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The Influence of Continuous DC Bias Application on Properties of Ti:$LiNbO_3$ Waveguide Devices

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Ti:$LiNbO_3$ optical waveguide devices must work stably over 20 years under a continuous dc bias application to adjust the optical output. Such dc bias is known to cause not only dc drift of the output signal, but also ferroelectric domain inversion of the substrate at higher temperatures. Here is presented the possible appearance of micro-domains under ordinary device operation conditions. Concerning the actual device chip with a z-cut $LiNbO_3$ substrate, the micro-domains were found to grow at 80~100 ℃ and at dc $\simeq$ 10 V and they increase with an increase of leak current between the hot and ground electrodes.

1. Introduction

Optical waveguide devices based on $LiNbO_3$ (LN) ferroelectric crystals have been applied progressively to optical communications, optical measurements, electromagnetic wave sensors, etc. Especially in communication systems, the LN external modulators have a practical use in analog and 2.5 GHz digital systems, and further promise to be used in a high speed 10 GHz system. In an optical communication system, devices must run stably and reliably for long periods of over 15 years. The dc drift phenomenon is regarded as one of the factors contributing to such stable device operation. However, dc bias application, the ultimate origin of the dc drift, is needed to adjust, the optical output modulation of the devices. The drift is caused by a chronological change in the dc voltage actually applied to the waveguides due to a dielectric relaxation of the bias voltage in the materials. Concerning the drift phenomenon, many experimental and theoretical results are reported from the viewpoint of realizing stable device operation.[1] Here, the experimental focus was changed to investigate the influence of the dc bias to the LN crystal itself.

In common LN modulators, the ac and dc fields are applied along the z-axis of the LN crystal in order to use its largest electro-optic constant r_{33}. Furthermore, to obtain effective electro-optic interaction, waveguides are designed as Mach-Zehnder interferometers accompanied with push-pull electrodes, in which the dc field is opposite to the spontaneous polarization of the LN in one of the waveguide arms. In such a situation, there is the possibility of the occurrence of 180° domain inversion in the LN waveguide because the domains are inversed in the LN crystal by a small displacement of cations along the z-axis. Previously, ferroelectric micro-domains were found to be generated by the thermal treatment of the LN near the Curie temperature for preparing Ti-indiffused waveguides. Furthermore, in our experiments using actual LN modulators, the micro-domains were found to grow even at lower temperatures, 80~100 ℃, caused by the high dc field application between the hot and ground electrodes (10~15 V bias voltage).

2. Experiments

Three kinds of experiments were carried out using LN modulator chips cut from the z-cut LN wafer. The LN chip was composed of a Mach-Zehnder Ti-indiffused waveguide formed on the −z-face, an approx. 1 μ m thick SiO_2 buffer layer, a thin Si layer, and Au coplanar electrodes with 25 μ m gaps between the hot and ground electrodes (see Fig. 1).

The first experiment was done to confirm whether the dc bias application induced the domain inversion at lower temperatures. The Au electrodes were cut completely at the middle of the chip (A-B in Fig. 1), and the bias was applied to one of the divided hot electrodes. Two samples were prepared for the experiment; sample 1 showed 205 k Ω for electrical resistance between the hot and ground ($R_{h\text{-}g}$) at room temperature, and sample 2 showed $R_{h\text{-}g}$ = 700 k Ω. dc bias voltages of 10 and 15 V were continuously applied to samples 1 and 2, respectively, at 80 °C for 100 hours. Then, the samples were chemically etched by a 1 : 5 mixture of HF : HNO_3 for an observation of inversed domains.

In the second experiment, the temperature dependence of the domain inversion was investigated using two samples, 3 and 4, with a complete electrode length. Sample 3 ($R_{h\text{-}g}$ = 2.05 M Ω) was placed in a 80 °C oven and sample 4 ($R_{h\text{-}g}$ = 2.24 M Ω) was in 100 °C, while a dc 10 V bias voltage was applied to both samples for 100 hours. During the bias application, a leak current between the hot and ground electrodes was monitored.

The third experiment was carried out on two samples, 5 and 6, at 80 °C for 1000 hours to examine the relationship between the distribution of micro-domains and the direction of the applied

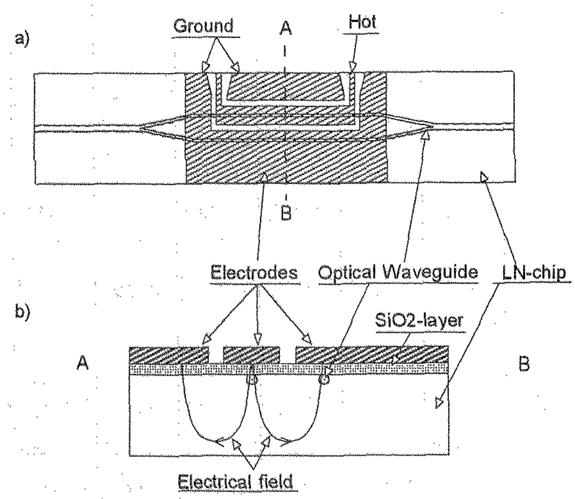

Fig.1 Schematic of samples, a) is a surface of LN, b) is a cross section between A and B.

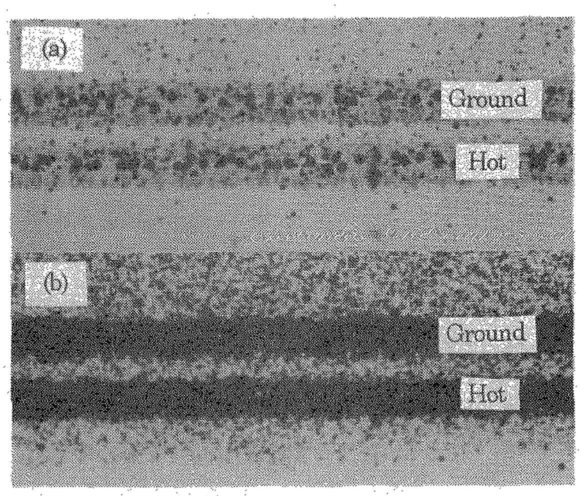

Fig.2 Etched LN surface strage at 80 °C for 100 hours (a) without dc bias and (b) with dc 10V bias.

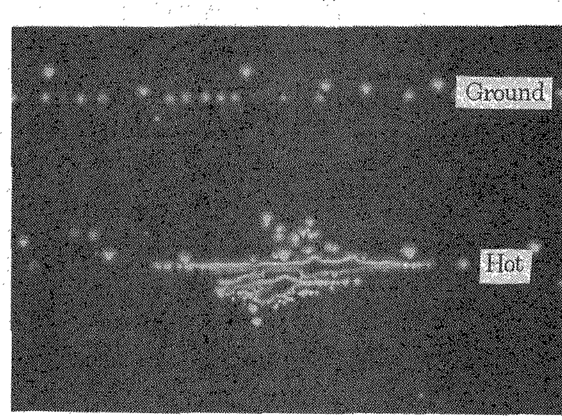

Fig.3 Etched LN surface strage at 80°C for 100 hours with dc 10V bias.

dc field. A dc bias voltage of +10 was applied to sample 5 ($R_{h\text{-}g}$ = 2.17 M Ω) and a −10 V bias voltage was applied to sample 6 ($R_{h\text{-}g}$ = 2.18 M Ω) between the hot and ground electrodes at a normal temperature. During the bias application, a leak current between the hot and ground electrodes was monitored.

3. Results

3.1. First Experiment

Figure 2 shows optical micrographs of surfaces for sample 1 after the chemical etching: (a) for the unbiased waveguides and (b) for the biased waveguides. The bright area corresponds to the intrinsic −z LN surface, and the black spots (and area) indicate the micro-domains with +z polarity. The micro-domains appear as hillocks because of their lower etching rate compared to the −z face. The larger spot-like micro-domains in the waveguides of Fig. 2 (a) were caused by the Ti-indiffusion process.[2] In the biased waveguides, Fig. 2 (b), the micro-domains were concentrated in the region under the electrodes, indicating that the domain inversion occurred due to the dc bias application, even at 80 °C. The 10 V dc bias for sample 1 was estimated to be on the order of 10^5 V/m from the gap between the hot and ground electrodes. The micro-domains were also observed in sample 2, but the amounts were smaller than in sample 1.

3.2. Second Experiment

Amounts of the micro-domains in samples 3 and 4 were significantly smaller than in samples 1 and 2. However, the linked micro-domains, possibly due to the dc bias application, appeared in the waveguide under the hot electrode, as shown in Fig. 3 of SEM image for sample 3. Unfortunately, the temperature dependence of the micro-domain formation could not be clarified in this experiment.

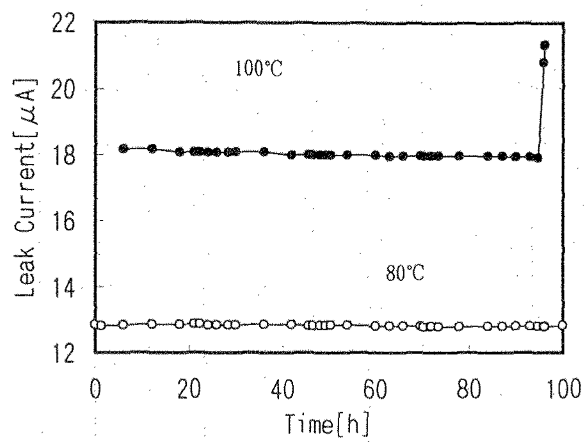

Fig.4 Changes of leak current

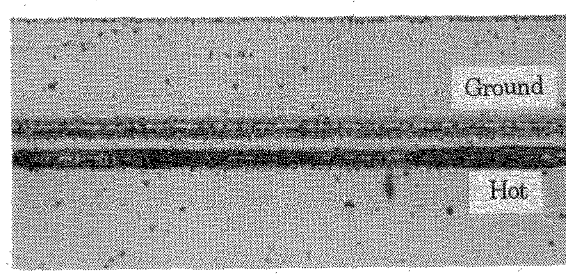

Fig.5 Etched LN surface strage at 80°C for 1000 hours with dc +10V bias.

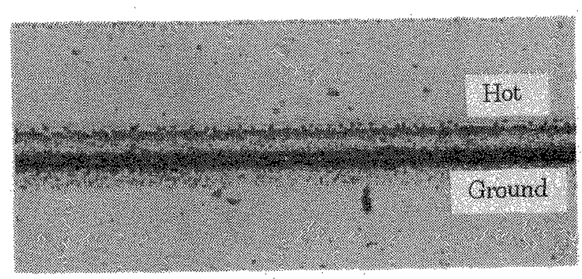

Fig.6 Etched LN surface strage at 80°C for 1000 hours with dc −10V bias.

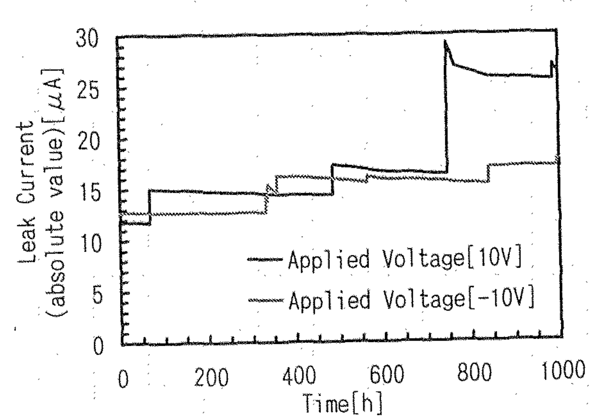

Fig.7 Time changes of leak current

Figure 4 revealed changes of the leak current between the hot and ground electrodes during the bias application for samples 3 (80°C) and 4 (100°C). The leak currents decreased gradually and the decreasing rate was faster for sample 4 at a higher temperature. Further, the leak current of this sample shot up from 17 to 21 μ m at about the 90th hour.

3.3. Third Experiment

Figures 5 and 6 show optical micrographs of the etched surface for samples 5 (+10 V) and 6 (-10 V), respectively. Contrary to expectation, the micro-domains grew on the hot waveguides for both samples independent of the polarity of the applied bias. However, the number of micro-domains seemed to be greater for sample 6 (Fig. 6) in which the bias was applied opposite to the spontaneous polarization of the LN.

Figure 7 shows a time dependence of the absolute leak currents for samples 5 and 6. The leak current in step like pattern characterized by sudden increasis followed by slight decreases over longperiods again followed by sudden, rapid increase.

4. Discussion and Conclusion

The above experimental results indicated that 180° domain inversion occurred even at lower temperatures, 80～100 °C, due to ordinary dc bias application. In the first experiment, the micro-domains were observed to be greater in the 10 V applied sample than the 15 V one, suggesting the influence of the leak current magnitude on domain inversion. The leak current of the 10 V applied sample was estimated to be two times larger than the other, judging from the inter-electrode resistance at room temperature. The micro-domains were expected to grow in the waveguide under the negatively biased electrode, because −z LN chips were used. However, in the third experiment, when the polarity was reversed, the micro-domains unexpectedly remained on the same side of the wave guide. Reason for such a phenomenon is not clarified in this moment.

The leak current between electrodes might be the origin of not only the domain inversion, but also the dc drift phenomenon of the device. In Fig. 4, the decreasing rates of the leak current differed 4.2 times for a temperature difference of 20°C, corresponding to an active energy (*Ea*) of 0.9 eV. This *Ea* value was close to 1 eV for the dc drift phenomenon. When the constant bias voltage was applied to dielectric materials, the leak current decreased gradually, as observed here, due to an increase of the absorption current in the materials.[3] However, a step-like increase of the leak current was found here and is to be further investigated as to its origin from the viewpoints of dc drift and of a formation of electrical path in the material possibly causing domain inversion. If a relationship between the current leak and the dc drift is clarified, a measurement of the leak current will be adopted as a simple method to screen the fabricated device chip instead of the conventional dc drift measurement for fully assembled devices.

References

1. H.Nagata and J.Ichikawa : *Opt. Eng.* 34 (1995) 3284; H.Nagata, N.Mitsugi, T.Sakamoto, K.Kiuchi and J.Ichikawa : *Appl. Phys. Lett.* 68 (1996) 301.
2. T.Nozawa and S.Miyazawa : *Jpn. J. Appl. Phy.* 35 (1996) 107.
3. H.Nagata, H.Takahashi, H.Takai and T Kougo : *Jpn. J. Appl. Phy.* 34 (1995) 606.