Design of Ultra-Broad-Band $LiNbO_3$ Optical Modulators with Ridge Structure

Osamu Mitomi, Kazuto Noguchi, and Hiroshi Miyazawa

***Abstract*—This paper describes novel coplanar waveguide (CPW) electrode and asymmetric coplanar strip line (A-CPS) electrode structures, introducing ridged $LiNbO_3$ substrates and thicker electrodes, for ultra-broad-band $LiNbO_3$ optical modulators. The structures are designed here with quasistatic analysis using the finite-element method. Ridged-structures with CPW and A-CPS electrodes are shown to be able to reduce the driving-voltage below that of the conventional planar-type electrodes and are suitable for modulation of exceeding 100 GHz and driving voltage of far less than 4 V under an optical wavelength of 1.55 μm and 50 Ω characteristic-impedance system. The ridge-type CPW can provide a broader bandwidth characteristic with a relatively thinner buffer layer and thinner electrode than the ridge-type A-CPS and is easier to fabricate. The ridge-type $LiNbO_3$ modulators are consequently candidate devices for future ultra-high-speed optical fiber transmission systems.**

I. Introduction

HIGH-SPEED $LiNbO_3$ optical modulators are essential for high-speed and long-haul optical fiber transmission systems using optical fiber amplifiers [1]–[4]. This is because the modulators eliminate the large wavelength chirping that occurs in high-speed direct modulation of laser diodes, a phenomenon that severely limits the system span-rate product. Two types of traveling-wave electrodes are widely used for high-speed $LiNbO_3$ modulators, coplanar waveguide (CPW) electrodes and asymmetric coplanar strip line (A-CPS) electrodes. The bandwidth of the traveling-wave type modulators is mainly restricted by the velocity mismatch between microwave and optical wave in the devices, which is caused by the high dielectric constant of $LiNbO_3$ itself. Various modulator structures for reducing this mismatch have been proposed [5]–[9] and developed, structures that introduce a shielding plane on the CPW electrodes [5] and structures making use of a thicker A-CPS or CPW electrode [6]–[9]. These methods, however, make the characteristic impedance of electrodes far lower than 50 Ω under a low driving-voltage condition. This is because the electrode capacitance increases markedly when the microwave effective-index becomes lower and achieves the velocity-matching condition. Furthermore, the modulation characteristics have not been numerically compared between the CPW and A-CPS electrodes, so that the suitability of the electrodes for high-speed modulators has not been clarified.

On the other hand, ridge-type modulators that introduce an etched $LiNbO_3$ substrate between the center and earth electrodes and that use a thicker SiO_2 buffer layer and CPW electrodes have been proposed recently [10]–[12]. These structures can reduce the electrode capacitance and increase the microwave field intensity at the Ti-diffused optical waveguides. The ridge-type modulators have consequently achieved broadband and relatively low driving-voltage characteristics of 40 GHz-3.6 V [11] and 75 GHz-5 V [12] in a system with characteristic-impedance of 50 Ω. To make a modulator with a broader bandwidth for future ultra-high-speed optical transmission systems, it is very important to clarify the optimum electrode structures for obtaining a lower conductor loss, velocity-matching, and impedance-matching in addition to a lower driving-voltage characteristic. Because the frequency response of modulators over 75 GHz range have been confirmed to be still limited by the electrode characteristics and not by any other effects such as dielectric loss, radiation loss or the Pockels effect of $LiNbO_3$ [11], [12].

This paper presents novel CPW and A-CPS electrode structures introducing thicker electrodes and a ridged-$LiNbO_3$ substrate. These structures for ultra-broad-band $LiNbO_3$ modulators are designed here by quasistatic analysis using the finite-element method and their modulation abilities are compared.

II. Analysis Model and Method

The schematic and cross-sectional configurations of proposed ridge-type $LiNbO_3$ Mach-Zehnder optical modulators with CPW or A-CPS electrodes are shown in Fig. 1. The ridge of depth t_r is formed in a z-cut $LiNbO_3$ substrate by dry-etching [12]. The gold electrodes of thickness t_m lie on the top of SiO_2 buffer layer of thickness t_b that is deposited on the ridged $LiNbO_3$ substrate. In the calculations, the relative dielectric constant of SiO_2 is 3.9, whereas the relative dielectric constant of the z-cut $LiNbO_3$ substrate is 28 perpendicular to the substrate surface and 43 parallel to it. The optical spot-sizes of the Ti-diffused optical waveguides are set to be 3.5 μm for perpendicular and 5 μm for parallel, and the operating optical wavelength is 1.55 μm. These spot-sizes are produced under standard Ti-diffusion conditions in our laboratories [13]. The optical waveguides have a low optical propagation-loss of less than 0.2 dB/cm. The center conductor width W and the gap G between the electrodes

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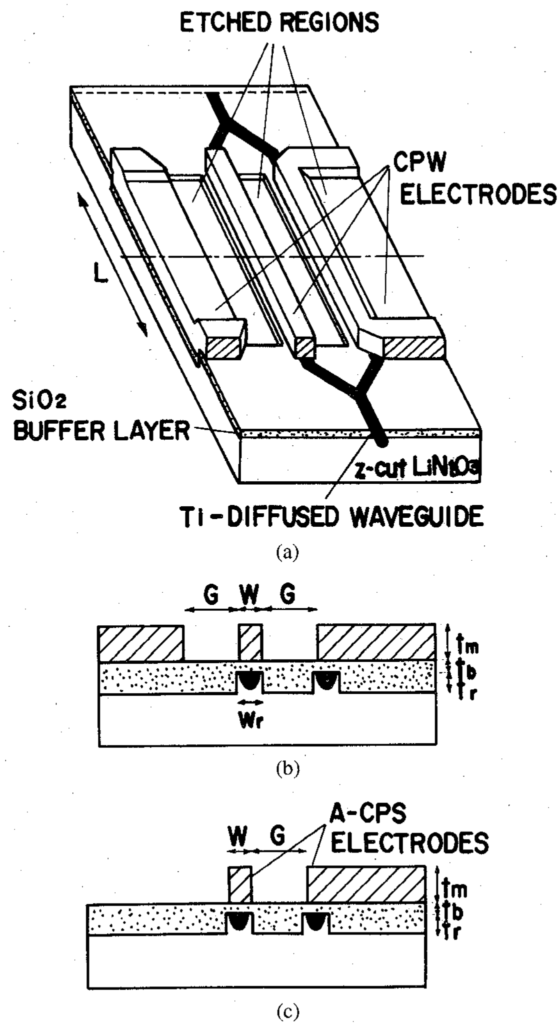

Fig. 1. (a) Schematic and (b) cross-sectional configurations of CPW electrodes and (c) cross-sectional configurations of A-CPS electrodes for ridge-type $LiNbO_3$ Mach-Zehnder optical modulators.

are, respectively, 8 and 15 μm. The W is almost the same as the optical spot-sizes for efficient modulation. The ridge width w_r is 9 μm, that is, slightly more than the optical waveguide width, in order to make the degradation of the optical propagation-loss negligibly small [12] in comparison to that of the conventional planar-type ($t_r = 0$) waveguide. As shown in Fig. 1(b) and (c), the top surface of the SiO_2 buffer-layer is assumed to be flat to simplify the numerical treatments. The structures are slightly different from the actual modulator shown in Fig. 1(a) but were confirmed by the numerical simulations to yield almost same results.

A quasistatic analysis using the finite-element method was used for numerical simulations on $LiNbO_3$ modulator structures. This analysis is considered to be effective for the anisotropic $LiNbO_3$ substrate up to several 10 GHz because the frequency dependency of microwave characteristics for a dominant mode has been confirmed to be negligibly small for the CPW electrodes by using the full-wave analyses [14]. Considering an effect of the dispersion on the microwave characteristics, the cross-sectional sizes of CPW and A-CPS electrodes are set sufficiently small compared with the electrical signal wavelength.

In the quasistatic analysis, the electric potential-distributions are first calculated from Laplace's equation with the finite-element method and the capacitances of electrodes are then obtained by using Gauss' theorem. The characteristic impedance Z and the effective index n_m are given by

$$Z = 1/[v_0 \cdot (C\,C_0)^{1/2}], \qquad (1)$$

$$n_m = (C/C_0)^{1/2} \qquad (2)$$

where C is the capacitance per unit length of the electrodes, C_0 is the free-space capacitance per unit length of the electrodes, and v_0 is the velocity of light in the free-space. For calculating the conductor loss α of electrodes, the incremental inductance formula [15] is used. That is

$$\alpha = \epsilon_0^{1/2} R_s(\partial Z_0/\partial n)/(2\mu_0^{1/2} Z), \qquad (3)$$

where $R_s = (\pi\,\mu_0 f \rho)^{1/2}$ and Z_0 is the free-space characteristic impedance of electrodes. $\partial Z_0/\partial n$ denotes the derivative of Z_0 with respect to incremental recession of electrode surfaces, R_s expresses the surface resistivity of the electrodes, f is the modulation frequency, and ρ is the metal resistivity. The driving voltage (half-wavelength voltage) V_π is calculated from the overlap-integrations between the microwave and optical wave fields.

III. Numerical Result and Discussion

To determine an optimum ridge depth for the $LiNbO_3$ optical modulators with CPW and A-CPS electrodes, we first investigated the effects of ridge depth on the modulation characteristics. The calculated microwave characteristics of the effective index n_m, the characteristic impedance Z and the conductor loss α_0 at $f = 1$ GHz ($\alpha = \alpha_0 \cdot f^{1.2}$) are shown in Fig. 2(a) as a function of the ridge depth for the CPW and A-CPS electrodes. In the figure, thicknesses of the buffer layer and the electrodes are, respectively, 1.2 and 10 μm. It is shown that for a certain thickness of buffer layer and electrode, n_m and α_0 decrease monotonously when the ridge depth increases, while Z increases for both CPW and A-CPS electrodes. As shown by (1)–(3), these are caused by the reduction of the electrode capacitance with increasing ridge depth.

Fig. 2(b) shows the product of the driving voltage V_π and the electrode interaction length L as a function of the ridge depth for the optical wavelength of 1.55 μm. The product $V_\pi \cdot L$ decreases as the ridge depth increases for the buffer layer thicknesses of 0.75 and 1.20 μm and becomes minimum at a depth between 3 and 4 μm. The decreasing $V_\pi \cdot L$ is caused by the concentration of lines of electric force at the ridged optical-waveguide regions, which is due to the surrounding $LiNbO_3$ substrate being replaced by the lower dielectric-constant materials SiO_2 and air and results in the electric field increasing. In the figure, the experimental values of $V_\pi \cdot L$ agree well with the calculations for CPW electrodes. Considering these results and the ease of fabricating devices with ridge structures, the optimum ridge depth for high-speed $LiNbO_3$ modulators is found to be 3 or 4 μm.

Figs. 3 and 4 show the effective index n_m, the characteristic impedance Z, the conductor loss α_0 at $f = 1$ GHz, and the

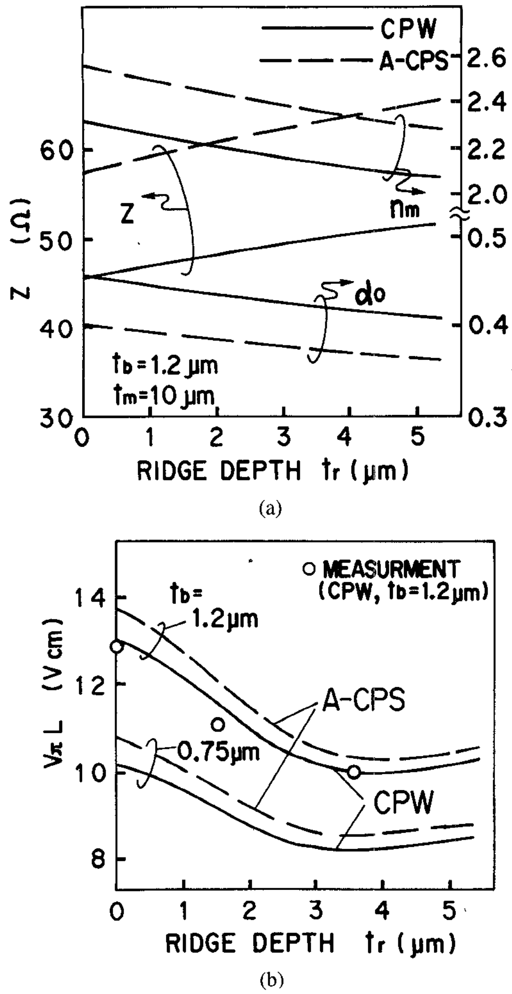

Fig. 2. Calculated results of (a) effective index n_m, characteristic impedance Z, and conductor loss α_0 at $f = 1$ GHz and (b) product $V_\pi \cdot L$ of driving voltage and electrode interaction length for an optical wavelength of 1.55 μm as a function of the ridge depth t_r for CPW (solid curves) and A-CPS (broken curves) electrodes.

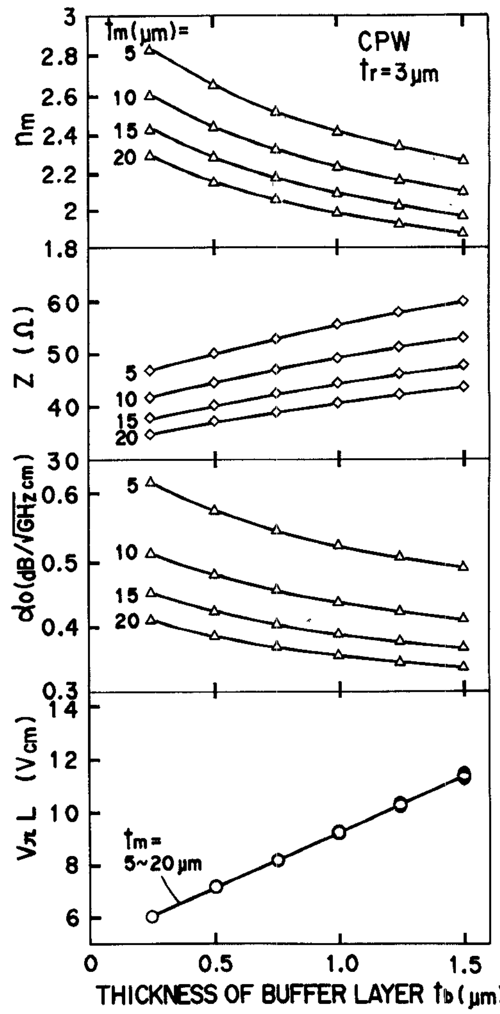

Fig. 3. Modulation characteristics of n_m, Z, α_0, and $V_\pi \cdot L$ as a function of buffer layer thickness t_b for CPW electrodes, where ridge depth is 3 μm.

$V_\pi \cdot L$ as a function of the buffer layer thickness t_b for the CPW and A-CPS electrodes when the ridge depth is 3 μm and the electrode thickness t_m is the parameter. The microwave characteristics n_m, Z, and α_0 depend strongly with both buffer layer and electrode thickness. The electrode thickness has, on the other hand, little effect on the driving voltage V_π, and the values of n_m and α_0 decrease as t_b and t_m increase. Z increases as t_b increases, whereas it decreases as t_m increases. Comparing Figs. 3 and 4 shows that for a certain thickness t_b and t_m, the values of n_m, Z, and $V_\pi \cdot L$ are remarkably smaller for the CPW electrodes than they are for the A-CPS electrodes, whereas the values of α_0 is slightly larger for the CPW electrodes than it is for the A-CPS electrodes.

For the velocity match between the microwave and optical wave, n_m needs to be n_o, which is the optical effective index of optical waveguide and which is 2.15 for the optical wavelength of 1.55 μm. It should, therefore, be noted in Figs. 3 and 4 that the velocity matching conditions can be easily produced by using the proper thicknesses t_b and t_m. Comparing those figures with Fig. 2(a) shows that when the t_r is 3 μm, the values of n_m and α_0 become less than, and the value of Z becomes remarkably larger than, those of the conventional planar-type ($t_r = 0$) modulators for the same buffer layer and electrode thicknesses. The ridge-type electrodes are thus more suitable than the planar-type electrodes for broader bandwidth modulators in systems with a characteristic-impedance 50 Ω.

The optical 3-dB modulation bandwidth Δf and the driving voltage V_π are shown in Figs. 5(a) and (b) as a function of the buffer layer thickness for the CPW and A-CPS electrodes using the ridged structure of $t_r = 3$ μm, where the interaction length of electrodes is fixed to be $L = 2.7$ cm. The optical 3-dB bandwidth Δf signifies here the 6-dB bandwidth of electrical response. These bandwidths were calculated considering the velocity mismatch, characteristic impedance mismatch, and conductor loss for the modulators. The frequency response of modulators had been confirmed to be still limited by the electrode characteristics and not by any other effects, such as dielectric loss of $LiNbO_3$ substrate, radiation losses or the Pockels effect of $LiNbO_3$ over 75 GHz range [11], [12]. Fig. 5 shows that the bandwidth can be increased significantly by using thicker electrodes and a thicker buffer layer. The maximum bandwidth under a constant electrode thickness is obtained at the velocity-matching condition ($n_m = n_o$). As

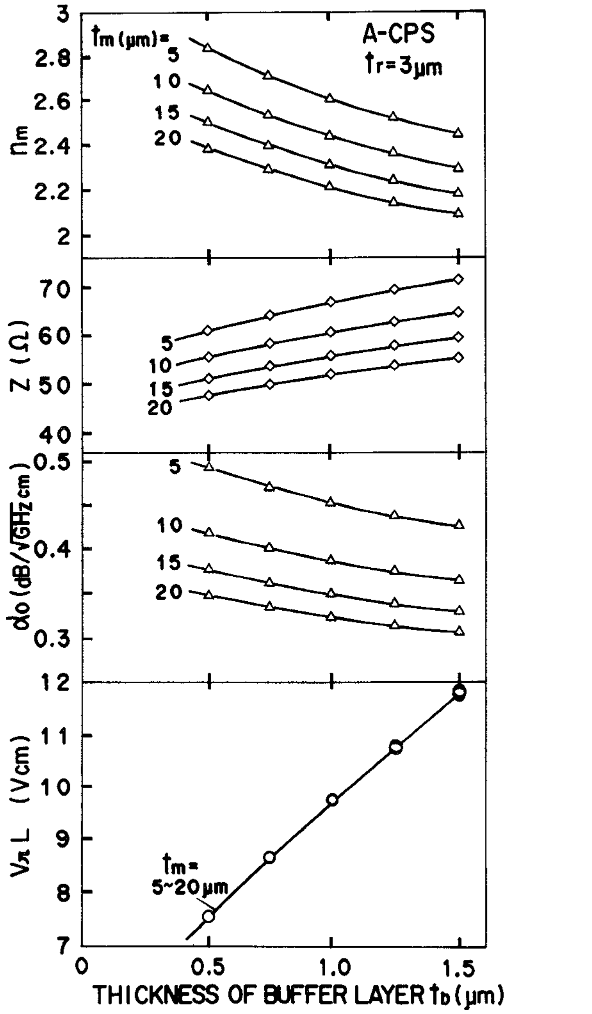

Fig. 4. Modulation characteristics of n_m, Z, α_0, and $V_\pi \cdot L$ as a function of buffer layer thickness t_b for A-CPS electrodes, where ridge depth is 3 μm.

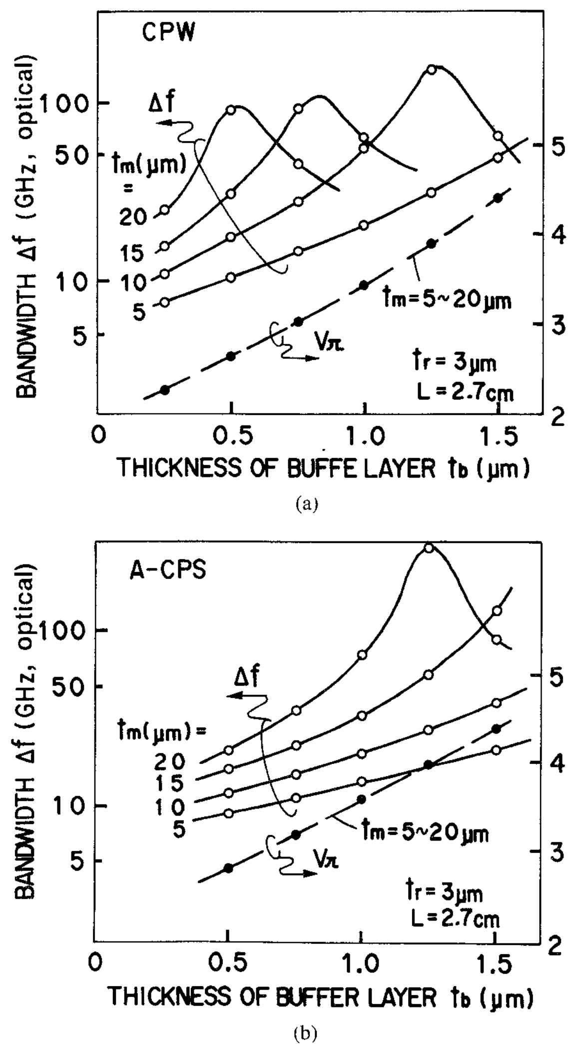

Fig. 5. Optical 3-dB bandwidth Δf and driving-voltage V_π as a function of the buffer layer thickness for (a) CPW and (b) A-CPS electrodes with the ridged structure of $t_r = 3$ μm and where the interaction-length of electrodes is $L = 2.7$ cm. The optical 3-dB bandwidth Δf signifies the 6-dB bandwidth of electrical response.

the buffer layer thickness increases, on the other hand, the driving voltage increases and the CPW electrodes are shown in Fig. 5(a) to have a potential of the maximum bandwidth exceeding 100 GHz under the driving voltages of far less than 4 V.

Fig. 5(a) and (b) shows that the CPW structure can, when the buffer layer and electrode are relatively thin, achieve a broader bandwidth than the A-CPS structure can. This means that a high-speed modulator using the CPW structure can be fabricated comfortably. The CPW confines the electric field near the electrodes more tightly than dose the A-CPS. The CPW can thus significantly reduce the electrical radiation-loss and is suitable for ultra-high-speed modulators. A ridge-type $LiNbO_3$ optical modulator using a CPW electrode with $tr = 3.4$ μm, $t_b = 1.2$ μm, $t_m = 10$ μm, and $L = 2.0$ cm has been fabricated and been measured to have a bandwidth of 75 GHz and a driving voltage of 5.0 V with its characteristic impedance is 50 Ω [12]. The A-CPS, however, is shown here to have a capability of broader bandwidth $\Delta f >\sim 100$ GHz under the driving voltage of $V_\pi = 4.0$ V when both buffer layer and electrodes become thick: $t_b = 1.25$ μm and $t_m = 20$ μm. For conventional planar-type A-CPS electrodes with $t_b = 1.25$ μm and $t_m = 20$ μm, the bandwidth and driving voltage were calculated to be $\Delta f = 37$ GHz and $V_\pi = 5.2$ V. Consequently, the ridged structures with either CPW or A-CPS electrodes are confirmed to be suitable for ultra-broad-band $LiNbO_3$ optical modulators with a lower driving voltage under a 50-Ω characteristic impedance condition.

IV. Conclusion

Electrode structures of CPW and A-CPS introducing ridged $LiNbO_3$ substrates and thicker electrodes have been presented for ultra-broad-band $LiNbO_3$ optical modulators. These structures were designed with quasistatic analysis using the finite-element method. Ridged structures with CPW and A-CPS electrodes were shown to be able to greatly reduce the driving voltage below that of conventional planar-type structures and to be suitable for ultra-broad-band modulation when the driving voltage is less than 4 V and the characteristic impedance is 50 Ω. The fabrication of the ridge-type high-speed modulators using CPW structures become easier than that using A-CPS structures, because the ridged CPW electrodes can provide a broader bandwidth with a relatively thin buffer layer and thin electrode. The ridge-type $LiNbO_3$ modulators with CPW and A-CPS are consequently confirmed to be candidate devices for future optical fiber transmission systems exceeding several tens gigabits per second.

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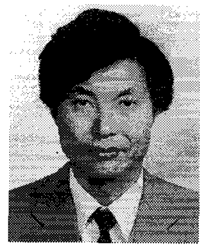

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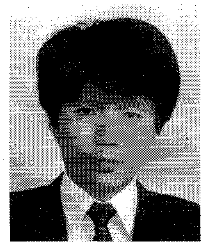

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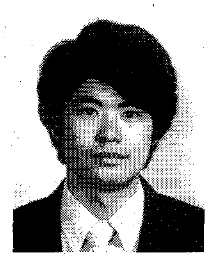

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