, for energy and momentum:

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$$\hbar\omega_2 = \hbar\omega_1 \pm \hbar\Omega \qquad (1)$$
$$\vec{K}_2 = \vec{K}_1 \pm \vec{g}_s$$

where ω_1, ω_2 and Ω denote the frequencies of incident light, diffracted light and sound waves, respectively; $\vec{K}_1$, $\vec{K}_2$ and $\vec{g}_s$ are the related wave vectors. The diffraction efficiency η defined as a ratio of the diffracted light intensity of the first order I_1 to the incident one I_o ($\eta = I_1/I_o$) may be presented as follows [4]

$$\eta \simeq \sin^2(\Gamma_{mn} P_s d), \qquad (2)$$

where Γ_{mn} is the coupling coefficient of the input (n-mode) and output (m-mode) optical modes. P_s is the SAW power, d is the interaction length. Because Γ_{mn} is a complex function of the spatial overlapping of the fields of SAW[1)] and the pair of coupled light modes with its very complicated shapes (see, for example, Fig. 1), to enhance η we need to optimize all these distributions. In cases of the inplanar AO scattering it was shown [5] that the optimal condition is the transition $TE_o \to TE_o$ in a single-mode planar waveguide under AO interaction with a high frequency (300-800 MHz, typically) surface acoustic (Rayleigh) wave.

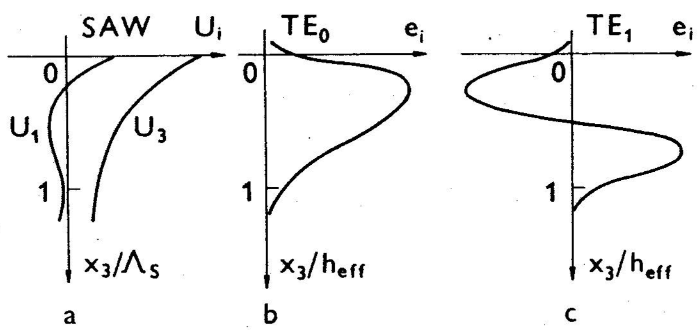

Fig. 1. The typical patterns of SAW (a) and the lowest optical modes (b,c) spatial distributions under substrate surface.

In case of the collinear AO interaction when SAW and the incident light mode are co- (or contra) propagated one can find two different possibilities (see, Fig. 2): the diffraction of one guided mode to another guided one ($TE_i \to TE_j$ or $TE_i \leftrightarrow TM_j$) and the guided mode to the volume one irradiated into the substrate (called the substrate mode) with the same as the incident mode or with the orthogonal

[1)] more exact the distribution of sound induced variations of the material permittivity (the photoelastic term) and sometimes of the periodic corrugation of the surface (the ripple term).

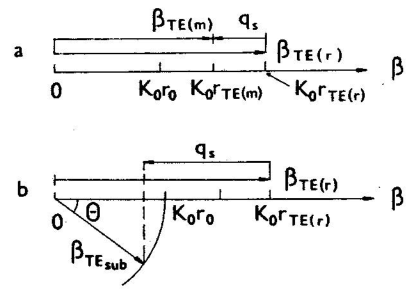

Fig. 2. Wave vector diagrams for guided intermodes (a) and guided-substrate modes (b) transitions under collinear AO interactions in an isotropic planar waveguide.

plane polarizations ($TE_i \to TE_{sub}, TM_{sub}$ or $TM_i \to TE_{sub}, TM_{sub}$). The related laws of the momentum conversation (phase matching conditions) for the isotropic media may be written as

$$\left.\beta_m \pm g_s = \beta_n\right\} \quad \begin{matrix} TE_i \to TE_j \quad (i \neq j) \quad i,j = 0,1,\dots \\ TM_i \leftrightarrow TE_j \end{matrix} \qquad (3)$$

$$\left.\beta_m - g_s = K_o n_o \cos\Theta\right\} \quad \begin{matrix} TE_i \to TM_{sub}, TE_{sub} \\ TM_i \to TM_{sub}, TE_{sub} \end{matrix}, \qquad (4)$$

where $\beta_m = K_o n_{\text{eff}(m)} = K_o(n_o + \Delta n_{\text{eff}(m)})$ is the propagation constant of the guided m-mode, n_o and n_{eff} are the refractive index of the substrate mode and the effective index of the guided m-mode, Θ is the outgoing angle of the substrate mode.

As it was shown in Reference [6] in cases of anisotropic waveguides one can find a much more complex situation. For instance, in the single-mode uniaxial waveguide under the incidence of the light mode and SAW along the perpendicular to the optical axis the phase-matching conditions may be expressed as (see also Fig. 3): in case of TE-mode incidence:

$$\left.\begin{matrix} \beta_{TE_o} - q(f) = K_o n_e \cos\Theta_1 \\ \omega_{TE_o} - \Omega_1 = \omega_1 \end{matrix}\right\} \quad TE_o \to TE^-_{sub}$$

$$\left.\begin{matrix} \beta_{TE_o} - q(f) = K_o n_o \cos\Theta_2 \\ \omega_{TE_o} - \Omega_o = \omega_2 \end{matrix}\right\} \quad TE_o \to TM^-_{sub} \qquad (5)$$

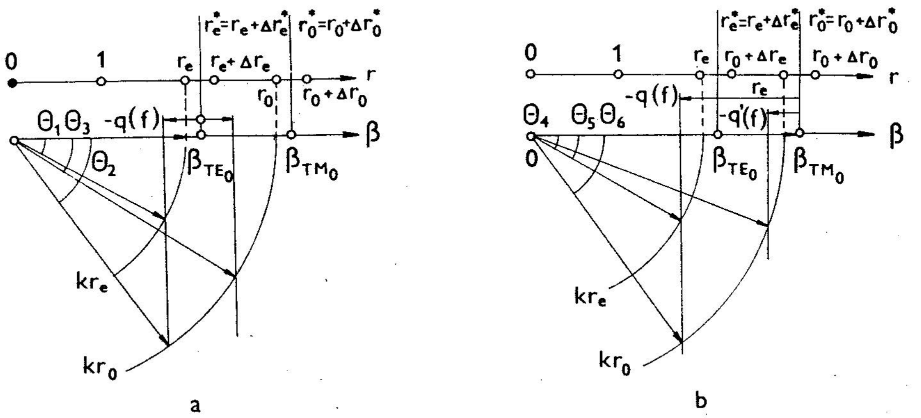

Fig. 3. Wave vector diagram of a collinear AO interaction of SAW and TM_o-mode in an anisotropic planar waveguide.

$$\left.\begin{array}{l}\beta_{TM_o} + q(f) = K_o n_o \cos\Theta_3 \\ \omega_{TE_o} + \Omega_3 = \omega_3\end{array}\right\} \quad TE_o \rightarrow TM^+_{sub}$$

and for the TM-mode incidence:

$$\left.\begin{array}{l}\beta_{TM_o} - q(f) = K_o n_o \cos\Theta_{4,5} \\ \omega_{TM} - \Omega_{4,5} = \omega_{4,5}\end{array}\right\} \quad TM_o \rightarrow TM^-_{sub}$$

$$\left.\begin{array}{l}\beta_{TM_o} - q(f) = K_o n_e \cos\Theta_6 \\ \omega_{TM} - \Omega_6 = \omega_6\end{array}\right\} \quad TM_o \rightarrow TE^-_{sub} \qquad (6)$$

where n_o and n_e denote the ordinal and extraordinal refractive indices, respectively. Thus due to anisotropy of the substrate and the waveguide each incident guided mode may be transformed under collinear AO interaction into several (up to 3) substrate modes without or with 90° rotation of the plane polarization. The outgoing angle of the substrate mode contains a valuable information about the related guided mode and it will allow in the next section the new AO method of determinating waveguide parameters to be developed. As it is shown in Fig. 4, for the Ti-diffused YX-$LiNbO_3$ waveguide there are just two allowed transitions under collinear AO interactions which occur at quite high SAW frequencies near to $f_{sopt} = v_s/h$ (v_s is the SAW velocity, h is the effective guide thickness) with $\Theta \rightarrow O : TE_o \rightarrow TM^-_{sub}, TM_o \rightarrow TE^-_{sub}$. It is important to have a large diffraction efficiency because under these conditions the coupling factor $\Gamma_{os} \sim 1 - a\Theta^2$ (a is a constant).

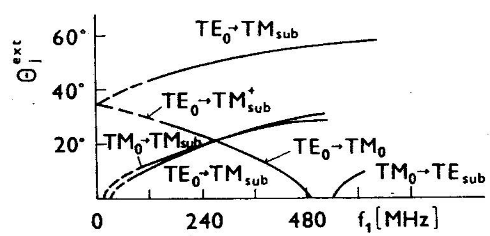

Fig. 4. Experimental frequency dependences of the outgoing angles for substrate optical modes under collinear AO iteractions in a Ti-diffused YX-$LiNbO_3$ waveguide. [6]

The special computer calculations and experiments [7] in Ti-diffused single mode waveguides on YX-$LiNbO_3$ have definitely shown this conclusion: $TE_o \rightarrow TM^+_{sub}$ and $TM_o \rightarrow TE^-_{sub}$ transitions are the most efficient "radiative processes" under collinear AO interactions (at 1-2 orders of magnitude more comparable to the others) and for SAW frequencies of about 300-700 MHz its efficiencies are comparable with the one of the in-planar intermode transition $TE_o \rightarrow TE_o$ i.e. $\sim 10 - 20$ %/W. Since the range of the optimal SAW frequencies depends on the substrate anisotropy (for $LiNbO_3$: $f_{opt} \simeq v_s/\lambda_o|n_e - n_o| \simeq 500 - 600$ MHz), in general it is possible to change it by selection crystal cuts or optical wavelength variations. A very wide variation of f_{opt} (from 20 MHz to 700 MHz) was observed in the proton-exchanged ZX-$LiNbO_3$ waveguides with a special thermal treating of the sample under preparation [8].

III. AO MEASUREMENTS OF GUIDED MODE PARAMETERS IN PLANAR WAVEGUIDES

The collinear AO interactions of SAW and guided optical modes with the radiative substrate mode diffraction open a new sophisticated method for measuring the guided mode parameters: the contributions to the effective refractive indices $\Delta n_{eff}(m)$ and the attenuation constant α_L. In fact, as it is seen from (4) if $\Theta \rightarrow 0$, we have (see also Fig. 5a):

$$\Delta n_{eff}(m) = \frac{\lambda_o}{V_s} f_{min}(m), \qquad (7)$$

where $f_{min}(m)$ is the sound frequency under $\Theta \rightarrow 0$.

Thus one can measure the minimum of the SAW frequency f_{min} (with defined λ_o and V_s) to obtain the value Δn_{eff} for a desirable guided mode. In case of an

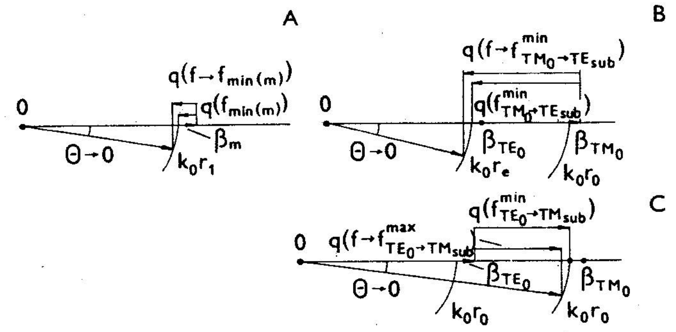

Fig. 5. Vector diagrams of the collinear AO interactions under measuring the effective refractive indices in optically isotropic (A) and anisotropic (B,C) planar waveguides.

anisotropic substrate the same technique to measure $\Delta n_{eff}(m)$ is also available with a new set of measurements (see also vector diagrams on Fig. 5-b,c):

$$f_{min}(TE_m) = f^{min}_{TM_m \to TE_{sub}} - f_{TE_m \leftrightarrow TM_m}, \tag{8}$$

$$f_{min}(TM_m) = f_{TE_m \leftrightarrow TM_m} - f^{max}_{TE_m \leftrightarrow TM_{sub}}, \tag{9}$$

where $f_{TE_m \leftrightarrow TM_m}$ is the SAW frequency for the transition $TE_m \leftrightarrow TM_m$ etc. Using eqs. (8) and (9) in eq. (7) it is easy to obtain Δn_{eff} for TE_m – or TM_m – modes as functions of the above mentioned frequencies, all of which are variable (for different waveguides) in a small frequency bandwidth compared with usually available interdigital transducer used for SAW generation.

That gives an attractive simplification of this technique. Another advantage of the measurement based on the anisotropic collinear AO interaction is always the high diffraction efficiency appearing while high frequency AO measurements are near to f_{opt} (see, eqs. (8) and (9)) in spite of very large variations of f_{min} apart of f_{opt} in different waveguides.

But the most important advantage of the collinear light scattering by SAW is the very high accuracy of the frequency measurements (the high SAW spectral resolution ∂f), because $\partial f \simeq 1/\tau_{int} = V_s/d_{int}$ where the interaction lenght d_{int} may simply increase up to the distances restricted by the crystal length or the light/sound attennation distances. Nowadays, we have experimentally reached on Ti-diffused waveguides on Y-$LiNbO_3$ the resolution $\partial f_{min} \simeq 5 \times 10^4$ Hz (it must to be compared with the typical case of AO planar noncollinear interaction, where $\partial f_{min} \simeq 2 \times 10^6$ Hz).

The typical results for a Ti-diffused single-mode waveguide on YX-$LiNbO_3$ substrate are the following [9]: $f^{(max)}_{TE_o \to TM_{sub}} = 487.0 \pm 0.5$ MHz, $f^{(min)}_{TM_o \to TE_{sub}} =$

538.1 ± 0.5 MHz and $f_{TE_o \leftrightarrow TM_o} = 504.0 \pm 0.5$ MHz, from which according to eqs. (9) and (10) one can obtain $f_{min}(TE_o) = 34.0 \pm 1$ MHz and $f_{min}(TM_o) = 17.0 \pm 1$ MHz and after substitution into eq. (8) $\Delta n_{eff}(TE_o) = 0.0057 \pm 0.0002$ and $\Delta n_{eff}(TM_o) = 0.0028 \pm 0.0202$ ina good agreement with the independently made, more complicated prism method measurements. This kind of AO measurements has been successfully applied to reconstruct the refractive index profiles in Ti-diffused and Li_2O out-diffused $LiNbO_3$ waveguides [10].

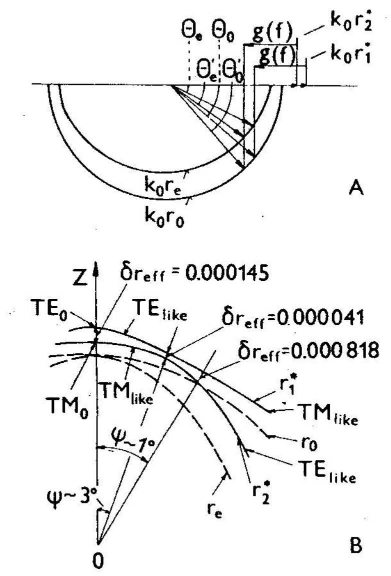

Fig. 6. Vector diagram (A) and experimental results (B) for measuring the propagation constant anglum dependences for TE- and TM-like modes in Y-$LiNbO_3$. [11]

The collinear light diffraction by SAW allows to obtain the big interactions length d_{int} to got a very precise tool for the investigation of the optical modes propagation constants as a function of its directions. Recently, this was successfully used [11] for the investigation of the space dispersion of the lowest hybrid TE- and TM-like modes in Ti-diffused Y-cut $LiNbO_3$ waveguides near to the direction where the expected difference in the refractive indices for split guided modes must be equal to the extremely small value $\sim 10^{-5}$. Fig. 6a shows a vector diagram for the collinear AO interaction corresponding to the experiments where two hybrid guided modes propagate in the direction closed to the Z-axis of the substrate. It is seen to measure the difference of the effective refractive indices for these modes (n_1^*

and n_2^* for TM- and TE-like modes, respectively), one can use its diffraction into four different radiative modes with different plane polarizations (extra-ordinary and ordinary beams) and outgoing angles $\Theta_{e,o}$ according to the vector equations:

$$K_o n_1^* - q(f) = K_o n_{e,o} \cos\Theta_{e,o}, \tag{10-a}$$
$$K_o n_2^* - q(f) = K_o n_{e,o} \cos\Theta_{e,o}, \tag{10-b}$$

where n_e and n_o are extraordinary and ordinary indices for light waves in the substrate. According to eqs. (10), the value $(n_1^* - n_2^*)$ may be obtained under fixed f_o of SAW from the measurements of one couple of angles (Θ_o, Θ_o') or another (Θ_e, Θ_e'), but also under fixed indication angle (Θ_o or Θ_e) from the measurements of the frequency difference Δf needed to equalize the outgoing angles for different modes, i.e. $\Theta_e'(f_o) = \Theta_e(f_o + \Delta f)$ or $\Theta_o'(f_o) = \Theta_o(f_o + \Delta f)$. In the last method one can evaluate the refractive index difference as follows:

$$\partial n_{\text{eff}} \equiv n_1^* - n_2^* = \frac{\lambda_o}{V_s}\Delta f. \tag{11}$$

In the experiments the SAW was generated by IDT along ~Z-direction in Y-$LiNbO_3$. The optical quided modes were excited by laser with the prism coupler. The AO interaction length was equal to ~ 3 cm, which allowed a frequency resolution ~ 150 kHz. The typical experimental dependeces are drawn in Fig. 6b. When the modes direction was along Z-axis ($\phi = 0$) the value of ∂n_{eff} was equal ~ 14.5×10^{-5}($\Delta f \simeq 800$ kHz), but when ϕ goes up, the value ∂n_{eff} slowly decreases to a minimum $\partial n_{\min} \simeq 4.7 \times 10^{-5}$($\Delta f = 260$ kHz) under $\phi = 3°$, and then monotonically increases to $\partial n_{\max} = 81.8 \times 10^{-5}$($\Delta f = 4500$ kHz) under $\phi \geq 7°$, when the leaky wave appears. So firstly it were observed the dispersion splitting TE- and TM-like hybrid modes in the single mode Ti-diffused waveguides in Y-cut $LiNbO_3$.

Another application of the collinear AO interaction is the measurement of the light guided mode and SAW attenuation constants [12]. The main idea takes into consideration the diffracted light kinetics of the scattering of continuous light mode by the short pulse of SAW at long distance and large time of the collinear AO interactions (Fig. 7a) when the amplitude of the scattered light into the substrate has a time variation as

$$U(t) \sim \exp\{-(\alpha_S \pm \alpha_L)V_s t\}, \tag{12}$$

where α_L and α_S denote the light and SAW attenuation coefficients, respectively, the signs + and − correspond with two cases, the reverse and the codirectional propagation of the SAW and the input light. After two measurements of $(\alpha_L + \alpha_s)$ and $(\alpha_s - \alpha_L)$ one can obtain α_L and α_S independently. Fig. 7b shows an example

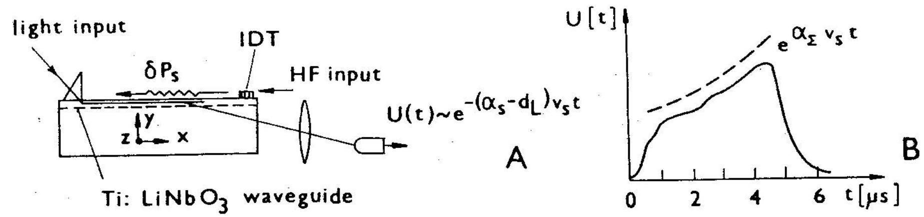

Fig. 7. Scheme (A) and experimental results (B) for measuring the optical and acoustical attenuation in a Ti-diffused planar waveguide in YX-$LiNbO_3$. [8]

of measurements in Ti-diffused waveguide on $LiNbO_3$: there were $f_s \simeq 93$ MHz, $\alpha_s \simeq 0.08$ dB/cm $\alpha_L \simeq 2.7 \pm 0.3$ dB/cm.

Another very new application of this AO technique was performed in [13] to study kinetics of the infrared ($\lambda_o \simeq 10.6 \mu m$) surface electromagnetic waves guided by the metalic film (Cu) on piezoelectric substrate $LiNbO_3$ (so-called plasmon-polariton waves). For this case one can draw the vector diagram as shown in Fig. 12, where the radiative mode goes out to air. Under a very short ultrasonic pulse excitation the diffracted beam irradiated by SAW due to surface corrugation (see Fig. 8) in the form indicated in Fig. 9 was observed. For the Cu-film thickness $h_{Cu} \simeq 30$ nm deposited on YZ-$LiNbO_3$, the observed guided plasmon-polariton mode scattered by SAW ($f_s \simeq 42$ MHz) was characterized by $\alpha_{pp} \simeq 1$ dB/cm in good agreement with the special very complicated measurements based on the moving coupler method.

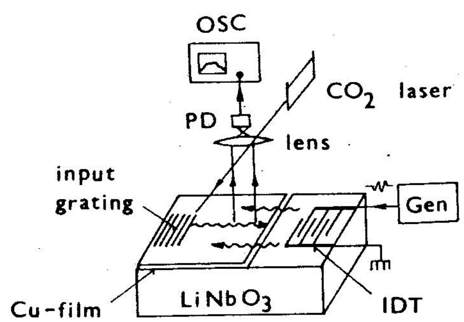

Fig. 8. Scheme for measuring the plasmon-polariton diffraction by SAW.

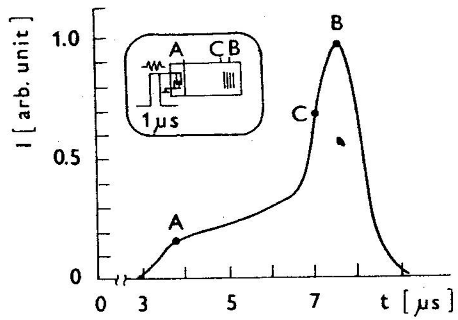

Fig. 9. Kinectics of the output signal under measuring the plasmon-polariton absorption coefficient in Cu-$LiNbO_3$. [13]

IV. CONCLUSION

SAW applications for studies of the integrated optical structures as it has been demonstrated above are very promissing because they open new beautiful facilities in the measurements of the guided light mode propagation parameters, i.e. the improved accuracy and the wide range of the spectrum of the refractive indices or its variations, the attractive simple measuring of the optical and SAW attenuation constants and the wide range of optical wavelengths etc. All of these properties are recently based on the specific collinear AO interaction of the guided light modes with SAW which attains an enhanced diffraction efficiency and very high spectral selectivity.

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ПРИМЕНЕНИЕ ПАВ В ИЗУЧЕНИИ СВОЙСТВ ОПТИЧЕСКИХ ВОЛНОВОДОВ

В работе приведен короткий обзор по развитию приеменений поверхностных акустических волн (ПАВ) при исследовании оптических волноводов основаных на планарном акустооптическом взаимодействии. На основании результатов новых точных измерении параметров волновода в Ti-$LiNbO_3$, PE-$LiNbO_3$ и Cu-$LiNbO_3$ демонстрируется, в частом случае, рассеяние линейной резонансной проводящей моды на ПАВ в световое изучение.