Long-term DC drift in x-cut $LiNbO_3$ modulators without oxide buffer layer

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Abstract: Long-term DC drift in x-cut $LiNbO_3$ modulators without any oxide buffer layer is examined by temperature accelerated biased aging tests. Based on the experiments at 140, 120 and 85℃, an activation energy of E_a = 1.4 eV is proposed for estimation of log-term DC drift of x-cut $LiNbO_3$ modulators. Further, the normalised applied voltage $A(t) = V(t)/V(0)$, in which $V(0)$ is the initially applied DC voltage, is estimated to be less than 2, even after DC drift throughout 20 years of operation at 65℃.

1 Introduction

The purpose of this report is to demonstrate the DC drift performance of the simplest x-cut $LiNbO_3$ (LN) optical intensity modulators without any oxide buffer layers. Such a design is sometimes applied to devices having proton exchange waveguides, because the process of the oxide layer formation needs heating of LN wafers and possibly deteriorates the waveguides. However, in order to realise broadband modulators applicable to 10 Gb/s systems for instance, the oxide buffer layer such as SiO_2 must be inserted between waveguides and electrodes for adjustment of the microwave propagation speed [1, 2]. Thus, investigation of the stability of device performance from the viewpoint of its long-term application in systems has been focused on z-cut and x-cut LN devices with SiO_2 layers, rather than the simplest x-cut LN devices [3–5]. In this regard, a DC drift phenomenon is the most notable, and the DC-biased aging tests of devices with SiO_2 are conducted to examine the device reliability [1]. In contrast, reports on DC drift of x-cut LN without SiO_2 seem to be limited to some fundamental investigations [6, 7].

On the other hand, recent dense and complex optical communication systems demand high speed LN modulators integrated with a DC driven port in order to easily adjust the optical output state of devices. Integration of a Mach–Zehnder part without SiO_2 into the x-cut modulator is a promising structure because a reduced DC driving voltage can be expected. Installation of the SiO_2 layer increases the driving voltage $V\pi$ [8]. In order to provide such x-cut integrated LN devices into actual systems, the long-term DC drift behavior of bare LN modulators must be examined. This report represents experimental results on x-cut LN modulators without SiO_2 from multiple device fabrication lots from the viewpoint of actual usage of devices. Further, an activation energy E_a of the DC drift was found to be almost the same as that of x-cut modulators with SiO_2 [9]; approximately E_a = 1.4 eV.

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IEE Proceedings online no. 20000626

DOI: 10.1049/ip-opt:20000626

Paper first received 21st January 2000 and in revised form 19th May 2000

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2 Experiments

Two kinds of x-cut modulator samples, both consisting of Ti-indiffusion Mach–Zehnder waveguides and common coplanar electrodes, were prepared for DC drift measurements at temperature accelerated conditions. The difference between the samples was the size of the LN wafers; one modulator type (a sample code X3 in following Section) was fabricated using a 3 in diameter and 0.5 mm thick wafer, and the other (sample codes X4A and X4B) were from 4 in diameter and 1 mm thick wafers.

In most of the experiments, the unbiased modulator samples were placed in an oven kept at 120℃. After 4 h storage the modulators reached this temperature and the measurements were started. Then, the initial DC bias (7 ~ 11 V) was applied individually to each of the AC driven modulators, and the optical output signal (λ = 1.55 μm) was monitored. The DC voltage applied to each of the modulators was controlled to maintain the optical output modulation at the initial DC biased state (control frequency = 1 kHz) using a follow-up bias control circuit. Similar measurements were conducted at 140 and 85℃ using different samples in order to examine the temperature dependency of the drift and to obtain the E_a value.

3 Experimental results

On seven X3 samples made from the same 3 in wafer, five different levels of the initial bias voltages from 7 to 11V were applied at 120℃, and the initial bias dependency of their DC drift was investigated. Fig. 1 shows the measured results as a relationship between applied DC voltage (including the initial DC bias voltage) and device operation time at 120℃. The data is replotted in Fig. 2 as a correlation between the applied DC voltage and the initial DC bias obtained after 10 h, 100 h and 600 h of operation. Similar results were obtained for other data from different operation times, and the relationship $V(t) = A(t) \times V(0)$ was found. Here, $V(0)$ is the initial DC bias, $V(t)$ is the applied DC voltage at time t including the initial DC bias, and $A(t)$ is a proportional factor as a function of the op-

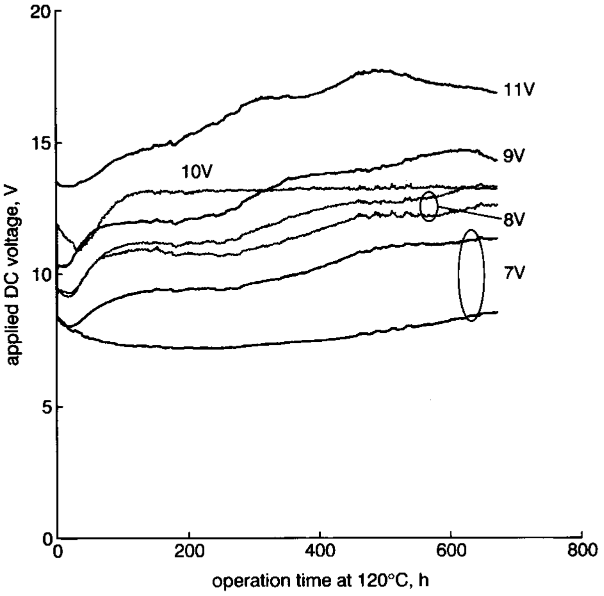

Fig. 1 *DC drift measurement results at 120℃ on x-cut LN modulators without SiO_2. Initial DC bias voltage was changed from 7 V to 11 V sample by sample*

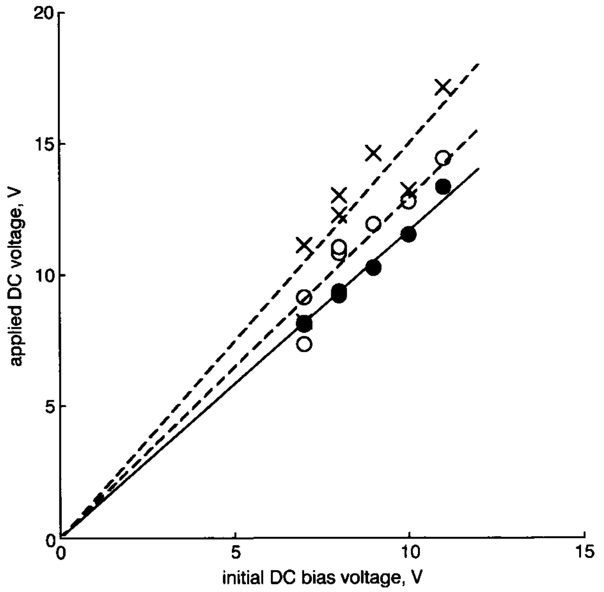

Fig. 2 *Relationship between applied DC voltage of Fig. 1 and corresponding initial DC bias voltage after 10, 100 and 600 h of operation*
● 10 h
○ 100 h
× 600 h

eration time t at the same temperature. A similar relationship was also observed in z-cut LN modulators and is consistent with the fact that unbiased (DC bias = 0V) modulators do not drift at a constant temperature [10].

Then, the operation time dependency of the factor $A(t)$ is examined.

Concerning x-cut LN modulators with the SiO_2 layer, the following equation is proposed:

$$A(t) = at^n = (bt)^n, \qquad (1)$$

considering the fact that the DC drift rate decreases chronologically during long-term operation [9]. Further, the coefficient b of eqn. 1, which was set as a rate coefficient (inverse time), was experimentally shown to be an

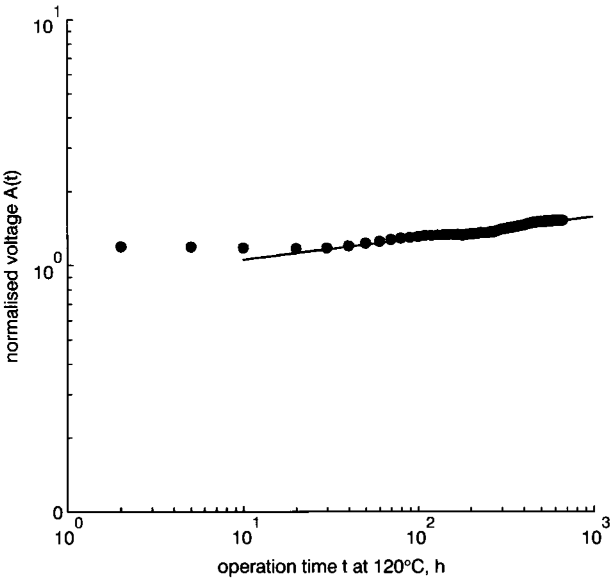

Fig. 3 *Relationship between normalised applied voltage A(t) and operation time t at 120℃ for results of Figs. 1 and 2*

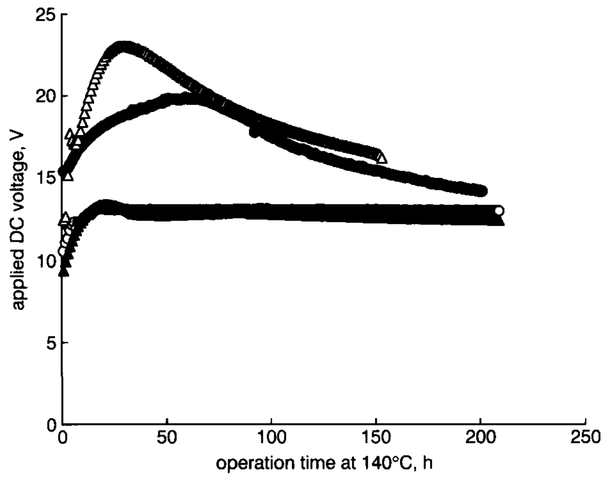

Fig. 4 *DC drift measurement results at 140℃ on x-cut LN modulators without SiO_2. Initial DC bias voltage was set at 10 V for all samples*

Arrhenius-type function of temperature T and a Boltzmann constant $k = 8.62 \times 10^{-5}$ eV/K such as [9]:

$$A(t) = [B \exp(-E_a/kT) \times t]^n. \qquad (2)$$

Fig. 3 reveals an expression of all data of Fig. 1 by eqn. 1, in which the normalised voltages $A(t)$ were derived from plots of Fig. 2 at each of the measured times; i.e., a gradient of the fitting line from zero. Except for the initial drift stage, the obtained data was found to be well expressed by eqn. 1, suggesting the possibility that the long-term DC drift of x-cut LN modulators without SiO_2 can be estimated using the simple equation.

In order to calculate the E_a which is necessary for DC drift estimation at various temperatures, the temperature dependency of the DC drift was examined at 140, 120, and 85℃ on X4A and X4B samples. Fig. 4 shows an example of the measurements at 140℃ on four X4A samples prepared from four different 4 in wafers (wafer number X4A-21, -25, -26, and -27). The initially applied DC bias was set at 10 V for all samples. As a result of temperature acceleration of the DC drift, a steep increase in the applied voltage was observed immediately after the initial DC bias application. A surprising fact is that after

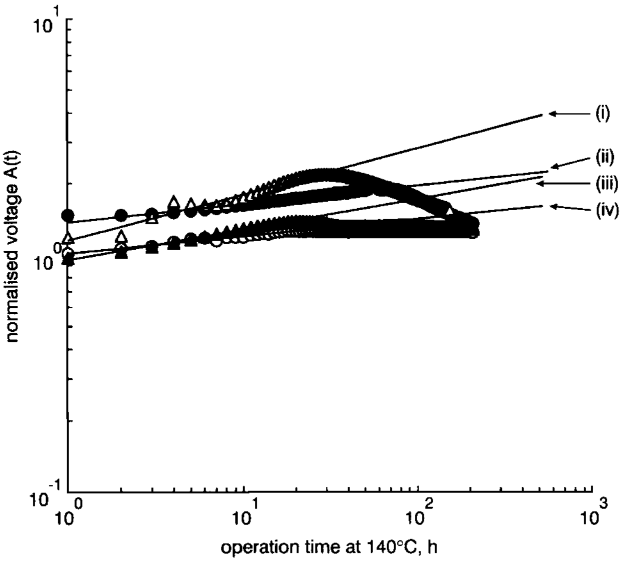

Fig. 5 *Relationship between normalised applied voltage A(t) and operation time t obtained for samples of Fig. 4 at 140℃*
(i) $A(t) = 1.1505 \times t^{0.1959}$
(ii) $A(t) = 1.3762 \times t^{0.0078}$
(iii) $A(t) = 0.9516 \times t^{0.1296}$
(iv) $A(t) = 1.0138 \times t^{0.0739}$

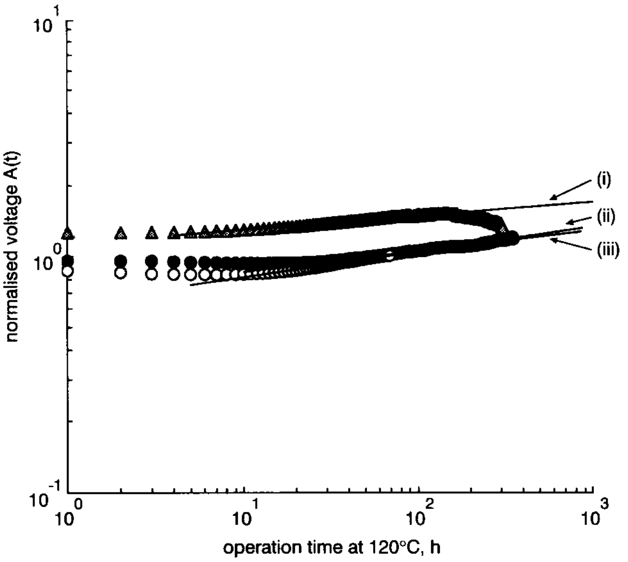

Fig. 6 *Relationship between normalised applied voltage A(t) and operation time t obtained for other samples at 120℃*
(i) $A(t) = 1.1396 \times t^{0.0591}$
(ii) $A(t) = 0.6371 \times t^{0.1084}$
(iii) $A(t) = 0.7017 \times t^{0.0892}$

several tens of hours of operation, the drift rate changed to be negative or almost zero.

The data of Fig. 4 was replotted in Fig. 5 as a relationship between $A(t)$ voltage normalised by the initial DC bias of 10 V and operation time t at 140℃. In Fig. 5, fitting results of the data by eqn. 1 are denoted. The other results obtained at 120 and 85℃ using X4B samples from six wafers are similarly shown in Figs. 6 and 7, respectively. The initial DC bias voltages were set at 11 V for 120℃ measurements and at 6 ~ 8 V for 85℃ measurements, and were used to calculate the corresponding normalised voltage $A(t)$. A change of the drift direction was also observed in the 120℃ operation results (sample no. X4B-29-7). In the 85℃ operation, the initial drift stage exhibiting no significant voltage change continued for

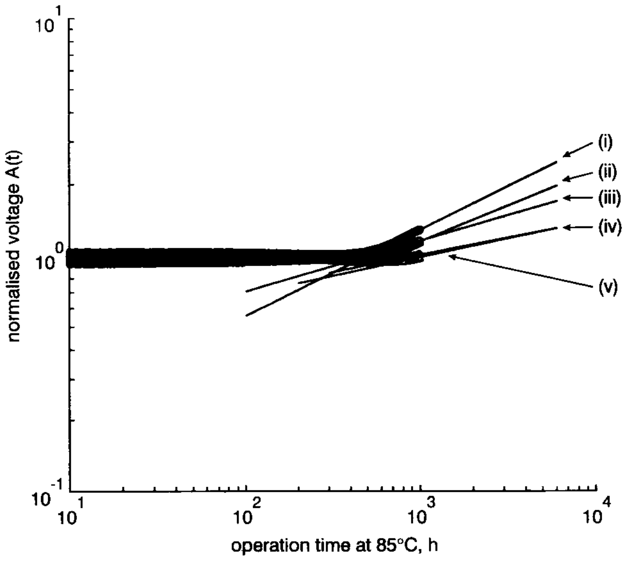

Fig. 7 *Relationship between normalised applied voltage A(t) and operation time t obtained for other results at 85℃*
(i) $A(t) = 0.1039 \times t^{0.3646}$
(ii) $A(t) = 0.1439 \times t^{0.3009}$
(iii) $A(t) = 0.2621 \times t^{0.2149}$
(iv) $A(t) = 0.3698 \times t^{0.1449}$
(v) $A(t) = 0.3297 \times t^{0.1582}$

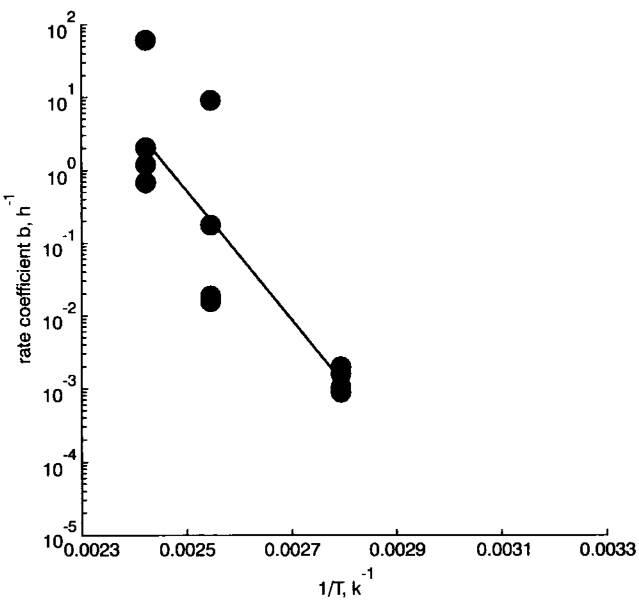

Fig. 8 *Arrhenius plots for DC drift measurement results of Figs. 3, 5, 6 and 7. Plotted parameters are listed in Table 1*

about 500 h, and the large positive DC drift canceling the applied DC bias voltages was generated.

The E_a of x-cut LN modulators without SiO_2 was calculated from Arrhenius plots of the fitting results of Figs. 3, 5, 6 and 7, as shown in Fig. 8. It is noted that the vertical axis of Fig. 8 denotes the rate coefficient b in eqn. 1 and not the constant a, because the Ea should be calculated using the rate coefficient. Parameters plotted in Fig. 8 are listed in Table 1. From the gradient of the plots, the activation energy Ea = 1.7eV was obtained.

4 Discussion

Firstly, the meaning of eqns 1 and 2 must be commented on. A relaxation phenomen of of the applied bias in the dielectric materials, i.e. DC drift, can be expressed by an

Table 1: Parameters for plots of Fig. 8 obtained from experimental data of Fig. 5 at 140℃, Figs. 3 and 6 at 120℃, and Fig. 7 at 85℃

Sample no.	Temperature, °C	coefficient, *a*	index, *n*	rate coefficient, *b* (1/hour)
X4A-21-6	140	1.3762	0.0778	60.61
X4A-25-1	140	1.0138	0.0739	1.204
X4A-26-4	140	0.9516	0.1296	0.6820
X4A-27-5	140	1.1505	0.1959	2.046
X4B-14-4	120	0.7017	0.0892	1.885×10^{-2}
X4B-28-18	120	0.6371	0.1084	1.562×10^{-2}
X4B-29-7	120	1.1396	0.0591	9.126
X3-1-1 ~ 7	120	0.8634	0.0849	0.1773
X4B-13-6	85	0.1439	0.3009	1.592×10^{-3}
X4B-14-2	85	0.3698	0.1449	1.043×10^{-3}
– 15	85	0.2621	0.2149	1.968×10^{-3}
X4B-18-6	85	0.3297	0.1582	8.994×10^{-4}
– 17	85	0.1039	0.3646	2.008×10^{-3}

equation (*CR* circuit model) being proportional to the applied voltage and the time dependent term [1– exp; (– t/τ)], in which the a constant τ is a relaxation time for the material system [3, 4]. However, in actual device operations, the applied bias is changed continuously by a follow-up bias controlled method, and the situation becomes complicated [11]. Eqn. 1 is proposed to simply express the observed drift profile based on the experimental fact that the DC drift rate decreases chronologically during long-term operation. Thus, although the proposed equation does not express accurately the physical meaning of drift phenomena, I believe that the equation is usable to fit and extrapolate actually obtained drift data, as demonstrated in Fig. 3. Similarly, eqn. 2 is assumed to examine the temperature dependency of the rate coefficient *b* of eqn. 1, and from a physical viewpoint, the obtained E_a is not a real activation energy of the material and should be used for the system determined by eqn. 1. In other words, it is valid to apply this modified E_a to drift profiles well fitted by eqn. 1.

Based on similar measurements and assumptions, I found previously that the *Ea* of DC drift in common x-cut LN modulators with an SiO_2 buffer layer was 1.4 eV [9]. The previous measurements had been conducted on the same samples by changing the operation temperatures, while completely different samples were used in the present experiments. Fig. 9 shows a comparison of the previous results for modulators with SiO_2 and present results for modulators without SiO_2, in which some data with larger *b* values are waived from the present data set (140 and 120℃ data). Although E_a = 1.7 eV was obtained for the x-cut LN modulators without any oxide layers as described above, 1.4 eV is thought to be acceptable for both types of x-cut modulator with and without SiO_2. Because the use of a smaller E_a in the life-time calculation provides more conservative estimation results, the adoption of E_a = 1.4 eV for all x-cut modulators does not create problems for their quality assurance.

The E_a = 1.4 eV in my experiments seems to be larger than E_a reported for z-cut modulators; approx, 1 eV [4, 5]. However, Seino *et al.* reported similar E_a = 1.4 ~ 1.6 eV on z-cut LN modulators based on their investigation on the temperature dependency of DC drift failure rates fitted by a lognormal distribution function [3]. Recently, Lanfredi and Rodrigues reported about 1.2 eV as the E_a for high-temperature electrical conductivity of polycrystalline $LiNbO_3$ [12]. Although further investigation is needed to clarify a crystal orientation dependency of the DC drift, there is a possibility that E_a = 0.7 ~ 1 eV for modulator devices [13] may be underestimated.

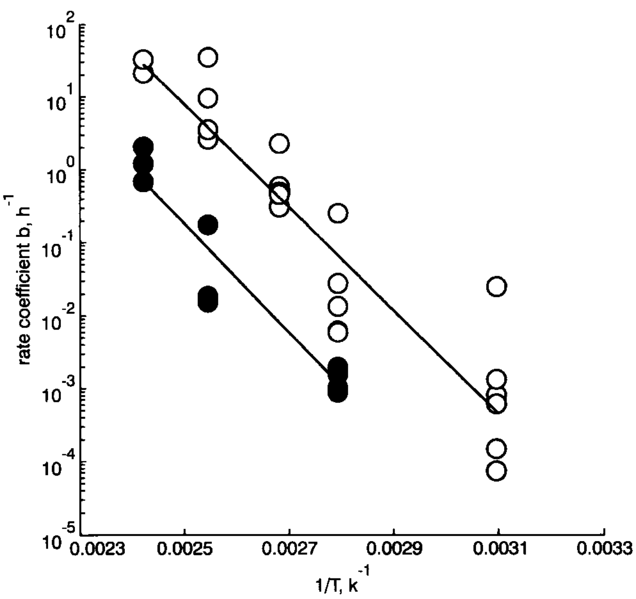

Fig. 9 *Arrhenius plots of the DC drift rate coefficient b for x-cut LN modulators with and without SiO_2 buffer layer*
○ with buffer layer
● without buffer layer

Another feature seen in Fig. 9 is a tendency that the x-cut LN modulators without SiO_2 have a slower rate coefficient *b* than modulators with SiO_2. In other words, the duration of the initial DC drift stage at lower temperatures is expected to be longer for modulators without SiO_2. Actually, the initial stage showing the slower drift rate was observed to be less than 10 h at 85℃ for modulators with about 1 μm thick SiO_2 layers [9], but 500 h in the present experiments.

If E_a = 1.4 eV is used as the conservative activation energy for long-term DC drift estimation, a common device operation time of 20 years at 65℃ is converted to be 210 h (9 days) at 120℃, and only 29 h at 140℃. Thus, the abnormal negative drift observed in Figs. 5 and 6 is expected not to appear within the common device oration conditions. The negative drift does not cancel the applied bias voltages and does not shorten the device life-time. However, because the origin of this dramatic change in the drift direction has not been clarified yet, the appearance of the abnormal drift within the actual device operation may be undesirable from the viewpoint of assurance of device performance and stability.

On two samples (X4A-21-6 and X4A-27-5) of Fig. 4 and 5, the optical performance was checked before and after the DC drift measurements at 140℃. Because installed optical fibres had been thermally damaged, the fibres of the other two samples were broken when removing them from the oven for a performance check. The optical insertion loss was deteriorated due to the effect of 140℃ aging from 6.3 dB to 8.5 dB for X4A-21-6, and from 6.2 dB to 7.8dB for X4A-27-5. The $V\pi$ measured at 1 kHz was found to change slightly from 8.2 V to 7.4 V (X4A-21-6) and from 7.8 V to 6.8 V (X4A-27-5) after the aging. However, no significant change was found in their on/off extinction ratio: from 27.6 dB to 26.9 dB (X4A-21-6) and from 29.4 dB to 27.4 dB (X4A-27-5). At least, there is no appearance of a significant change in optical performance, even after the abnormal drift behavior was observed at the temperature accelerated conditions.

Finally, from the viewpoint of the screening (burn-in) test of x-cut LN modulators without the oxide buffer layer, the results of Fig. 7 at 85℃ seem to be inconvenient in setting the specific screening criterion for the DC drift, because the positive drift depending on modulators does not appear within a short time for the screening test. Regarding this problem, a lot screening test at higher temperatures (120 ~ 140℃) seems to be effective. The lot screening test corresponding to the full operation time at 65℃ can be completed within 9 days at 120℃ and 29 h at 140℃ (E_a = 1.4 eV). For instance, from the present experiments at 140℃, the normalised $A(t)$ value is suspected to be less than or equal to 2 at the point of 20 years at 65℃. In other words, assuming the maximum driving voltage of systems at V_{max}, an initially applied bias voltage for each of the devices from the tested fabrication lots should be smaller than $V_{max}/2$. Because the drift performance depends sometimes on a difference in device production lots, the lot screening test seems to be effective in completely rejecting defective devices. Although the influence of LN wafer quality on the DC drift is not known at this time, some processes for wafer surface treatment, such as etching, resist removing, etc. largely affect the DC drift behavior of devices [14].

5 Conclusion

The activation energy E_a = 1.7 eV was experimentally obtained for the long-term DC drift of x-cut LN modulators without any oxide buffer layer. When considering the E_a previously reported for common x-cut modulators with an SiO_2 layer, the conservative value E_a = 1.4 eV can be proposed for all x-cut LN modulators. Thus, the lot screening of x-cut LN modulators for 20 years system operation at 65℃ is to be completed by 29 h of accelerated aging test at 140℃ (9 days at 120℃).

6 Acknowledgments

I am grateful to Mr. Sugimoto, Mr. Akizuki, Mr. ltoh and Mr. Mori for their help in DC drift measurements.

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