Zero-Chirp Broadband *Z*-Cut Ti:LiNbO$_3$ Optical Modulator Using Polarization Reversal and Branch Electrode

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***Abstract*--In this paper, a novel zero-chirp *Z*-cut LiNbO$_3$ optical modulator using ferroelectric polarization reversal and a branch electrode is proposed. The optical modulator with a Ti-diffused optical waveguide had a very small chirp parameter, which was less than 0.02. The performance showed a preferable 10-Gb/s eye opening and bias stability.**

***Index Terms*–Broadband, chirp, LiNbO$_3$, optical modulator, polarization reversal (PR).**

I. Introduction

LiNbO$_3$ (LN) optical modulators with Ti-diffused waveguides have been used for long-haul communication systems because of their high performance and high reliability. LN modulators also look promising for next-generation systems, such as carrier-suppressed return-to-zero (CS-RZ) systems and intensity-modulation differential phase-shift keying (IM-DPSK) systems [1], [2], other than conventional non-RZ (NRZ) systems. Because these next-generation systems require that optical modulators have almost zero chirp, *Z*-cut dual-electrode (DE-) Mach–Zehnder LN modulators (MZMs) or *X*-cut MZMs have been used conventionally. *Z*-cut DE-MZMs can be used with differential output drivers, by adjusting phases and amplitude of electrical signals precisely. *X*-cut MZMs can be driven using single-ended drivers, but driving voltages in *X*-cut MZMs are larger than those in *Z*-cut MZMs, in general. Recently, *Z*-cut LN-LiTaO$_3$ Optical modulators with zero chirp and single electrode were reported using a polarization-reversal (PR) technique [3]–[5]. These modulators have potentialities to be driven by single-ended drivers with driving voltages lower than these in *X*-cut MZMs. Murata proposed a single-sideband modulator with a traveling-wave electrode and a periodical PR; however, the modulator had a narrowband operation because of a quasi-velocity-matching technique [3]. Courjal *et al.* proposed a chirp-adjusted MZM with electrode inversion and a PR structure. The chirp parameter of the modulator depends on modulated frequencies because of the electrical loss [4]. These modulators are not suitable for the systems where very small chirps are required in a wide frequency range.

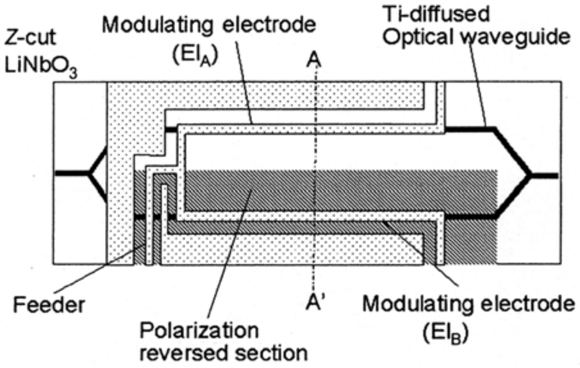

Fig. 1. Schematic figure of a *Z*-cut LiNbO$_3$ modulator with a PR structure and a branch electrode.

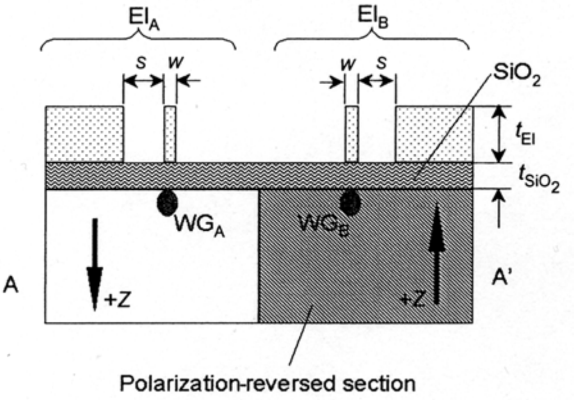

Fig. 2. Cross section of the proposed modulator in Fig. 1.

In this paper, we designed and fabricated a novel zero-chirp *Z*-cut Ti:LiNbO$_3$ optical modulator with a ferroelectric PR technique and a branch-electrode structure [5]. The optical modulator showed broadband optical modulation and high reliability for practical communication systems.

II. Structure of Modulator

The schematic figures of the proposed modulator are shown in Figs. 1 and 2. The equivalent circuit is shown in Fig. 3. A branch electrode, consisting of a feeder and two modulating electrodes, is located on Ti-diffused Mach-Zehnder waveguides. The ferroelecinc polarization direction of the LN substrate is opposite at each modulating electrode section, as shown in Fig. 2. The electrical signal applied from the feeder is

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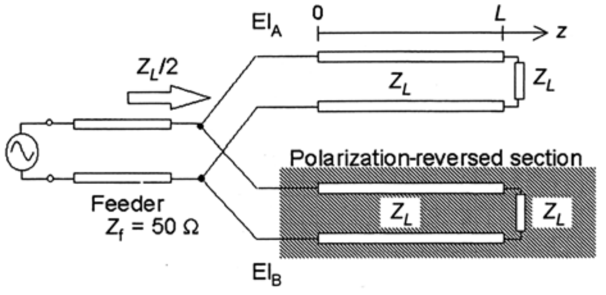

Fig. 3. Equivalent circuit of the proposed modulator.

divided into two signals on the modulating electrodes El$_A$ and El$_B$ With the same phases and the same amplitude because of the symmetric structure of El$_A$ and El$_B$.

The optical phase shifts ϕ_A and ϕ_B in the optical waveguide WG$_A$ and WG$_B$ can be expressed by

$$\phi_i = \frac{\pi}{\lambda_0} n_o^3 r_{33} \frac{\Gamma}{s} \frac{2Z_L}{2Z_f + Z_L} \times \int_0^L \mathrm{Re}\left[V_{\mathrm{in}} \mathrm{e}^{-\alpha z} \exp\left(\frac{2\pi f}{c}(n_m - n_o)z - 2\pi f t \right) \right] \mathrm{d}z \quad (i = \mathrm{A}, \mathrm{B}) \tag{1}$$

where c is the speed of light, λ_0 the wavelength of light, n_m the refractive index of the microwave on the modulating electrode, n_o the refractive index of the lightwave, a the attenuation constant of the modulating electrode, s the gap between the signal electrode and the ground plane, L the length of the modulating electrode, Γ the overlap integral between the optical field of the lightwave and the electrical field induced by the electrode, r_{33} the electrooptic coefficient, Z_f the characteristic impedance of the feeder, Z_L the characteristic impedance of the modulating electrode, V_{in} the amplitude of the input voltage, and f the frequency of the input voltage. The amplitude of the voltages is the same and the polarization directions of the substrate have opposite signs on El$_A$ and El$_B$. Thus, the relation between ϕ_A and ϕ_B is expressed by

$$\phi_A = -\phi_B. \tag{2}$$

The chirp parameter α_0 in a small-signal operation can be defined by [6]

$$\alpha_0 \equiv \frac{\phi_A + \phi_B}{\phi_A - \phi_B}. \tag{3}$$

Because the relation between ϕ_A and ϕ_B is given by (2), α_0 of the proposed modulator is independent of modulating frequencies .

III. DESIGN

We calculated the parameters of the modulating electrode: impedance Z_L , effective microwave index n_m, and attenuation constant a as a function of the gap s, by using a finite element method (FEM), HP HFSS ver.5.4. The following parameters were used for numeric calculations: $\varepsilon_{sio_2} = 3.98$; $\varepsilon_{LiNbO_3X} = 43.0$; $\varepsilon_{LiNbO_3Z} = 28.0$; and $\sigma_{El} = 4.3 \times 10^7\ \Omega \cdot \mathrm{m}^{-1}$. ε_{SiO_2} denotes dielectric constant of SiO$_2$, and ε_{LiNbO_3X} and ε_{LiNbO_3Z} denote dielectric constants of LiNbO$_3$ in X- and Z-directions, respectively. σ_{El} denotes conductivity of the electrode (Au).

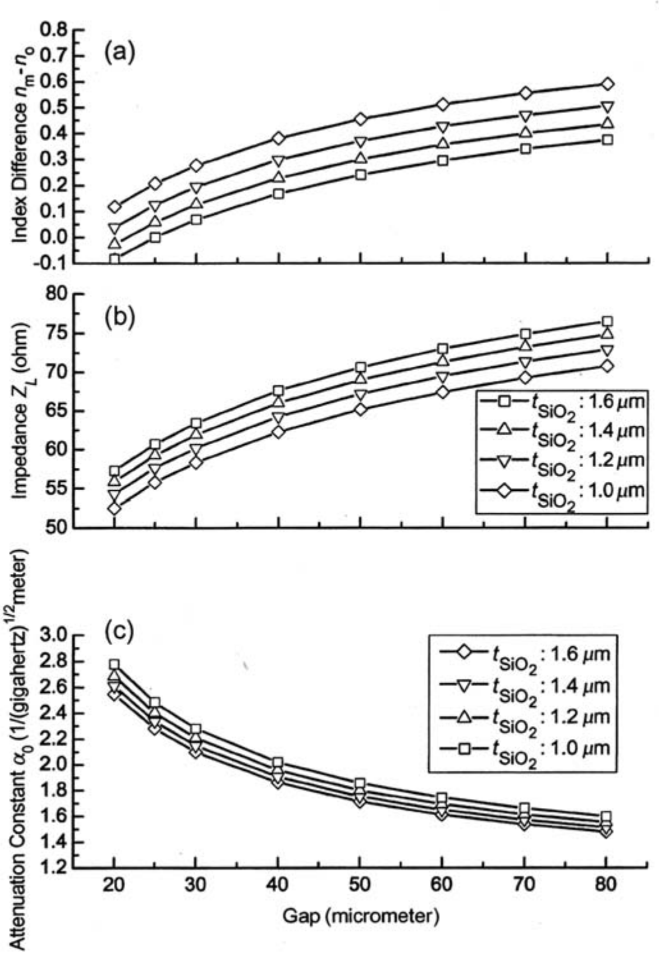

Fig. 4. Calculated index difference n_m - n_o between the microwave on the electrode and the lightwave on the waveguides, impedance ZL , and attenuation constant a of the modulating electrode, as a function of the gap s where the signal-electrode width w = 5 μm and the electrode height t_{El} = 22 μm.

Here, we assume a signal-electrode width w of 5 μm and an electrode height t_{El} of 22 μm, The calculated results are shown in Fig. 4. $n_m - n_o$ in Fig. 4(a) denotes the index difference between the microwave on the electrodes and the lightwave on the waveguides. As s increases, the capacitance between the signal electrode and the ground plane decreases; therefore Z_L and $n_m - n_o$ increase. As t_{SiO_2} increases, the effective dielectric constants of the substrate decrease; therefore Z_L increases, and $n_m - n_o$ decreases.

We examine optical response and electrical reflectivity of the proposed modulator. The optical response $M(f)$ in small-signal optical modulation [7] is derived from (1), as follows

$$M(f) = 20 \log_{10} \left[\exp^{-\left(\frac{\alpha L}{2}\right)} \left(\frac{\sinh^2\left(\frac{\alpha L}{2}\right) + \sin^2\left(\frac{\xi L}{2}\right)}{\left(\frac{\alpha L}{2}\right)^2 + \left(\frac{\xi L}{2}\right)^2} \right)^{\frac{1}{2}} \right] \tag{4}$$

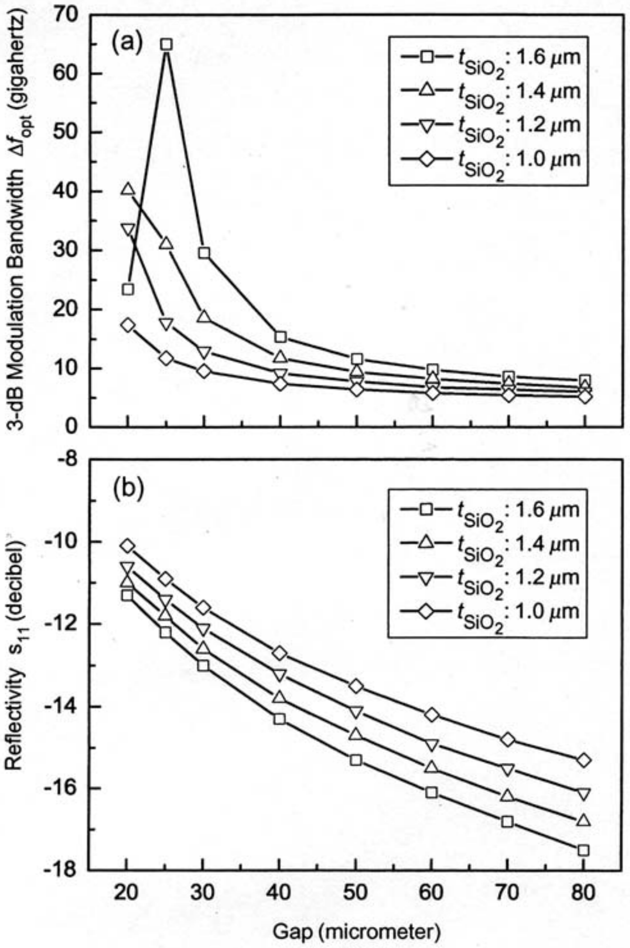

Fig. 5. Calculated 3-dB modulation bandwidth Δf_{opt} and electrical reflectivities S_{11} of the proposed modulator where the signal-electrode width $w = 5$ μm, the height $t_{\text{El}} = 22$ μm, and the modulating-electrode length $L = 40$ mm.

where

$$\xi = (n_{\text{m}} - n_o)\frac{2\pi f}{c}. \tag{5}$$

We define 3-dB modulation bandwidth Δf_{opt} , where $M(f_{\text{opt}})$ is –3 dB.

In the branch-electrode structure, the total characteristic impedance of modulating electrodes is Z_L /2, as shown in Fig. 3 . We design the modulating electrode to match with the feeder; therefore Z_L should be of high impedance, ideally 100 Ω. But the practical Z_L is not high, as shown in Fig. 4(b). The electrical reflectivity S_{11} of the modulating electrodes is defined by

$$S_{11} = 20\log_{10}\left(\frac{Z_L - 2Z_{\text{f}}}{Z_L + 2Z_{\text{f}}}\right). \tag{6}$$

Fig. 5 shows the calculated dependences of Δf_{opt} and S_{11} on the gap s. Δf_{opt} becomes larger as the gap decreases because the index difference approaches zero, as shown in Fig. 4(a). This result showed $n_{\text{m}} - n_o$ had an impact on Δf_{opt}. S_{11} becomes smaller as the gap increases because Z_L approaches 100 Ω, as shown in Fig. 4(b). In this letter, we considered a practical 10-Gb/s optical modulator, where Δf_{opt} was more than 10 GHz and S_{11} was less than – 15 dB. We selected the condition: the gap s was 50 μm, and the thickness t_{SiO_2} was 1.6 μm, where Δf_{opt} was 11.6 GHz and S_{11} was – 15.3 dB.

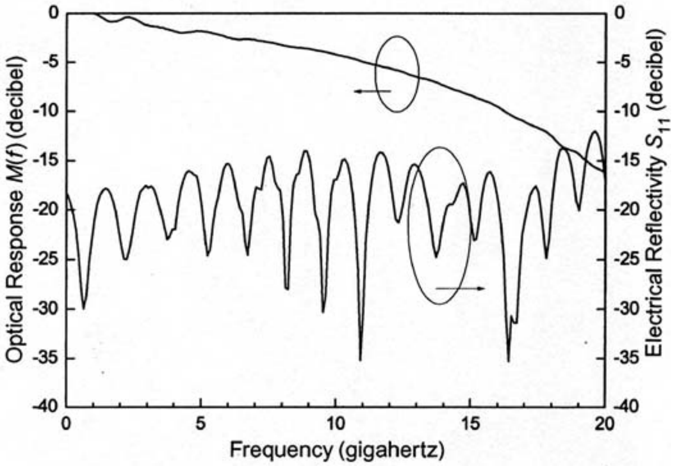

Fig. 6. Experimental results of optical response and electrical reflectivity.

IV. FABRICATION

At first, Mach–Zehnder waveguides for a light wavelength of 1.55 μm were fabricated. We selected Ti-diffusion method considering the bias stability [8]. In the second step, rectangular windows of photoresist on the + Z plane were patterned to define polarization-reversed sections. We used a transparent liquid-electrode system consisting of the transparent plastic plates and O rings for the selected area poling [9]. A high voltage pulse of 22 kV/mm was applied through liquid electrodes at room temperature. An SiO_2 buffer layer was deposited on the wafer by the conventional vapor deposition method, and finally branch electrodes were defined by photolithography and electro plating.

Two types of DE-MZMs were also fabricated on the same wafer as references: one was a DE-MZM without a PR section (nonpoled DE-MZM) and the other was a DE-MZM with a PR section (PR DE-MZM).

V. CHARACTERIZATIONS

The extinction ratio of the fabricated modulator was more than 30 dB at the directional coupler. The total insertion loss including coupling loss from the pigtailed fibers, was 3.5 dB . These properties were similar with those of nonpoled DE-MZMs. The driving voltages of both arms of PR DE-MZM, with and without a PR section, were the same. These results suggest that the poling process does not affect the quality of the primary LN substrate.

The optical response of the fabricated modulator was measured to 20 GHz by an optical component analyzer (Agilent 86030A) at a wavelength of 1.55 μm, as shown in Fig. 6. The response curve was very smooth without any dips. The electrical reflectivity was less than – 12 dB up to 20 GHz. Any degradation of electrical reflections caused by the branch-electrode structure was not observed.

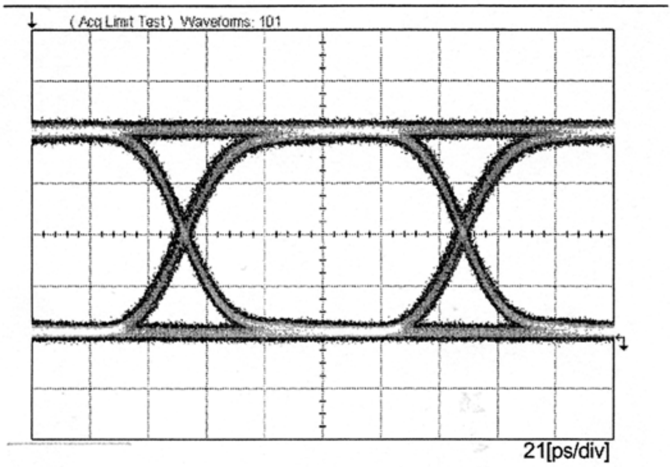

Fig. 7. Optical eye diagram with $2^{31} - 1$ PRBS at 10 Gb/s.

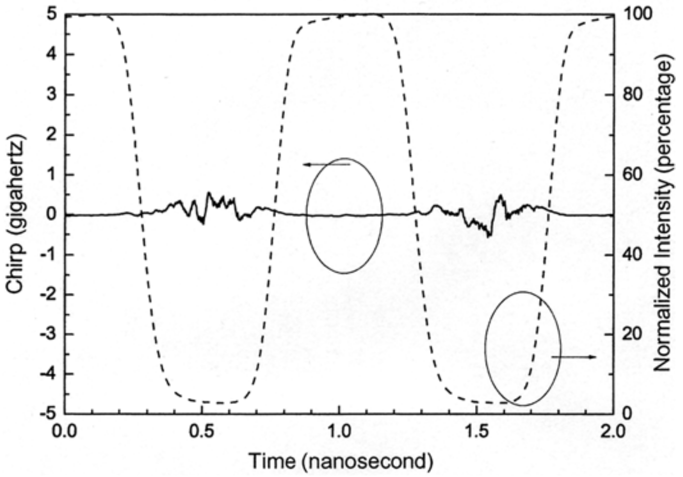

Fig. 8. Frequency chirp in 10-Gb/s intensity modutation.

Fig. 7 shows the optical eye diagram recorded from the $2^{31} - 1$ pseudorandom bit sequence (PRBS) at the 10-Gb/s operation. The eye opening was good and stable. The dynamic extinction ratio was confirmed to be 14.6 dB with a 4.1 $V_{\mathrm{p-p}}$ modulation. The time jitter [root mean square value (rms)] was as small as 1.4 ps.

The chirp parameter was less than 0.02 measured by the fiber-response method [10]. In addition, the dynamic chirp at a 10-Gb/s digital signal was measured by an optical chirp testset (ADVANTEST Q7607). The optical signal modulated by the proposed modulator caused no chirp, as shown in Fig. 8.

To estimate dc-bias stability for long-time use, acceleration tests were carried out at 85 °C for 1 d. The applied dc voltage has shifted within 30% of initial applied voltage (3.5 V) and saturated as shown in Fig. 9. The operation time of 1 d at 85 °C is equivalent to 1 year at 30 °C, assuming activation energy of 1.0 eV [8]. No difference for dc-drift characteristics was observed between the proposed modulator and a nonpoled DE-MZM.

These properties are practical in use for conventional long-haul communication and next-generation systems.

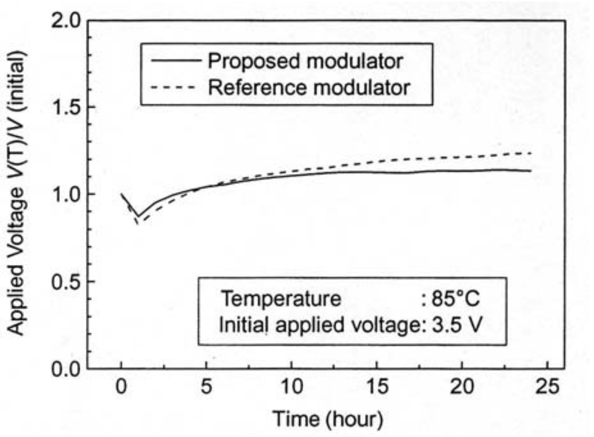

Fig. 9. Acceleration test of dc drift at 85 °C. The operation time of 1 d at 85 °C is equivalent to 1 year at 30 °C.

VI. CONCLUSION

In this paper, a novel zero-chirp and broadband *Z*-cut Ti:LiNbO$_3$ modulator with a PR structure and a branch electrode was proposed. The optical response and the electrical reflectivity satisfied requirements for 10-Gb/s operations. The driving voltage of the proposed modulator with the 4-cm electrode length was 4.1 V at 10 Gb/s. It is expected that the driving voltage is reduced by adopting a ridge structure [11] into the proposed modulator.

The modulator operated at 10 Gb/s with a very small chirp parameter of less than 0.02 and showed high dc-bias stability. The modulator will work stably for a long time similar with commercial LN modulators.

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REFERENCES

[1] A. Hirano, Y. Miyamoto, S. Kuwahara, M. Tomizawa, and K. Murata, "A novel mode-splitting detection scheme in 43-Gb/s CS- and DCS-RZ signal transmission," *J. Lightw. Technol.*, vol. 20, no. 12, pp. 2029–2034, Dec. 2002.

[2] C. Rasmusssen, T. Fjelde, J. Bennike, F. Liu, S. Dey, B. Mikkelsen, P. Mamyshev, P. Serbe, P. Wagt, Y. Akasa, D. Harris, D. Gapontsev, V. Ivshin, and P. Reeves-Hall, "DWDM 40 G transmission over trans-Pacific distance (10 000 km) using CSRZ-DPSK, enhanced FEC and all-Raman amplified 100 km ultra wave fiber spans," presented at the Optical Fiber Communication Conf. (OFC), Atlanta, GA, 2003, Paper PD 18- 1 .

[3] H. Murata, S. Yamamoto, H. Sasai, and A. Enokihara, "Novel guided-wave electrooptic single-sideband modulator by using periodically domain-inverted structure in a long wavelength operation," presented at the Optical Fiber Communication Conf. (OFC), Atlanta, GA, 2003, Paper MF53 .

[4] N. Courjal, H. Porte, A. Martinez, and J. P. Goedgubuer, "LiNbO$_3$ Mach-Zehnder modulator with chirp adjusted by ferroelectric domain inversion," *IEEE Photon. Technol. Lett.*, vol. 14, no. 11, pp. 1509–1511, Nov. 2002.

[5] S. Oikawa, F. Yamamoto, H. Honda, J. Ichikawa, Y. Nomura, and S. Kurimura, "Zero chirped broadband-type Z-cut LiNbO$_3$ optical modulator using by domain-inversion structure," (in Japanese), in *Proc.*

64th Autumn Meeting, Japan Society Applied Physics, Fukuoka, Japan, 2003, p. 1072, 30p-YK-6.

[6] A. Djupsjöbacka, "Residual chirp in integrated-optic modulators," *IEEE Photon. Technol. Lett.*, vol. 4, no. 1, pp. 41–43, Jan. 1992.

[7] N. Dagli"Wide-bandwidth lasers and modulators for RF photonics," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 7, pp. 1151–1170, Jul. 1999.

[8] H. Nagata and J. Ichikawa, "Progress and problems in reliability of Ti:LiNbO$_3$ optical intensity modulators," *Opt. Eng.*, vol. 34, no. 11, pp. 3284–3292, 1995.

[9] S. Kurimura, I. Shoji, T. Taira, J. H. Ro, and M. Cha, "Coercive field dependence on Mg concentration in Mg:LiNbO$_3$," presented at the Conf. Lasers and Electro-Optics, Baltimore, MD, 2001 , CTuI3.

[10] F. Devaux, Y. Sorel, and J. F. Kerdiles, "Simple measurement of fiber dispersion and chirp parameter of intensity modulated light emitter," *J. Lightw. Technol.*, vol. 11, no. 12, pp. 1937–1940, Nov. 1993.

[11] K. Noguchi, O. Mitomi, H. Miyazawa, and S. Seki, "A broadband Ti:LiNbO$_3$ optical modulator with a ridge structure," *J. Lightw. Technol.*, vol. 13, no. 6, pp. 1164–1168, Jun. 1995.

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