Film-Loaded SAW Waveguides for Integrated Acousto-Optical Polarization Converters

Oscar A. Peverini, Harald Herrmann, Member, IEEE, and Renato Orta, Senior Member, IEEE

Abstract—We report on a detailed theoretical and experimental investigation of film-loaded surface acoustic wave (SAW) waveguides in lithium niobate (LiNbO₃) for integrated acousto-optical (AO) polarization converters. The numerical analysis is based on both a scalar and a full-vectorial model. Dispersion plots and figures of merit for several structures are given, which lead to design parameters for optimized polarization converters. It is pointed out that very attractive structures are metal/dielectric/LiNbO₃ strip waveguides and dielectric/LiNbO₃ slot waveguides, in which metal is either gold (Au) or aluminum (Al), and the dielectric film is an optical transparent material such as silicon oxide (SiO₂), magnesium oxide (MgO), or aluminium oxide (Al₂O₃). Polarization converters with the designed acoustical waveguides have been realized and characterized by optical conversion and laser probing measurements.

I. INTRODUCTION

DURING recent years, a variety of integrated acousto-optical LiNbO₃-devices has been developed, mostly for applications in wavelength division multiplexing (WDM) optical communication systems [1]–[3] and sensing applications [4]. The central building block of these devices is the acousto-optical (AO) polarization converter. Due to the interaction of a surface acoustic wave (SAW) with optical waves guided in Ti-indiffused stripe waveguides (fabricated in X-cut, Y-propagating LiNbO₃) a wavelength selective polarization conversion (i.e., transverse electric (TE) → transverse magnetic (TM) or TM → TE) is performed. A propagating SAW induces a periodic perturbation of the dielectric tensor, which results in a coupling of orthogonally polarized optical modes. To achieve an efficient polarization conversion, the process must be phase matched (i.e., the difference between the wave numbers of the optical modes must be compensated by the wave number of the SAW):

\[ |n_{\text{eff}}^{\text{TE}} - n_{\text{eff}}^{\text{TM}}| / \lambda_0 = f_{\text{SAW}} / V_{\text{SAW}}, \]

where \( f_{\text{SAW}} \) and \( V_{\text{SAW}} \) are the frequency and the velocity of the SAW, respectively; \( n_{\text{eff}}^{\text{TE}} \) and \( n_{\text{eff}}^{\text{TM}} \) are the effective indices of the TE and TM polarized optical modes.

The phase-matching condition makes the conversion process wavelength selective, so that the optical wavelength \( \lambda_0 \) of the mode to be converted can be adjusted via the radio frequency (RF) applied to the interdigital transducer. For wavelength in the third communication window around \( \lambda_0 = 1.55 \mu m \) the RF for phase matching is about 170 MHz, and the tuning slope is about 8 nm/MHz.

Nowadays, most of the AO devices take advantage of integrated acoustical waveguides to confine the SAWs into localized regions, yielding large acoustical power densities even at moderate overall acoustic power levels. The most common technique to fabricate SAW waveguides (SAWG) is via Ti-indiffusion into the cladding regions of the waveguide, which stiffens the material and, hence, increases the acoustic velocity [5]. The SAW is guided in the undoped region between the Ti-indiffused claddings. Such guiding structures are reliable, easy to fabricate, and compatible with the other processing technologies applied for the fabrication of integrated AO devices in LiNbO₃. The acoustical waveguides typically induce losses of only 0.5 dB/cm or less for the guided SAW. However, the small SAW velocity change of about 0.3% in the Ti-diffused regions relative to the undoped material requires relatively broad acoustical guides (typically, 100 µm and more) [5]. Furthermore, optical waves may leak into the Ti-diffused boundaries of the acoustical guides if the separation between the optical waveguides and the acoustical boundaries are not large enough. Therefore, the objective of this work was to look for alternative means to fabricate acoustic waveguides with a tighter confinement of the SAWs. This promises also a reduced RF-drive power for the converters and a larger integration density.

It is well-known that, in addition to Ti-indiffusion, other techniques can be applied to realize acoustical waveguides [6]. Recently, AO devices with new film-loaded SAWG have been reported [7], [8], in which the SAW velocity is decreased in the core region by the deposition of an optical transparent material such as SiO₂ [7] or In₂O₃-doped SiO₂ [8]. In the case of a pure SiO₂ film, the confinement of the SAW is almost the same as in the Ti-indiffused SAWG, but the confinement can be remarkably increased by adding the In₂O₃ compound. Although this new type of SAWG appears to be very attractive for integrated AO devices, up to now a detailed numerical and experimental investigation has not been published yet. However, a profound understanding of the SAWG is a prerequisite for the optimization of integrated AO devices. Therefore, in this paper we investigate film-loaded strip and slot waveg-
Films-loaded acoustical waveguides (SAWG) are used in integrated AO polarization converters. The numerical analysis of the waveguides is based on both a scalar model [9] and a full-vectorial model [10]. The modes of the Ti-indiffused optical waveguide are computed via the finite-element method (FEM) [11]. The numerical analysis has been applied to metal/dielectric/LiNbO$_3$ stripe waveguides and to dielectric/LiNbO$_3$ slot waveguides, in which the metal overlay is either Au or Al, and the dielectric film is a transparent material such as SiO$_2$, MgO, or Al$_2$O$_3$. Dispersion curves and figures of merit for several structures are reported, from which design parameters for optimized AO polarization converters can be derived.

II. NUMERICAL METHODS FOR THE ANALYSIS OF FILM-LOADED SAWG

For a preliminary analysis of the film-loaded waveguides, a one-dimensional (1-D) model is used, in which only the dominant SAW elongation component is considered [9]. This model provides a simple and computational-efficient method for the investigation and design of film-loaded SAWG. Such a model already has been applied extensively for the design of Ti-diffused acoustical waveguides and directional couplers [12], [13]. But this scalar model does not take into account the anisotropy of materials as well as the influence of the step discontinuities and does not provide the 2-D modal profiles, which are necessary for the evaluation of the AO interaction as reported in Section IV.

For these reasons, the acoustical waveguides also are analyzed via a full-vectorial model based on the multimode transverse resonance technique (MTRT) [10], in which the waveguiding structure is accurately described by a multimode equivalent network. In both models, a modal analysis in the depth direction of the planar regions composing the waveguides is carried out via a pseudo-spectral elements method (PSEM) [9].

A. Modal Analysis of Planar Piezoelectric Waveguides

Both the scalar and the full-vectorial model require the knowledge of a certain number of modes of each planar stratified region composing the 3-D SAWG. Planar stratified media are typically analyzed along the depth direction via the T-matrix model [14], matrix methods [15], and the impedance model [16]. The propagation constants of guided modes then can be found by imposing the transverse resonance condition and solving the resulting transcendental dispersion equation. Though complex-function theory can be invoked, automated search for the roots, however, is a hard task and some of them may be missed. To overcome this drawback, we adopted the PSEM reported in [9], that allows to compute modal fields and propagation constants without solving any transcendental equation. The basic concept is the expansion of the fields on a set of functions [17]. The differential problem turns into an algebraic generalized eigenvalue one, in which the eigenvalues are the propagation constants, the field configuration are readily obtained as linear combinations of the expansion functions, the weights of which are the eigenvector elements. An exponential convergence is ensured if Legendre polynomials are adopted as expansion functions [18].

B. Scalar Model

A SAW in a piezoelectric material such as LiNbO$_3$ is completely described by four components: the elongations along the three geometrical directions and the electrical potential. For $X$-cut, $Y$-propagating SAWs the amplitude of the elongation parallel to the crystalline $X$-direction (geometrical $y$-axis in Fig. 1) is dominant [19]. Therefore, we assume that the SAW can be described reasonably well in a scalar approximation by regarding only this component. Similar to the effective index method for optical strip waveguides [20], a reduction to a 1-D problem can be made using a 1-D velocity profile $V_{SAW}(x)$ in the transverse di-
transmission line has to be associated to each mode. Both the state vector $\Psi_{k,\pm}(y)$ and the propagation constant $\xi_{k,\pm}$ are functions of the angular frequency $\omega$ and of the propagation constant along the $z$-direction $\beta_{AC}$. The $S^{(A)}$ and $S^{(B)}$ are the generalized scattering matrices (GSM) associated to the steps of the film-loaded waveguide at the sections A and B, respectively.

In order to evaluate the GSM of each single step, the equations describing the relevant boundary and continuity conditions are solved by the mode matching technique (MMT). This is a well established technique in the analysis of discontinuity problems in electromagnetic waveguides and was recently applied to SAW problems [23].

Once the relevant blocks of the transverse equivalent network have been evaluated, the modes of the film-loaded waveguide can be computed by searching for the zeros of the transverse resonance condition [10]:

$$\det \left( I - S^{(A)} e^{j\xi^{(1)}_{k,\pm} W} S^{(B)} e^{-j\xi^{(1)}_{k,\pm} W} \right) = 0. \quad (3)$$

In (3) the following matrix notation has been adopted:

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}, \quad (4)$$

and, hence, $S^{(A)}_{22}$ and $S^{(B)}_{11}$ are the left and right reflection blocks of $S^{(A)}$ and $S^{(B)}$, respectively. In applying the transverse resonance condition, it is very convenient to subdivide the modes in region (1) into accessible and localized modes. Only the first class is considered in the resonance condition. In fact, the second class consists of the cut-off modes that are so strongly attenuated they do not interact appreciably with the neighboring step. This implies an efficient code because the matrix, whose determinant has to be evaluated, has a size equal to the number of accessible modes.

### III. Acoustical Waveguides for AO Devices

Two different types of film-loaded acoustical waveguides for integrated AO polarization converters in LiNbO$_3$ have been investigated: stripe and slot-type waveguides (Fig. 1). The first type consists of a layer or a layer system deposited in the core region of the acoustical guide. This means, to achieve guiding the SAW velocity in the film-loaded region must be smaller than the velocity of the unloaded substrate. For AO polarization converters, one has to consider that the film is on top of the optical waveguide as well. Therefore, the film should not strongly influence the properties of the optical waveguide; especially, no significant loss should be induced for the optical waves. In slot-type guides, the cladding regions of the acoustical guide are covered with a film. Therefore, the film-loading must result in an increase of the SAW velocity to obtain guiding.
A. Acoustical Planar Structures

To study the influence of deposited films on top of LiNbO$_3$ substrate, the SAW velocity change has been calculated. In the simulations, we used the material constants reported in [24] for Al, Au, MgO, and SiO$_2$, in [25] for LiNbO$_3$, and in [26] for Al$_2$O$_3$. In Fig. 3 the calculated relative velocity changes $\Delta V$ are shown for a substrate loaded with different materials as a function of the film thickness. The relative velocity changes refer to SAW velocity in X-cut Y-propagating LiNbO$_3$ ($V = 3697$ m/s). The frequency is set to 170 MHz. The lower diagram has been calculated assuming a SiO$_2$ film. The velocity change varies as function of the film thickness. For a thin layer (i.e., $h < 2 \mu m$), the change is negative; but for layer thickness between about 2 $\mu$m and 8 $\mu$m the velocity change is positive. For thicker films, the velocity approaches the SAW velocity of bulk SiO$_2$, which is smaller than the velocity of LiNbO$_3$. The maximum velocity reduction for small layer thickness is about 0.3%, which is comparable to the velocity change of Ti-diffused guides. Therefore, it should be possible to realize stripe waveguides with simple SiO$_2$ films, but it cannot be expected to get a better confinement of the SAW mode as for Ti-diffused guides. Moreover, the strong velocity reduction for thick layers seems to be less appropriate for integrated AO devices as a processing of very thick layers would be necessary.

Other possible materials for deposition on the surface of LiNbO$_3$ are MgO and Al$_2$O$_3$. The corresponding calculated SAW velocity changes as a function of the layer thickness are shown in the upper diagram of Fig. 3. These structures consist of a fast film on top of a slow substrate, so that the range of existence of a nonleaky Rayleigh wave is limited to values beyond the cutoff thresholds. One observes a monotonically increase of SAW velocity in the range of existence. For layer thicknesses of about 0.5 $\mu$m the velocity change is already more than 2%. Therefore, it should be possible to realize slot-type acoustical waveguides with a good confinement of the SAW.

Instead of using a single SiO$_2$ film, a layer system might be used as well. It is well known that a metal layer on top of the substrate slows down the SAW velocity. This is due to the short circuiting of the surface as well as to the mass loading. As depositing a metal layer directly on the substrate would induce strong losses for the optical waves, a dielectric buffer layer is required. Therefore, we studied the SAW velocities of LiNbO$_3$ covered with a layer system consisting of a dielectric layer followed by a metal layer. The thickness of the buffer layer should be large enough to avoid additional optical losses.

In Fig. 4 the SAW velocity change at 170 MHz is plotted as a function of the thickness of the SiO$_2$ layer, which is used as a buffer layer. The metal layer consists of either aluminium or gold. As expected, with such layer systems the SAW velocity is slowed down. The solid line shown in
the diagram refers to an infinitesimal thin ideal conductor on top of the buffer layer. This means, this conductor induces a short circuiting but no mass loading. It becomes clear from the results that the short circuiting leads to a decrease of the SAW velocity of about 0.5% for a buffer layer thickness of 0.5 µm. The additional decrease of the SAW velocity is due to the mass-loading. Therefore, using Al as metal results in a relatively small change of the SAW velocity; but Au (high density metal) induces velocity changes in the order of a few percent already with very thin layers.

From these numerical results Au/SiO$_2$ stripe waveguides appear to be very attractive for AO devices because of a large change of the SAW velocity in the core region of the waveguides. Unfortunately, experimental investigation of the acoustical properties of planar SiO$_2$ films obtained by e-beam evaporation revealed that these structures exhibit acoustical losses in the range of $6 \div 10$ dB/cm, depending on the width of the waveguide. It is known that the acoustical properties of SiO$_2$ are strongly dependent on the fabrication processes. For instance, films with low acoustic losses can be fabricated using RF magnetron sputtering [27] or plasma enhanced chemical vapor deposition (PECVD) [28]. However, these techniques were not available in our laboratory. Therefore, we concentrated on the investigation of strip waveguides with an Al$_2$O$_3$ film as a buffer layer.

As discussed above using Al$_2$O$_3$ as dielectric material, the SAW velocity increases. Nevertheless, with an additional metal on top of the dielectric film, the SAW velocity can be remarkably decreased as the SAW velocity increase due to the dielectric overlay is overcompensated by the mass-loading effect of the metal film. Some numerical results are shown in Fig. 5. The relative SAW velocity change at 170 MHz is plotted versus the dielectric layer thickness for structures with 400-nm thick Al and 200-nm and 100-nm Au. Furthermore, some experimental data also are reported. They have been obtained by investigating the conversion characteristics of integrated AO polarization converters. These were realized using conventional Ti-indiffused acoustical waveguides. The layer system was deposited on top of a part of the converter. We compared the phase-match frequency for the polarization conversion in the uncoated and in the coated regions. From the frequency shift, the difference of the SAW velocities has been calculated using (1). The frequency shift can be almost completely attributed to the SAW velocity change as the film loading has negligible influence on the effective indices of the optical modes. Moreover, the velocity dispersion due to the guiding effect in the Ti-diffused waveguide could be neglected, too, because of the small change of the SAW velocity relative to the substrate. For small dielectric layer thickness, the mass-loading effect of the metal is dominant. With the Al loading, a negative velocity change is obtained for the Al$_2$O$_3$ layer thickness below 0.3 µm. Using the Au film, the effect is much more pronounced. The much higher density of Au results in strong mass loading, and, hence, in a tremendous reduction of the SAW velocity. Even for the Al$_2$O$_3$ layer thickness of 0.5 µm, the SAW velocity change is still larger than 3% as also experimentally observed. Moreover, we observed acoustical losses in the range of $2 \div 3$ dB/cm that makes Au/Al$_2$O$_3$ stripe waveguides feasible for integrated polarization converters, even if the fabrication parameters could be further optimized in order to achieve losses comparable with those exhibited by Ti-diffused waveguides.

B. Film-Loaded SAW Waveguides for Acousto-Optical Polarization Converters

In Fig. 6 the calculated normalized velocity of the fundamental and of the first three higher order modes of a Au/Al$_2$O$_3$ stripe-type waveguide is shown as function of the waveguide width (i.e., the width of the stripe). The Au and Al$_2$O$_3$ films are 200-nm and 600-nm thick, respectively; and the SAW frequency has been taken to be 170 MHz. Both the results obtained via the scalar model and via the full-wave model are shown. In Fig. 6, $V_{so}$ and $V_{cl}$ represent the SAW velocity in the core and in the cladding regions of the stripe waveguide, respectively. Because of the anisotropy of the LiNbO$_3$ crystal, the values of these velocities differ slightly in the scalar and in the full-wave models. From these results, one can infer that below about 40-µm width, the acoustical waveguide is single mode; but at larger widths, higher order modes are guided, too. For a 35-µm wide waveguide, the elastic displacements and the electrical potential at a frequency of 170 MHz are displayed in Fig. 7. The fields are normalized so that the SAW power is 10 mW. As in the $X$–$Y$ LiNbO$_3$ substrate, the SAW still is polarized mainly in the sagital plane (geometrical $yz$ plane), with $u_y$ being the main component. Moreover, due to the strong mass loading induced by the Au film, the lateral confinement of the mode is very pronounced.

On the basis of the numerical results, polarization converters with Au/Al$_2$O$_3$ stripe waveguides have been real-
Fig. 6. Calculated normalized modal velocities of the fundamental mode \((m = 0)\) and of higher order modes \((m > 0)\) in a film-loaded stripe waveguide as a function of the stripe width \(W\) at \(f_{\text{SAW}} = 170\) MHz. The data have been calculated assuming a layer system consisting of an \(\text{Al}_2\text{O}_3\) buffer layer (thickness 600 nm) and an Au-layer of 200-nm thickness. The computations have been performed via both the scalar model and the full-wave model.

Fig. 7. Calculated fundamental mode of a film-loaded stripe-type acoustical waveguide realized with an Au/\(\text{Al}_2\text{O}_3\) layer system. The width of the waveguide is 35 \(\mu\)m, the Au-film is 200-nm thick, and the \(\text{Al}_2\text{O}_3\)-layer thickness is 600 nm. For the calculation, a SAW frequency of 170 MHz has been assumed, and the amplitudes have been scaled to guide an acoustical power of 10 mW.

In Fig. 8 the measured conversion characteristics obtained in polarization converters with a 60-\(\mu\)m and 120-\(\mu\)m wide Au/\(\text{Al}_2\text{O}_3\) acoustical stripe, respectively, are shown. The width of the waveguide is 35 \(\mu\)m, the Au-film is 200-nm thick, and the \(\text{Al}_2\text{O}_3\)-layer thickness is 600 nm. For the calculation, a SAW frequency of 170 MHz has been assumed, and the amplitudes have been scaled to guide an acoustical power of 10 mW.

In the previous section, it was pointed out both theoretically and experimentally that an \(\text{Al}_2\text{O}_3\) film deposited on top of \(\text{LiNbO}_3\) increases the SAW velocity. This effect can be exploited in the fabrication of slot-type acoustical waveguides by covering the cladding regions of the \(\text{LiNbO}_3\) substrate with an \(\text{Al}_2\text{O}_3\) layer. The main advan-
tage of these structures in comparison with stripe-type waveguides is that smaller losses have to be expected. In fact, in both configurations the loss mechanism is due to the propagation of the acoustical wave in the overlay. However, in stripe-type structures, the overlay is deposited in the region in which the SAW exhibits its maximum values; and in slot-type waveguides, the losses of the layer affect only the evanescent fields of the SAW. The experimental investigation, slot-type waveguides with an 800-nm thick Al$_2$O$_3$ layer and width $W = 40 \div 100$ $\mu$m were fabricated (Fig. 10). As expected, all the structures exhibit losses smaller than 1 dB/cm, as can be observed in Fig. 11, in which the result of a laser probing measurement on a 100- $\mu$m wide, slot-waveguide is reported. The measured propagation losses in this structure are $\approx 0.5$ dB/cm. In Fig. 12 the converted power in the corresponding polarization converter is shown. The converted power is normalized to its maximum at 174.3 MHz, in which a rejection of already $\approx -12$ dB to the incident polarization is achieved. The length of the interaction region was set to $\approx 45$ mm in order to provide a better homogeneity within the structure and the RF driving power was about 3 dBm. In this case, only a pronounced conversion peak at $\approx 174.3$ MHz can be observed; but we could not observe in the conversion characteristics more conversion peaks corresponding to the interaction of the optical modes with higher-order acoustical modes. In fact, in 800-nm thick Al$_2$O$_3$-loaded regions, a relative change of the SAW velocity of $\approx -0.7\%$ was measured. Although a higher velocity change was predicted on the basis of the available physical data for Al$_2$O$_3$, the SAW velocity can be further decreased by depositing thicker Al$_2$O$_3$ films, depending on the technological capa-
In Fig. 13 we plotted the computed coupling coefficient as a function of the waveguide width \( W \) for both metal/AI\(_2\)O\(_3\) film-loaded stripe waveguides and AI\(_2\)O\(_3\) film-loaded, slot waveguides. For the stripe-type structure, the buffer layer thickness is 600 nm in order to provide enough insulation of the optical waveguide from the 200-nm thick Al\(_2\)O\(_3\)-layer; and for the slot configuration, the thickness of the Al\(_2\)O\(_3\) layer is 800 nm. The optical waveguides are 7-\( \mu \)m wide, Ti-indiffused waveguides, and the optical wavelength is 1550 nm. One can observe that the stripe-type structure leads to higher coupling coefficients in comparison with the slot waveguide. Indeed, in the stripe configuration the SAW profile in the depth direction is modified in the core region, leading to a better overlap between the acoustical mode and the optical modes. For both structures the maximum coupling coefficients are obtained for waveguide widths at about 40 \( \mu \)m as better overlaps in the lateral direction are achieved. In particular, for the Au/AI\(_2\)O\(_3\) structure with 200-nm Au, a coupling coefficient of about 352 m\(^{-1}\) can be achieved with a stripe width of 35 \( \mu \)m. This value of the coupling coefficient is about twice that of a 120-\( \mu \)m wide, Ti-diffused waveguide [30], so that the RF driving power necessary for the conversion is reduced by a factor of four.

In order to compare the efficiency of AO polarization converters with different straight acoustical waveguides, in Table I the driving power and the interaction length are reported for the structures with Ti-indiffused SAWG [31], [32] and with the presented Al\(_2\)O\(_3\)-slot SAWG. The comparison is not applicable for the Au/AI\(_2\)O\(_3\)-stripe waveguides as several acoustical modes are excited in the structure with unknown amplitude ratio. As is well-known, the AO conversion efficiency at perfect phase-matching conditions is given by:

\[
\eta = \sin^2 \left( \frac{\gamma \sqrt{P_{RF}} L}{\lambda} \right),
\]

where the electric field associated to the SAW, \( \{p_{ijkl}\} \) and \( \{r_{kij}\} \) are the elasto-optical and electro-optical coefficients tensors, respectively.

In the computation of the coupling coefficient in X-cut Y-propagating LiNbO\(_3\) devices, the following approximation proves to be very accurate [30]:

\[
k \approx k_{yx} = \frac{\omega}{8P_0} \int \int (E_y^{TM})^* \Delta \epsilon_{yx} E_x^{TE} \mathrm{d}x \mathrm{d}y.
\]

In order to achieve a high interaction efficiency (i.e., a high coupling coefficient), the overlap integral between the profiles of the optical modes and of the SAW should be maximized. This requires the knowledge of the 2-D profiles of both the optical modes in the Ti-indiffused waveguide and of the modes of the film-loaded acoustical waveguide. The optical modes have been computed via the finite-elements method described in [11]; and the film-loaded acoustical waveguides have been analyzed via the MTRT. In Fig. 13 we plotted the computed coupling coefficient as a function of the waveguide width \( W \) for both metal/AI\(_2\)O\(_3\) film-loaded stripe waveguides and AI\(_2\)O\(_3\) film-loaded, slot waveguides. The optical waveguides are 7-\( \mu \)m wide Ti-indiffused waveguides, and the optical wavelength is 1550 nm. For the calculation, a SAW frequency of 170 MHz has been assumed and the acoustical amplitudes have been scaled to guide an acoustical power of 10 mW.
TABLE I

<table>
<thead>
<tr>
<th>AO polarization converter</th>
<th>RF driving power</th>
<th>Interaction length</th>
<th>Normalized power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-indiffused SAWG [31]</td>
<td>35</td>
<td>11</td>
<td>4235</td>
</tr>
<tr>
<td>Ti-indiffused SAWG [32]</td>
<td>8</td>
<td>30</td>
<td>7200</td>
</tr>
<tr>
<td>Al2O3-slot SAWG</td>
<td>2</td>
<td>45</td>
<td>4050</td>
</tr>
</tbody>
</table>

with \( P_{RF} \) being the driving power, \( L \) is the interaction length, and \( \gamma \) is a constant depending on the structure and materials of the AO polarization converter. The complete conversion is achieved when the argument in (9) is equal to \( \pi/2 \) corresponding to a RF power \( P_{RF} = P_{100\%} \). In order to compare the values of driving power and of interaction length reported in Table I, it is convenient to define a normalized power factor \( \rho \) in [mW mm²] according to:

\[
P_{100\%} = \frac{\rho}{L^2}.
\]

The smaller the value of the normalized power \( \rho \) is, the more efficient is the AO process. The strong difference of \( \rho \) for AO polarization converters with Ti-indiffused SAWG calculated from the data present in [31] and [32] is probably due to different coupling conditions of the SAW into the waveguide. An optimization of the finger overlap of the transducer and of its tilt angle allows a more efficient coupling.

From the data reported in Table I, it can be inferred that the presented Al2O3-slot SAWGs are comparable in performance with the Ti-indiffused waveguides. However, an optimization of the fabrication process is still possible, which should lead to higher performance AO polarization converters.

V. Conclusions

In this paper we performed numerical and experimental investigations of film-loaded acoustical waveguides for AO polarization converters. The numerical analysis is based on both a scalar model and a full-wave model. From the numerical results, polarization converters with Au/Al2O3 and Au/SiO2 stripe waveguides appear to be very promising structures for integrated AO LiNbO3-devices, as high coupling coefficients and strong acoustical field confinement could be achieved.

Experimental investigation about polarization converters fabricated with Au/Al2O3 stripe waveguides confirmed the numerical predictions. However, the fabrication process has to be optimized because these structures exhibit acoustical losses in the range 2-3 dB/cm, and optical conversion characteristics are still far away from the predicted ones.

Polarization converters with slot waveguides loaded with a 800-nm thick Al2O3 layer have been realized as well. Acoustical losses smaller than 1 dB/cm were measured, and a clear guiding effect was obtained also in a 40-µm wide structure. Optical conversion characteristics are already quite close to the ideal case. Hence, Al2O3-based, slot-acoustical waveguides should enable one to increase the integration density of complex AO devices. In fact, the leakage of optical waves in the claddings, as in Ti-diffused waveguides, could be overcome due to the optical transparency of Al2O3. Moreover, an optimization of the fabrication process could yield higher SAW velocity changes. This means that even a stronger field confinement is feasible leading to lower drive RF power requirements.

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REFERENCES


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