Acousto-optic frequency shift modulators with acoustic and optic waveguides on X-cut lithium niobate substrates

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Abstract. An optimal configuration of the waveguide acousto-optic frequency shift modulators on the X-cut lithium niobate substrates was analyzed. The conditions for efficient excitation of surface acoustic waves (SAW) and their interaction with the guided light in integrated optical structures were found. The influence of acoustic waveguide presence and interdigital transducer (IDT) geometry and material on the SAW resonance excitation was investigated. An acoustic waveguide configuration was proposed for increasing the TE-TM optical mode conversion efficiency. A low power (about 15 dBm) high frequency modulation signal was required for full TE-TM mode conversion in the proposed modulator configuration.

1. Introduction
Acousto-optic modulators (AOMs) [1-4] are widely used for the light control in different fiber optic systems where perform functions of optical switches, optical pulse generators, optical frequency shifters, and etc. For example, optical frequency shifters can be used for well-known signal detection algorithm [5,6] for interferometric sensors [7-9]. A waveguide configuration of AOMs provides a number of advantages first of all lower power high frequency control signal and compatibility with standard single mode optical fibers. The lithium niobate (LN) crystals are widely used for integrated AOMs [10] (as for SAW electronic devices [11,12]) because of inherent piezoelectric properties and well elaborated technology of optical waveguide fabrication [13,14].

In previous work [15] we investigated parasitic effects related to SAW reflection, interference and transformation. However, the TE-TM optical mode conversion efficiency turned out less than required. In the previous case, a long interaction length (more than 40 mm) or a high power (more than 25 dBm) of modulation signal was required. A long interaction length led to an excessive narrowing of the mode conversion bandwidth. A high power of modulation signal led to unwanted heating effects. In this work an acoustic waveguide configuration was proposed for increasing the TE-TM optical mode conversion efficiency.

We used IDT admittance frequency dependence measurements for SAW excitation investigation. Also TE-TM mode conversion efficiency measurements were performed. The experimental results were applied to determine an integrated AOM optimal configuration.
2. Experimental samples and measuring techniques

2.1. Integrated AOM chips
Integrated AOMs are based on the Bragg diffraction on travelling SAW accompanied by a polarization mode conversion in optical waveguides [15]. The converted mode is frequency shifted on the signal frequency because of Doppler effect. The phase difference between two waveguide polarization modes is compensated at the resonance acoustic frequency and high length of the acousto-optic interaction with high mode conversion efficiency can be achieved.

The configuration of experimental samples of optical frequency shifter chips is shown on the figure 1. It is a single crystal congruent LN plate of X-cut (5x50x1mm) with straight channel optical waveguide fabricated by titanium thermal diffusion technique [16]. The optical waveguide was directed along the Y axis and supported single mode light propagation at the 1550 nm. An acoustic waveguide was fabricated by titanium thermal diffusion in the one technological process with the optical waveguide. The thin film (200 nm) IDTs were fabricated over optical waveguide by magnetron sputtering. Distances between centers of two adjacent fingers were 10 µm or 10.375 µm (in the final configuration). Two different materials (aluminum and gold) were used for IDTs fabrication in configuration without the acoustic waveguide. This configuration had IDTs with number of fingers \( N = 17 \) and overlap length \( D = 1.7 \) mm. An angle between the fingers and the Z axis was obtained in previous work [15] and equaled 5 degrees. An interaction length was 40 mm. Only aluminum was used for IDTs fabrication in configuration with acoustic waveguide. This configuration had other parameters of IDTs: number of fingers \( N = 40 \) and overlap length \( D = 0.1 \) mm. Two single mode polarization maintaining fiber optic pigtails were connected to the chip from the both sides using end fire coupling technique. UV-cured optical adhesive used for the pigtails fixation performed also SAW absorber function. The chip was mounted on the textolite plate and IDTs were welded to the plate tracks by gold wires. A high frequency control signal with frequency in the range of 150 - 250 MHz was applied to the plate through standard SMA connectors.

![Figure 1](image_url)

**Figure 1.** Configuration of the AOM chip and IDT geometry (\( D = \text{overlap length}, \ d = 10 \mu m \) or \( 10.375 \mu m \) – distances between centers of two adjacent fingers, \( \beta = 5^\circ \) – compensation angle between fingers and Z axis).
2.2. IDT admittance measurements
Electrical S-parameters of IDT (complex reflection coefficient) were measured by a vector network analyzer. They were used for IDT admittance calculation which gave information about resonance frequency, efficiency and electrical bandwidth of the SAW excitation.

2.3. AOM efficiency measurements
TE-TM mode conversion efficiency measurements were performed. DFB LD with polarization maintaining fiber gave at the output linear polarized light corresponded TE mode of the AOM (see figure 1). The light passed through the AOM chip to a fiber optic polarization splitter. The TE polarization from the fiber optic polarization splitter was directed to the photodetector. The conversion (modulation) efficiency was observed as a fall in the intensity at the resonance frequency of acousto-optic interaction during the sweeping of modulated signal from 150 MHz to 250 MHz.

3. Results and discussion
3.1. SAW and pseudo SAW excitation
The frequency dependences of the IDTs (without acoustic waveguide) admittance had a resonance character (see figure 2). However, the form of the resonance curves was rather complicated and could not described in the frameworks of simple theoretical model [12,17]. Behavior of the samples with the aluminum and gold IDTs were significantly different. Moreover, an addition resonance maximum was observed for the samples with the aluminum IDTs. We attributed these two resonance peaks to the SAW (175 MHz) and pseudo SAW (200 MHz) [18] excitation. In the case of the gold IDT the pseudo SAW was slowed down. The pseudo SAW resonance frequency shifted to 170 MHz and the SAW and the pseudo SAW resonances was merged.

![Figure 2. Real part of gold and aluminium IDTs (without acoustic waveguide) admittance as a function of exciting signal frequency. TE mode output power as a function of exciting signal frequency (at optical wavelength 1550 nm and exciting signal power 21 dBm).](image)

Note that significant part of a modulating signal power could be go to the pseudo SAW excitation. For IDTs made of gold, the resonance frequency of a delayed pseudo SAW close to the resonance frequency of the SAW, which leads to their interaction and can add addition noise in the optical signal.

This is one of the main arguments for the choice of aluminum for the IDT fabrication. For aluminum IDTs, pseudo SAW excitation losses can be minimized by increasing the number of fingers, however, the frequency bandwidth of the modulating RF signals will be narrowed.

The frequency dependence of admittance of the IDTs with acoustic waveguide was obtained (see figure 3). Resonant frequency of SAW excitation shifted to 179.5 MHz because of waveguide propagation of acoustic wave.
Respectively, the wavelength of maximum mode conversion efficiency shifted to 1505 nm. However, the configuration with acoustic waveguide demonstrated high mode conversion efficiency at this wavelength. So the IDT configuration was modified. Distance between centers of two adjacent fingers was changed from 10 µm to 10.375 µm. The frequency dependence of admittance of the IDTs with this configuration was obtained (see figure 4).

3.2. TE-TM polarization mode conversion efficiency

Rather high TE-TM polarization mode conversion efficiency (about 95%) was achieved on the AOM chip with the final configuration. The maximum of conversion was at resonance frequency about 173 MHz for the modulating RF signal power about 15 dBm (see figure 4). The width of the resonance on the conversion efficiency frequency dependence was about 80 kHz which corresponded to the 45 mm acousto-optic interaction length. Note, there was no the polarization mode conversion on the pseudo SAW resonance frequency (200 MHz). The 13 mm acousto-optic interaction length required the modulating RF signal power about 18.5 dBm (which even less than previous value for the 45 mm acousto-optic interaction length without acoustic waveguide).

4. Conclusions

Based on the results experimental investigations of excitation and propagation of SAW as well as diffraction and polarization mode conversion efficiency measurements an optimal configuration of the integrated AOMs on X-cut LN substrates was proposed (see figure 1). It comprises straight optical waveguide directed along Y-axis, aluminum IDT with number of fingers \(N = 40\) or higher which tilt on the compensation angle \(\beta = 5^\circ\) for SAW power angular walk-off compensation. An addition SAW concentration could be obtained by producing acoustic waveguide which can be form by titanium thermal diffusion [19] in the one technological process with the optical waveguide. The reduction of the full conversion modulating signal power from 100 mW to 30 mW was experimentally demonstrated (at equal acousto-optic interaction lengths).

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