COMMUNICATIONS

Comments on fabrication parameters for reducing thermal drift on $LiNbO_3$ optical modulators

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1 Introduction

In this paper, some comments are made about fabrication parameters to reduce undesirable thermal drift in the optical output of *z* cut Ti:$LiNbO_3$ (LN) modulators. In this regard, covering the LN surface with a semiconducting Si layer was reported to effectively shield the waveguides from pyroelectrically induced charges and to successfully suppress the drift.[1] However, thermal drift appears even for Sicoated modulators. As a reason for this drift, the following possibilities are proposed: effect of a pyroelectrically induced field applied along the *z* axis,[2] slow relaxation of pyrocharges through the LN bulk,[3,4] and thermal stress (strain) along the waveguide caused by coating layers.[5] Unfortunately, there was little to report proving these possibilities. In this communication, numerous experimental results are presented suggesting the influences of coating layers and waveguide asymmetry on the thermal bias drift of LN optical intensity modulators. Further, the results provide useful information for achieving fabrication of the reduced-drift modulators, indicating that the higher internal stress of the electrode layer, at least, increased the drift magnitude. Stress in other coating layers did not affect the thermal drift.

2 Influence of Coating Layers

Because the refractive index of the LN changes with the application of strain via the piezo-optic effect, the optical output drifts due to thermal fluctuation in strain. The strain inhomogeneously applied to the LN device chip deforms the Mach-Zehnder interferometer, also causing the drift phenomenon. Such an undesirable strain was introduced into the LN waveguide during the device fabrication processes for formation of Ti-indiffused waveguides, SiO_2 buffer layer, Si layer, and coplanar electrodes. After each process, the *z* cut LN wafer (0.5 mm thickness and 3 in. diameter) was observed to warp into a convex shape.

Figure 1 shows the relationship between the magnitude of thermal drift and the change in LN wafer defiection due to Ti thermal diffusion [Fig. 1 (a)], SiO_2 buffer layer formation [Fig. 1 (b)], Si layer deposition [Fig. 1 (c)], and the Au electrode plating processes [Fig. 1 (d)]. The wafer deflection was measured after each process. After all processes, the wafer was cut and the devices were fabricated for drift measurements. The magnitude of the drift is plotted for the maximum value measured when heating the device from 20 to 70∞C, and is not normalized by the halfwave voltage ($V\pi$). The data are for 64 devices fabricated from 32 different wafers; the device chips were cut from almost the center of the wafer. The wafer deflection means the maximum height difference within a 50-mm distance along the waveguides (*x* axis), which is a positive value for the convex wafer. An *A* + 10 μm defiection change, for instance, can be calculated to be 8×10^{-6} (8×10^{-4}%) of an additional tensile strain along the waveguide. The total wafer defiection after the processes were completed is derived by the sum of all the individual defiections. As is seen in Figs. 1 (a), 1 (b), and 1 (c), no correlation is observed between the magnitude of thermal drift and the wafer deflection in the processes for the Ti waveguide, SiO_2 buffer layer, and Si layer. This result is not surprising because the strain due to these processes distributes broadly throughout the wafer and influences each Mach-Zehnder waveguide arm in the LN chip almost equally. As described later, however, such strains have the possibility of causing an undesirable distribution of the zero-biased optical output modulation phase (initial operating point) on the wafer.

Figure 1(d) shows the correlation between the thermal drift and the wafer deflection due to the coplanar electrode formation, indicating a tendency for greater drift in wafers with greater warping. Although the magnitude of the wafer deflection due to the electrode formation process is comparable to the other processes, the strain might asymmetrically affect the Mach-Zehnder arms, because along one of the arms, the narrow hot electrode is formed while the large ground electrode covers the other waveguide arm and almost the rest of the remaining chip surface. Therefore, when the applied strain is fluctuated by a temperature change, the refractive index and the waveguide length are modified in each waveguide arm differently, leading to the thermal drift.

To confirm such an effect in the electrode layer, 52 pieces of dual-hot type LN modulators were fabricated from 24 different LN wafers and their thermal drift was similarly evaluated. These modulators had a pair of hot electrodes, which were fabricated above each Mach-Zehnder waveguide arm, resulting in a symmetric arrangement between the electrodes

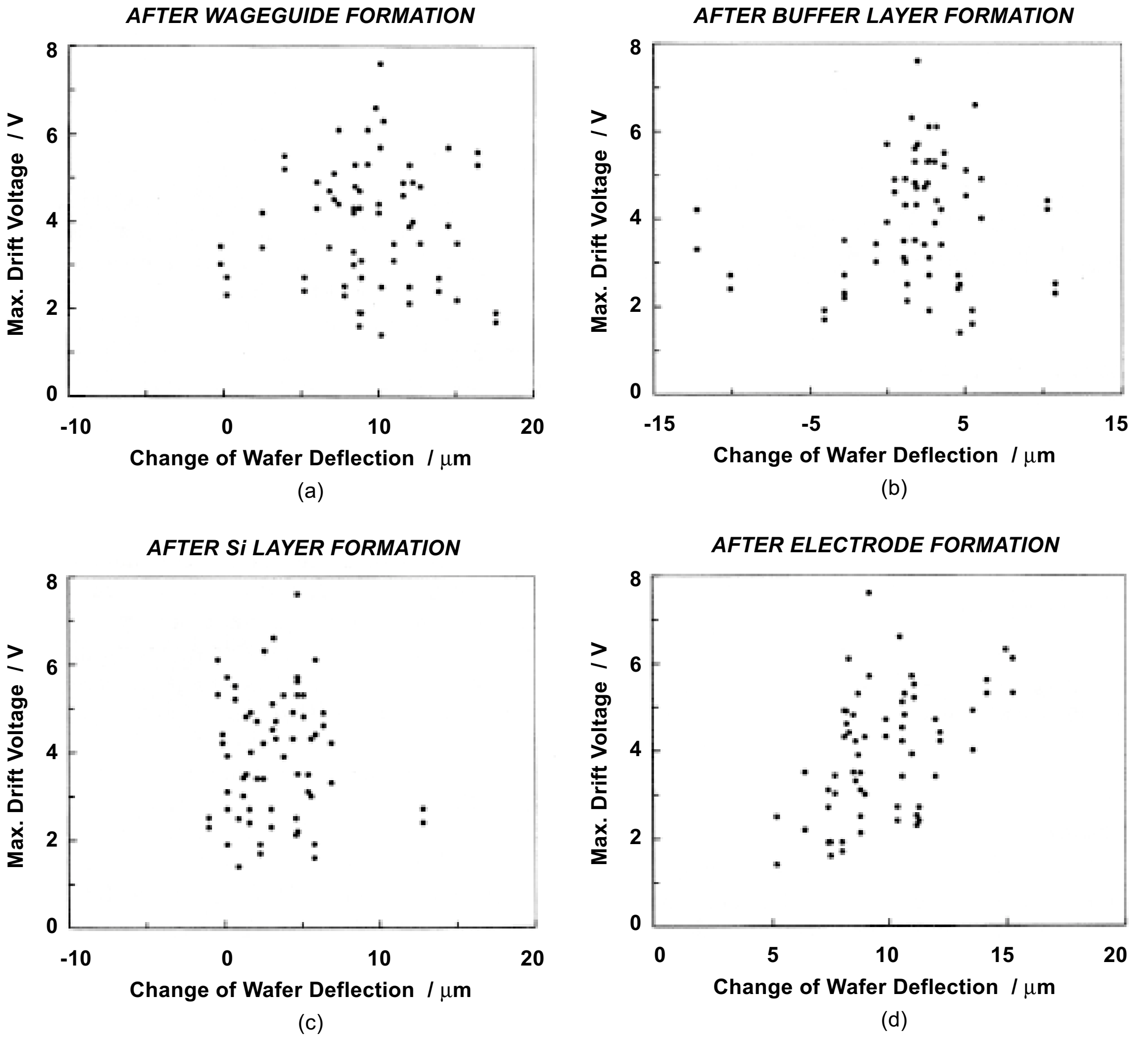


Fig. 1 Relationship between maximum drift voltage from 20 to 70∞C and a change of wafer deflection after the fabrication processes of (a) Ti-indiffused waveguide formation, (b) SiO_2 buffer layer formation, (c) Si layer formation, and (d) Au-plated electrode formation. The strain occurring along the waveguide is proportional to the wafer deflection and 8 x $l0^{-6}$ for the 10-µm deflection in the figure.

and the waveguide arms.[6] As shown in Fig. 2, there was no observed correlation between the magnitude of drift and the wafer deflection due to the electrode formation, supporting the fact that the asymmetric electrode configuration in the modulators of Fig. 1(d) leads to the larger thermal drift.

These results provide useful information for increasing the fabrication yield of *z* cut Mach-Zehnder LN modulators. Reducing the internal stress in the Au-plated electrodes and designing a symmetric electrode configuration are very effective for suppressing the magnitude of the thermal drift. A possible origin for the remaining drift seen in Figs. 1 (d) and 2 (about 2 V for devices having $V\pi$ =3.5 to 4.0 V), which was independent of the coating layers stress, is discussed next.

3 Influence of Waveguide Asymmetry

The introduction of asymmetry to the waveguide arms was previously found to affect the thermal drift behavior.[2,7] Here, the asymmetry in the arms was increased over the previous

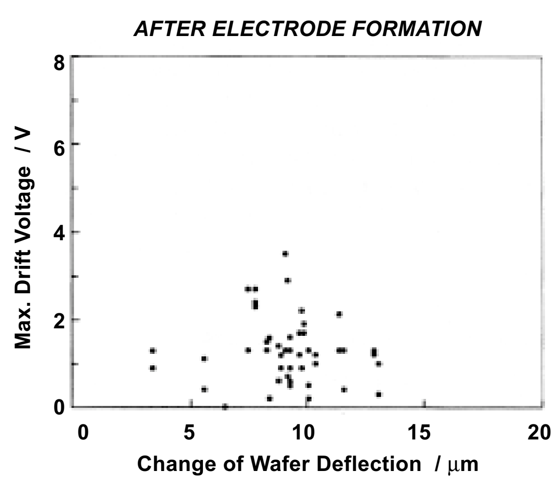
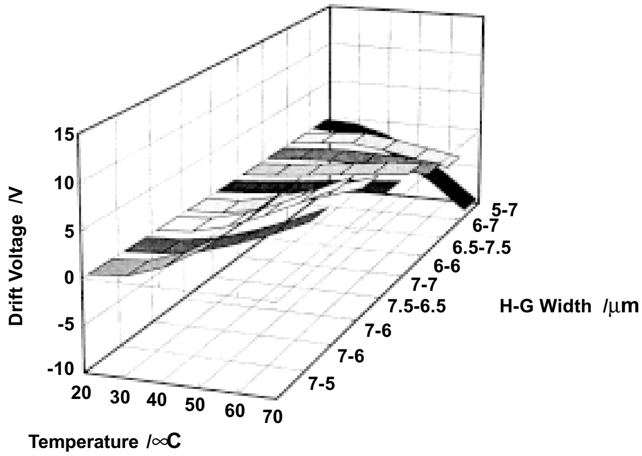
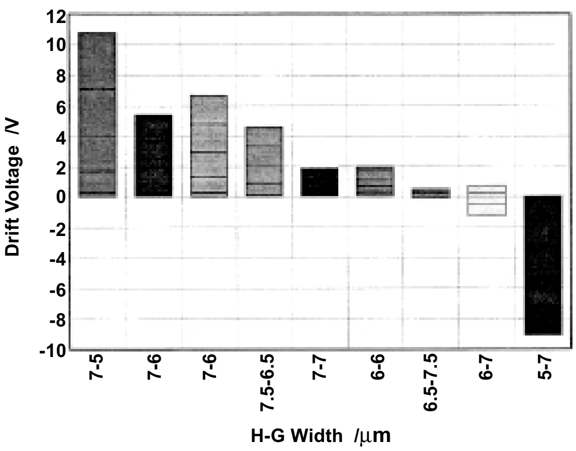


Fig. 2 Relationship between maximum drift voltage from 20 to 70∞C and a change of wafer deflection after the Au-plated electrode formation process for the dual-hot electrode type moduiators.



(a)



(b)

Fig. 3 Thermal drift voltages from 20 to 70∞C measured for single-hot electrode modulators having various asymmetric Mach-Zehnder waveguide arms. The "7-5" modulator has a 7-mm-wide hot waveguide arm and a 5-µm-wide ground waveguide arm: (a) drift curve profiles against the temperature and (b) drift extent against the waveguide asymmetry.

experiment and its apparent correlation with the drift was confirmed again (see Fig. 3). In Fig. 3(a), the drift voltage from 20 to 70∞C is plotted against temperature increase for modulators having various asymmetric waveguides; ì7—6î along the axis denotes the 7- and 6-μ m-wide waveguide arms under hot and ground electrodes, respectively. Similarly, the maximum extent of the drift is replotted in Fig. 3(b). As seen, the drift behavior strongly depends on the waveguide asymmetry, even though all the modulators had a Si layer for suppressing the pyrocharge effect. Decreasing the width ratio of the hot waveguide to the ground waveguide, i.e., toward the right side of the horizontal axis of Fig. 3(b), the drift magnitude becomes gradually smaller and changes to a negative value. Note that the drift voltage is close to zero for the ì6.5—7.5î configuration. A possible reason for the phenomenon was previously discussed by Nayyer and Nagata. [2]

The results indicate that the asymmetry in the waveguide arms affects the drift magnitude and direction, and that, in general, greater asymmetry increases the drift instead of eliminating it. In this regard, changes in the hot electrode width and in the overlapping area for the electrode and the waveguide are considered to be equivalent to a change in the waveguide width (i.e., asymmetric waveguides) and are important also with respect to the thermal drift behavior. If these parameters fluctuate uncontrolably during the electrode formation process, an asymmetry might be introduced into the interaction between the electrode and the waveguide, generating a large scattering of the drift magnitude even for the similarly designed modulators. For instance, because the LN wafer has been warped before the electrode formation process, there is the possibility that adjustment of the photolithographic electrode pattern is not completely achieved at edge of the wafer. Further, as the electrode thickness is increased over 10 μ m for broadband devices, an accurate control of the electrode width becomes difficult in general. Such possible failures in the device fabrication processes, which are difficult to check, are estimated to be the reason for the remaining thermal drift of Figs. 1(d) and 2.

4 Distribution of Thermal Drift in LN Wafer

Finally, the distribution of the thermal drift on the wafer was considered. Figures 4(a) and 4(b) show the thermal drift from 0 to 70∞C of a specific operating point (maximum in the optical output modulation, nearest to 0V) measured for 37 modulators fabricated from the same wafer (3 in. diameter). The horizontal axis denotes the modulator chip number arranged along the y axis of the z cut wafer; the about 60-mm-long waveguides were prepared along the x axis. The vertical axis denotes the operating point voltage, instead of the drift voltage from 0∞C, indicating operating points of the devices at certain temperatures.

As is seen in Fig. 4(a), the shape of the drift curve of the operating point voltage changes gradually depending on the chip number. In the smaller numbered chips, the peak maximum for the curve appears near 60∞C, and the peak shifts higher (>70∞C) as the chip number increases while the peak minimum appears at about 10∞C ultimately. Furthermore, the averaged operating point voltage shifted gradually depending on the chip number, as shown in Fig. 4(b) , although the magnitude of the thermal drift was independent of the chip number.

A possible origin of the gradual shift in the operating point voltage, which depended on chip position on the original wafer, is explained as follows. On the -*z* face of the LN wafer, the modulator chips were arranged in a manner in which the hot electrode (waveguide) of each chip was placed on the same side with respect to the *y* axis of the wafer against each ground electrode. However, the total strain (stress) introduced into the wafer by the deposition of homogeneous layers such as the SiO_2 was estimated to be smaller at the wafer center and greater at the wafer edge. Such unbalanced strain in the wafer caused a slight curving of the chip after cutting chips from the wafer via a stress relaxation process. The chips cut from -*y* and +*y* sides of the wafer, e.g., the smaller and greater numbered chips in Fig. 4, curved symmeincally from the center line of the wafer. As a result, modulator chips from one side of the wafer were concave toward its hot waveguide arm,

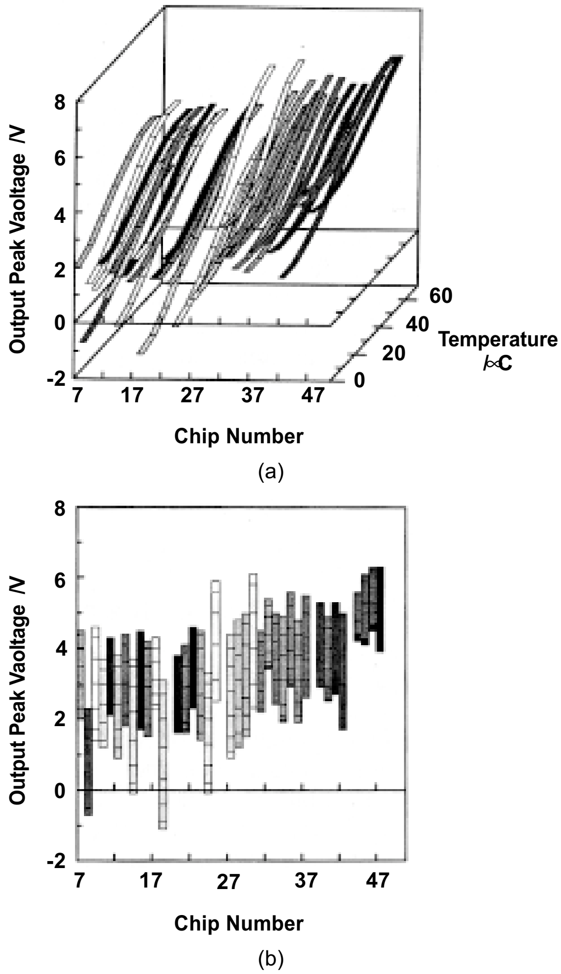


Fig. 4 Distribution of the thermal drift from 0 to 70∞C measured for conventional single-hot electrode modulators from the same wafer: (a) drift curve profiles of the operating point voltage against the temperature and (b) drift magnitude against the chip number (chip position in the wafer).

while chips from the other wafer side were concave toward the ground waveguide arm, leading to an opposite influence in the optical interaction of hot and ground arms. If the electrode pattern (for the photolithography process) were designed to be a symmetric configuration with respect to the wafer center line, the operating points might be expected to distribute symmetrically with respect to chip position, unlike the distribution in Fig. 4.

5 Summary

Although the devices are commonly used in vaJious optical systems, numerous fabrication parameter problems remain unsolved for $LiNbO_3$ waveguide devices. This communication comments on key factors in reducing the thermal drift in such Mach-Zehnder type modulators and in improving their fabrication yield. In this regard, achieving a symmetric arrangement in the physical configuration and the internal strain for the waveguide and electrode was found to be most effective. Note that if these problems are solved completely, the intentional introduction of a proper asymmetry in the waveguide arrns can almost eliminate the thermal drift.

Acknowledgments

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