Optimal configuration of the waveguide acousto-optic TE-TM polarization mode convertor on X-cut lithium niobate substrate

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Abstract. An excitation, distribution, and interaction of surface acoustic waves (SAW) with the guided light in integrated optical structures on X-cut lithium niobate substrates were studied. The resonance excitation frequencies, the spatial SAW distribution and the TE-TM optical mode conversion efficiency were investigated. An optimal configuration and most suited material of interdigital transducer (IDT) for integrated acousto-optic devices were found.

1. Introduction

Acousto-optic modulators (AOMs) [1] based on the Bragg diffraction have been widely used as optical control devices such as optical switches, optical detectors, optical frequency shifters, and etc.

Due to strong piezoelectric effect [2] the lithium niobate (LN) crystals are widely used for AOMs fabrication. Moreover, matured technology of optical waveguide fabrication [3, 5] makes this material very suitable for AOMs in integrated waveguide configurations. The main advantage of waveguide configurations is lower driving power.

An optimal configuration of integrated acousto-optic devices should combine a high efficiency of SAW excitation, SAW overlap with guiding light, long length and high efficiency of acousto-optic interaction. Parasitic effects due to SAW reflection, interference and transformation should be also taken into account.

In this paper, three experimental methods were used for SAW investigations. These are IDT admittance frequency dependence measurements, fiber optic interferometric SAW spatial distribution visualization, and acquisition of power dependence of TE-TM polarization mode conversion in optical waveguides. An optimal configuration of the acousto-optic TE-TM polarization mode convertor on X-cut LN substrate has been proposed based on the obtained experimental data.

2. Samples and experimental methods

2.1. Design and fabrication of TE-TM mode convertor chips

The mode conversion may be realized via the electrooptic or acoustooptic effect in dielectric optical waveguides [4]. If we employ the acousto-optic effect, the phase difference between two modes can be compensated along a path length by tuning the acoustic frequency, and the mode conversion can be easily realized with a high efficiency.
A TE-TM mode convertor chip based on a direct-channel optical waveguide (see figure 1) was chosen as the object of the research. The chip was fabricated on a single crystal plate (5x50x1mm), which was made of a congruent lithium niobate X-slice with a titanium-diffuse optical waveguide oriented along the Y axis [5]. 17 fingers IDTs with an overlap length 1.7 mm and thickness of 200 nm were fabricated on the crystal plate surface over optical waveguide. Different samples had different angle between the fingers and the Z axis which varied from 0˚ to 5˚. In addition two different materials (aluminum and gold) were used for IDTs fabrication. The chips were coupled with single mode polarization maintaining optical fibers by end fire technique using UV-cured optical adhesive which also performed SAW absorber function. To provide electrical connection the chips were mounted on the textolites plate by a UV curing adhesive along two lines perpendicular to the direction of the optical waveguide and IDTs were welded to the plate tracks by gold wires. An AC voltage with a power of 20 dBm and frequency of about 175 MHz was applied to the IDT to excite the SAW.

![Figure 1. Configuration of the TE-TM polarization mode convertor sample and IDT configuration](image)

2.2. Electrical measurements
A vector network analyzer was used to measure network parameters of IDT pairs.

Each IDT pair formed the system known as a SAW resonator filter [6]. So it could be used to measure electrical s-parameters (reflection and transmission) and control the SAW excitation efficiency. However, it should be noted that the overlap length and the distance between IDTs are larger in a TE-TM mode convertor than in a normal SAW filter. So it was obvious that s-parameters for the IDTs pairs studied were worse than for a normal SAW filter.

Also the reflection coefficients (S11) and the phase shift between initial signal and reflected one were used to calculate the real part of admittance.

2.3. Fiber optic interferometer
The fiber optic interferometric method (see figure 2) was used for obtain information about the SAW excitation and SAW spatial distribution on the lithium niobate substrate.

Distributed feedback laser diode (DFB LD) with fiber output was used as a light source (1550 nm, 100 mW). The tip of the optical fiber was approaching close to the sample surface and played the role of an optical probe. A small light spot diameter from the fiber provided high spatial resolution. The
sample was installed on a motorized 3-axis translation stage to scan along sample surface and adjust distance between fiber tip and sample. The interference signal on the frequency of SAW excitation from the light reflected by the fiber tip and the sample surface was detected. To detect the reflected optical signal a 50/50 fiber optic direction coupler and a high frequency photodetector (up to 200 MHz) were used. The signal of the photodetector proportional to the SAW amplitude was selectively measured at the frequency of the SAW excitation by lock-in amplifier. The maximum contrast of the interference signal was achieved by adjustment of the distance between fiber tip and sample surface. Addition modulation at the low frequency about 230 Hz was provided by piezo-actuator and was used for calibration and estimation of absolute value of SAW amplitude.

Figure 2. Fiber optic interferometer: 1 – DFB LD 1550 nm, 100 mW, 2 – fiber optic direction coupler, 3 – sample installed at the motorized translation stage, 4 – high frequency photodetector (up to 200 MHz), 5 – high frequency generator, 6 – Lock In amplifier, ΔY = -10, -1, 1, 16 mm – distance probe from IDT.

2.4. TE-TM mode conversion efficiency measurements
Observation of the TE-TM mode conversion was used to verify the assumptions about the best material and configuration of IDTs for integrated acousto-optic devices.

DFB LD with wavelength 1550 nm and power 15 mW produced the laser radiation with TE polarization (see figure 1). This radiation passed through the convertor chip to the polarization splitter. The TE polarization from the polarization splitter passed to the photodetector. The output light intensity was measured using a photodetector. Diffraction efficiency was determined from the decrease in the intensity of the undiffracted light. The RF modulating signal on the convertor chip had power 20 dBm and swept frequency from 150 MHz to 250 MHz.

3. Results and discussion
3.1. S-parameters of the IDTs
At first the samples with aluminum IDTs was investigated. The samples with different distances (L = 5, 11, 17 and 22 mm) between pairs of IDTs showed significant decreasing of the transmission (S21) with the growth of the distance (-22.7 dB, -26.3 dB, -31.0 dB, and -39.0 dB, respectively). It
should be noted that for LN X-cut there is a tilt angle between the direction of the acoustic power flow and the SAW wave front normal [7]. Thus the decreasing of $S_{21}$ can be explained by geometrical factors (decrease in the overlap zone of the SAW and IDT detector) rather than by the SAW attenuation. For the tilt angle $\alpha$ of 4.2 deg the overlap zone should be 78 %, 52 %, 25 %, and 3 % for the distances 5 mm, 11 mm, 17 mm, and 22 mm, respectively. These decreases in the overlap zone were in good agreement with the decreases in the $S_{21}$ parameter. The absence of a significant SAW attenuation was checked by the other methods. A slowing of the decreasing of $S_{21}$ parameter with increasing of the distance between IDT pairs could be explained by angular divergence of SAW, widening SAW beam and as consequence some slight increasing of the overlap zone. The estimated SAW widening was about 11 $\mu$m per 1 mm.

The reflection coefficients ($S_{11}$) and the phase shift between initial signal and reflected one were used to calculate the real part of IDT admittance (see figure 3). The frequency dependences of the admittance real part for the sample with the aluminum and gold IDTs were significantly different. Two resonance maxima corresponded to the excitation of the SAW (175 MHz) and the pseudo SAW (200 MHz) [8] was observed on the sample with the aluminum IDT. The gold IDT slowed down the pseudo SAW which resulted in the shift of the pseudo SAW resonance frequency to 170 MHz. It leaded to the merging of the SAW and pseudo SAW resonance excitation.

![Figure 3. Frequency dependences of admittance for gold and aluminum IDTs.](image)

3.2. SAW spatial distribution

The data obtained from the fiber optic interferometer allowed us to find out accurate SAW profiles (the SAW spatial distribution pattern) and the SAW attenuation with distance. The results for the sample with aluminum IDT which had fingers perpendicular to the channel optical waveguide (along Z axis $-\beta = 0^\circ$) are presented in figure 4.

Four SAW beam profiles obtained by fiber optic probe transverse scanning at 10 and 16 mm distance $\Delta Y$ from both sides of the IDT showed very weak SAW attenuation and insignificant change of the rectangular SAW beam shape. The tilt angle $\alpha$ about 4 deg between the direction of the acoustic power flow and the wave front normal was observed. It was found out that the compensation angle for the IDT finger $\beta$ should be equal 5$^\circ$ to obtain the SAW propagation along the optical waveguide (Y axis).
3.3. **TE-TM polarization mode conversion**

The best TE-TM polarization mode conversion efficiency (about 95%) was observed for the sample with the aluminum IDT which had compensation angle $\beta = 5^\circ$. The maximum of conversion efficiency was observed with the RF signal power 100 mW at resonance frequency about 175 MHz which corresponded to SAW excitation (see figure 5). The length of the acousto-optic interaction about 45 mm was estimated from the width of the conversion efficiency frequency dependence. Note, the polarization mode conversion wasn’t observed on the pseudo SAW excitation frequency (200 MHz).

4. **Conclusions**

Three methods of investigation of the SAW excitation efficiency and SAW spatial distribution on lithium niobate substrates were used. Their results proved to be in good agreement with each other. It was found that the restriction on the interaction length was imposed by the tilt angle between the direction of the acoustic power flow and the wave front normal rather than the SAW attenuation. It was also showed that the aluminum IDT was more preferable than the gold IDT. This was because of the fact that the gold IDT generated both the SAW and the pseudo SAW on the close resonance frequencies. The pseudo SAW is a parasitic wave that reduces the acoustic efficiency, since it propagates into the substrate and interact with the optical fields guided in the titanium-diffuse waveguide only slightly [9]. Also the pseudo SAW can create interference on SAW and add a noise to the optical signal. It was also found that the SAW attenuation was considerably lower on thin aluminum structures than on thin gold structures. The SAW properties were calculated and proved to be in good agreement with the known values for LN.
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