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Acousto-optic modulators driven by longitudinal leaky surface acoustic waves on LiNbO₃ thin-plate bonded structures

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To obtain an acousto-optic modulator (AOM) driven by a longitudinal leaky surface acoustic wave (LLSAW) with a low driving voltage and a high diffraction efficiency, proton-exchanged planar optical waveguide-type AOMs with structures consisting of an X-cut 36°Y-propagating LiNbO₃ (LN) thin-plate bonded to a AT-cut 45°X-propagating quartz or c-plane sapphire (Al₂O₃) substrate were fabricated and their diffraction properties were evaluated. The maximum diffraction efficiency in the zeroth transverse electric (TE₀) mode optical guided wave with an optical wavelength of 0.633 μm and the driving voltage required by the LLSAWs of the AOMs were 91% and 5.1 V_RMS for LN/quartz and 60% and 11 V_RMS for LN/Al₂O₃, respectively. The diffraction properties of the LLSAWs on the bonded structures were improved compared with those on a single LN substrate.

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1. Introduction

A light wave that is guided to the propagation region of a surface acoustic wave (SAW) is Bragg-diffracted by the acousto-optic (AO) effect and undergoes an optical frequency shift caused by the SAW frequency. AO modulators (AOMs) with a low driving power and high diffraction efficiency driven by SAWs with channel optical waveguides have been developed and applied to a frequency shift feedback (FSF) fiber laser as AO frequency shifters. Since the laser output of a FSF fiber laser consists of a chirp frequency comb, these lasers have been expected to be widely applied in optical measurements such as optical distance measurement.

To improve the accuracy and reduce the power consumption of such optical measuring devices, it is necessary to increase the frequency shift, lower the driving voltage and increase the diffraction efficiency of the AO. To increase the frequency shift, the authors previously fabricated an AOM using a longitudinal leaky SAW (LLSAW) that has 1.5–2-fold higher phase velocity than Rayleigh-type SAWs (R-SAWs) and evaluated its diffraction properties. A conventional AOM driven by a LLSAW was fabricated on an X-cut 36°Y-propagating LiNbO₃ (X36°Y-LN) substrate with a thickness of less than one wavelength of the SAW bonded to a AT-cut quartz or c-plane sapphire (Al₂O₃) substrate and experimentally found that high-coupling LLSAWs can be obtained by using a structure consisting of an X36°Y-LN thin plate with a thickness of less than one wavelength of the SAW bonded to a high-velocity substrate such as quartz or sapphire (Al₂O₃). In this paper, to lower the driving voltage and to increase the diffraction efficiency of an AOM using a LLSAW, structures consisting a thin LN plate bonded to a quartz or Al₂O₃ substrate were used in the AOMs. First, the optimum structures for the AOMs were determined by theoretically analyzing the propagation properties of LLSAWs when these bonded structures were used in the AOMs. Then, AOMs were fabricated on the bonded structures and their diffraction properties were evaluated.

2. Design of the AOMs

2.1. Configuration of AOMs on bonded structures

Figure 1 shows the configuration of planar waveguide-type AOMs on bonded structures fabricated in this study. Samples of bonded structures in which an X36°Y-LN thin plate with a thickness of 2.0 or 3.0 μm was bonded to an AT-cut quartz (AT-quartz) or c-plane Al₂O₃ (c-Al₂O₃) substrate were prepared. The propagation direction of the AT-cut quartz was set to 45°X for the LLSAW because a larger K² was obtained for this direction in the theoretical calculation.

In our previous study, the Ti diffusion method was used in the fabrication of the AOM optical waveguide. The Ti diffusion method requires heat treatment at a high temperature close to 1000 °C, but the bonded interface of the samples could not withstand such a high temperature and peeled off in a preliminary experiment. To avoid peeling at the bonded interface, a proton exchange (PE) method was used, which allowed a lower-temperature process than the conventional Ti diffusion method. In the region where the Ti diffusion layer or the PE layer was fabricated, the piezoelectricity was decreased from that of the bulk LN owing to polarization inversion or lattice distortion. To avoid the reduction of K² compared with that for LLSAWs during SAW excitation, the PE optical waveguide was fabricated only in the SAW propagation region, except for the SAW excitation region directly under the interdigital transducers (IDTs) as shown in Fig. 1.

2.2. Theoretical calculation

To determine the depth d of a PE optical waveguide, the effect of a PE layer on bonded structures on the propagation properties of LLSAWs and the optical mode dispersion of an optical guided wave (OGW) were calculated. The analysis of LLSAWs with propagation attenuation was based on the method of Ref. 20, and the analysis of the layer structure was extended to four-layer air/PE/LN/LN/Al₂O₃ or air/PE/LN/LN/quartz structures using the Farnell and Adler method. The material constants of LN and quartz reported in Refs. 22 and 23 and Al₂O₃ reported in Ref. 24 were used. It is known...
that the elastic constants and piezoelectric constants after PE
are approximately 60% and 20%, respectively, of those of the
bulk LN. In addition, the density and dielectric constants
after PE reported in Ref. 27 were also used. Figure 2 shows
the calculated phase velocity [Fig. 2(a)] and propagation
attenuation [Fig. 2(b)], and $K^2$ for LLSAWs [Fig. 2(c)] and
the optical mode dispersion for a transverse electric (TE)
mode as a function of the PE depth $d$ for a PE:LN/X36°Y-LN
($h = 3.0 \mu m$)/c-Al$_2$O$_3$ structure and a PE:LN/X36°Y-LN
($h = 2.0 \mu m$)/AT45°X-quartz structure [Fig. 2(d)]. The
SAW wavelength $\Lambda$ and optical wavelength $\lambda$ used in the
theoretical analysis were 20 and 0.633 $\mu m$, respectively.

The phase velocities of the LLSAWs on LN/Al$_2$O$_3$ and
LN/quartz were 7800 and 8400, and 6600 and 7000 m s$^{-1}$,
for the free and short surfaces, respectively. The LN/Al$_2$O$_3$
structure was more advantageous than the LN/quartz struc-
ture in terms of the larger optical frequency shift of an AOM
because the phase velocities of LLSAWs on c-Al$_2$O$_3$ and
AT45°X-quartz are 11 200 and 7030 m s$^{-1}$, respectively. Since the phase velocities of both structures decreased as $d$
increased, it is suggested that LLSAWs might become more
conzentrated at the surface by reducing the phase velocity
near the surface. Using the calculated phase velocity, $K^2$ was
determined from the relationship $K^2 = 2(v_f - v_s)/v_f$, where $v_f$
and $v_s$ are the phase velocities on the free and short surfaces,
respectively. $K^2$ for the LLSAWs on PE:LN/LN/Al$_2$O$_3$ or PE:
LN/LN/quartz was decreased with increasing $d$, because the
piezoelectricity of the bulk LN decreased after PE.

The propagation attenuation of LLSAWs on PE:LN/ LN/Al$_2$O$_3$ and PE:LN/LN/quartz had minimum values at $d$
of 1.0 and 0.40 $\mu m$, respectively, above which they mono-
tonically increased with increasing $d$. At the minimum
values, it is considered that the best phase matching between
the different layers was obtained for each structure, and the
PE depth $d$ for which this condition was realized varied
depended on the LN plate thickness $h$ and the material of the
support substrate. For the free surface of PE:LN/LN/quartz,
the propagation attenuation increased in the range of $d$ from 0
to 0.3 $\mu m$ because the phase velocity of the LLSAW was
close to the velocity of the longitudinal bulk wave on quartz,
and the LLSAW degenerated to a longitudinal bulk wave. In
addition, since the minimum propagation attenuation for PE:LN/LN/quartz and PE:LN/LN/Al$_2$O$_3$ was 0.005 and
0.243 dB $\Lambda^{-1}$, respectively, the PE:LN/LN/quartz structure
was found to be advantageous for an AOM with lower
driving power. An OGW with single-mode propagation for a
TE mode was obtained in the range of $d$ from 0.48 to
1.55 $\mu m$. From the above-calculated results, $d$ was set to
1.2 $\mu m$ for LN/Al$_2$O$_3$. On the other hand, for LN/quartz, $d$
was set to 0.65 $\mu m$ because the OGW was not guided at $d$
of 0.40 $\mu m$.

2.3. Finite element method analysis of LLSAWs
As shown in Fig. 3, using a finite element method (FEM)
system (Femtet version 2017, developed by Murata
Software), the particle displacements of LLSAWs on
LN/Al$_2$O$_3$ and LN/quartz were calculated.

Fig. 1. (Color online) Configuration of the proton-exchanged planar
optical waveguide-type AOMs with LN thin-plate bonded structures.19)
concentrated at the surface than for the case without the PE layer owing to the lower phase velocity of the PE layer than that of the bulk LN. In addition, the propagation of a longitudinal surface-skimming bulk wave (SSBW) was markedly suppressed because the phase velocity in the SAW propagation region with a PE layer was lower than that without one. Figure 4 shows the dependence on propagation distance of normalized particle displacement (dB) on the surface simulated by FEM analysis. To approximate the analysis to the structure of the SAW propagation path in the actual measurement, a PE layer was provided in the range of the propagation distance \( D = 0 – 250 \Lambda \) (0–5 mm) with respect to the structure with a PE layer, and \( D = 250 – 300 \Lambda \) (5–6 mm) without a PE layer. Moreover, the IDT parameters were the same as those in Fig. 3. The attenuation of particle displacement at \( D = 300 \Lambda \) was improved by approximately 1 dB after fabrication of a PE layer. The main propagation mode in the range of the fabricated PE layer was LLSAW, and the particle displacement decreased exponentially. On the other hand, in the absence of a PE layer, the main propagation mode was a longitudinal SSBW, and the particle displacement immediately declined at a short propagation distance. In the range of \( D = 250 – 300 \Lambda \) for the structure with a PE layer, the LLSAW was also degenerated to a longitudinal SSBW, and the particle displacement was also immediately reduced at a short propagation distance. Therefore, when a PE layer is fabricated on all SAW propagation paths, propagation loss is expected to be further reduced.

3. Evaluation of diffraction properties

3.1. Fabrication of AOMs

The process of fabricating the AOMs was as follows. First, as a 5-mm-wide optical waveguide mask, a 2500-Å-thick SiO\(_2\) thin film was deposited on LN/quartz or LN/Al\(_2\)O\(_3\) samples. Then, the samples were immersed in benzoic acid diluted with 3.0 Li mol\% lithium benzoate for LN/quartz or 1.0 Li mol\% lithium benzoate for LN/Al\(_2\)O\(_3\) at 240 °C to fabricate a PE optical waveguide with a depth \( d \) of 0.65 or 1.2 \( \mu \)m. Then, IDTs with a period \( \Lambda \) of 20 \( \mu \)m, an overlap length of 3 mm and a propagation length of 300 \( \Lambda \) (6 mm) were fabricated on a SiO\(_2\) mask using a 2500-Å-thick Al thin film.

Figure 5 shows the measured frequency responses between the input and output IDTs for the LLSAWs on the AOM samples and the LN/quartz sample without a PE process. The minimum insertion loss (MIL) for the LLSAW on LN/quartz was smaller than that on LN/Al\(_2\)O\(_3\) because the propagation attenuation of the LLSAW on LN/quartz was lower than that on LN/Al\(_2\)O\(_3\). In addition, the MIL for LN/quartz was decreased from 17.6 dB without the PE process to 15.6 dB with a depth \( d \) of 0.65 \( \mu \)m owing to the suppressed propagation of the longitudinal SSBW at 350 MHz. The simulation and experimental results showed rough quantitative agreement. On the other hand, since the frequency at the MIL for LN/Al\(_2\)O\(_3\) was approximately 20% higher than that for LN/quartz, the LN/Al\(_2\)O\(_3\) structure was more advantageous than the LN/quartz structure for an AOM with a larger optical frequency shift.

Fig. 3. (Color online) Simulated particle displacements of LLSAWs on LN/quartz (\( h = 2.0 \mu \)m): (a) without a PE layer, (b) \( d = 0.65 \mu \)m in the SAW propagation regions. \( \Lambda = 20 \mu \)m, free surface.

Fig. 4. (Color online) Simulated normalized particle displacements on the surface of LLSAWs on LN/quartz (\( h = 2.0 \mu \)m). \( \Lambda = 20 \mu \)m, free surface, \( D = 300 \Lambda \).

Fig. 5. (Color online) Measured frequency responses between the input and output IDTs for the AOM samples and an LN/quartz sample without a PE process.
3.2. Diffraction efficiency

To excite a TE-mode light beam, a He–Ne laser ($\lambda = 0.633 \mu m$) was guided into a PE optical waveguide using rutile prism couplers. A RF burst signal was applied to the input IDT, and LLSAWs or R-SAWs on LN/quartz or LN/Al$_2$O$_3$ were excited by adjusting the frequency $f_m$ of the input RF signal, as shown in Table I. The intensity of the undiffracted light was measured using a photomultiplier and the diffraction efficiency $\eta$ was determined from the decrease in the intensity.

Figure 6 shows the measured diffraction efficiency of AOMs driven by LLSAWs [Fig. 6(a)] and R-SAWs [Fig. 6(b)] as a function of the RF input voltage. The measured results were fitted using the $\sin^2$-curve solution of coupled-mode equations, as shown in Figs. 6(a) and 6(b). The maximum diffraction efficiency $\eta_{\text{max}}$ in the TE$_0$ mode using LLSAWs was increased from 50% for a single LN to 60% and 91% for LN/Al$_2$O$_3$ and LN/quartz, respectively. In particular, $\eta_{\text{max}}$ using the LLSAW on LN/quartz was markedly improved compared with that on a single LN substrate and increased to the same value as that for R-SAWs. On the other hand, $\eta_{\text{max}}$ for LN/Al$_2$O$_3$ was lower than that for LN/quartz. As shown in Fig. 7, using the FEM system the particle displacements of LLSAWs on a single LN [Fig. 7(a)], on LN/Al$_2$O$_3$ [Fig. 7(b)], on LN/quartz [Fig. 7(c)] and R-SAW [Fig. 7(d)] on a single LN with an Al thin film IDT with 14 finger pairs and Al thickness of 0.25 $\mu m$, were simulated. As shown in Fig. 7(a), it was observed that large radiation bulk waves were excited directly under the IDT for the LLSAW on a single LN, which were reflected from the back of the substrate and interfered with the LLSAW in the interaction region. For the LLSAW on LN/Al$_2$O$_3$, bulk waves were still radiated into the support substrate, as shown in Fig. 7(b). It was considered that, since the incoherent refractive index changes occurred due to the interference between the LLSAW and bulk waves, a diffracted beam was scattered in an AO interaction region and then $\eta_{\text{max}}$ deteriorated. On the other hand, for the LLSAW on LN/quartz, a similar phenomenon of the particle displacement to that for R-SAW on a single LN was obtained, as shown in Figs. 7(c) and 7(d). The driving voltage $V_{100}$ with maximum diffraction efficiency was reduced from 21 $V_{\text{rms}}$ to 11 and 5.1 $V_{\text{rms}}$ for LN/Al$_2$O$_3$ and LN/quartz, respectively. Moreover, the driving frequency of the AOM with LN/Al$_2$O$_3$ was approximately 10% higher than that for the AOM with a single LN substrate because the LN thin plate was bonded to the high-velocity substrate. On the other hand, experimental results for diffraction efficiency deviated from the fitting curve at high RF input voltage. In general, as the SAW power increases, harmonics are generated by a nonlinear effect, and the power is shifted from the fundamental wave to the harmonics. It was considered that the refractive index changed nonlinearly with increase in the input voltage, it decreased from the original refractive index change due to the fundamental wave at high input voltage and deviated from the fitting curve. Furthermore, for each structure or propagation mode of the SAW (since the energy density of a SAW is due to differing particle displacement), the SAW power at which the nonlinear effect appeared was different. As a result, it is considered that the deviation of the input voltage deviating from the fitting curve changed with respect to each structure or propagation mode of the SAW. From the above results, it was found that the diffraction properties of the LLSAWs on the bonded structures were improved compared with those on a single LN substrate.

4. Conclusions

In this paper, to obtain an AOM using a LLSAW with a low driving voltage and a high diffraction efficiency, AOMs with LN/Al$_2$O$_3$ or LN/quartz structures were fabricated, and their diffraction properties were evaluated.

The maximum diffraction efficiency in the TE$_0$ mode and the driving voltage required by the LLSAWs were 91% and 5.1 $V_{\text{rms}}$ for LN/quartz and 60% and 11 $V_{\text{rms}}$ for LN/Al$_2$O$_3$, respectively. In addition, the driving frequency of the AOM with LN/Al$_2$O$_3$ was approximately 10% higher than that for the AOM with a single LN substrate. Therefore, the

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<th>Table I. Driving frequency and measured diffraction properties of AOMs.</th>
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<td>$f_m$(MHz)</td>
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<td>Single LN$^{14)}$</td>
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<tr>
<td>LN/Al$_2$O$_3$</td>
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Fig. 6. (Color online) Measured diffraction efficiency of AOMs with LN/Al$_2$O$_3$ or LN/quartz using (a) LLSAWs and (b) R-SAWs. $\lambda = 20 \mu m$, $\lambda = 0.633 \mu m$.
The diffraction properties of the LLSAWs on the bonded structures were improved compared with those on a single LN substrate. Moreover, it was theoretically and experimentally revealed that the attenuation of LLSAWs on bonded structures decreased owing to the PE process.

In our next study, we will design and fabricate an optical channel waveguide-type AOM using a LLSAW on a bonded structure and optimize the cut angle and propagation direction of LN for use in an optical channel waveguide.

Acknowledgments

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Fig. 7. (Color online) Simulated particle displacements of LLSAWs (a) on a single LN, (b) on LN/Al₂O₃ with h of 3.0 μm, (c) on LN/quartz with h of 2.0 μm, and R-SAW (d) on a single LN. Λ = 20 μm.