New Structure of SAW Resonator Filters on 64° YX $LiNbO_3$

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Abstract

The double mode SAW resonator filters have the serious shortcoming that out-of-band rejection above the passband is quite poor. Hence a new structure of the double mode filter is designed with the COM (Coupling Of MOdes) theory with better out-of-band rejection characteristics while keeping all the beauties of the conventional type. The second goal of the design is to reduce the planar size of the structure so that mass productivity of low frequency devices can be improved. For those purposes, several IDT's and relfector gratings are added to or subtracted from the conventional structure so that the modification can lead to better overall performance as a filter. As results of the investigation, several new double mode SAW resonator filter structures are developed. A new structure shows 10dB more out-of-band rejection that the conventional type with 25% reduced device size. Good agreement is demonstrated between the analytical results and experimental results for an illustrative 325 MHz four pole resonator filter on 64° YX $LiNbO_3$.

Ⅰ. Introduction

There has been a strong need for wide band and low loss devices in RF filters for telecommunication equipment such as hand held cellular phones and pagers. The role has been taken by dielectric resonator filters. Yet SAW filters have attracted intensive research for their superior amenability to mass production, good performance, and their greater compactness than the dielectric resonator filters. On the other hand, the transversal filters present the problem that the insertion loss is inevitable by bi-directional radiation of the SAW away from the transducer. This has caused the invention of double mode SAW resonator filters.

The invention of double mode longitudinally coupled SAW resonator filters occurred in 1992 with the work of T. Morita, et al [1]. In contrast to narrow band transversely coupled multiple pole SAW resonator filters, the double mode filters offer device operation with wide fractional bandwidth capabilities, low insertion loss, flat passband response, and low group delay ripple. However, they have the serious shortcoming that out-of-band rejection around the passband is quite poor. It means that in order to meet the specifications given by mobile telecommunication systems, the number of poles in cascade should be increased, which leads to more complicated device structures, difficulties in photo-lithography, larger device size, and so on. Hence we are developing new type double mode SAW resonator filters with better out-of-band rejection characteristics while keeping all the beauties of the conventioal structure. The second goal of the design is to reduce the planar size of the structure so that mass productivity of low frequency devices can be improved.

The new structure is designed with the COM (Coupling Of Modes) theory. Based on the conventional structure, several IDT's and reflector gratings are added to or subtracted from it. Simple addition of more reflectors or IDT's may induce harmful effects. Hence, the optimum combination of the reflectors and IDT's is sought to reach the goal of better out-of-band rejection without sacrificing all the other performances. In addition to the general new structure development, the effect of many design factors is investigated. This paper will first discuss the principles for analyzing longitudinally coupled resonator filters on the basis of computer simulation. It will then present modification of the structure and demonstrate the characteristics of the new filter employing a leaky SAW (LSAW) on a 64° YX $LiNbO_3$ substrate. The numerically investigated performances are achieved experimentally, and comparison between them is made.

Ⅱ. Transmission matrices of double mode SAW resonator filters

Figure 1 shows a typical structure of a dual mode

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longitudinally coupled SAW resonator filters where leaky SAW propagates underneath the metallized pattern. A leaky SAW on a 64° YX $LiNbO_3$ substrate has a large electromechanical coupling factor of 11% and also has a relatively large frequency/temperature coefficient of -70ppm/℃. This large frequency/temperature coefficient requires a wide operating frequency bandwidth. When these IDT's are connected as shown in the figure, the second longitudinal mode will no longer be excited so that it will be possible to configure a filter using only the first and third longitudinal modes. Even though Fig. 1 has a simple structure, a thorough analytical understanding is not available [2, 3, 4]. This paper analyzes characteristics of the double mode filter with modified COM theory [5, 6]. The COM theory has certain limitations when applied to the design of wide band devices [7]. However, it is still a good tool to predict the performance of SAW devices at a preliminary examination stage. In the COM theory, a transmission matrix relates the forward and backward traveling wave amplitudes at the left side of an element to those on the right side. Coupled mode theory is applied to derive the 2 × 2 transmission matrix relating the acoustic wave amplitudes at the input and output of a surface wave reflection grating as follows [2, 3, 4, 5].

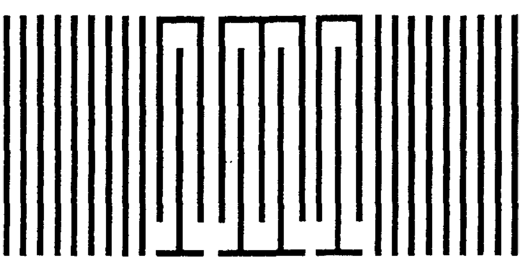


Figure 1. Conventional double mode SAW resonator filter structure.

$$G = \frac{\kappa_{12}}{\sigma}\cosh(\sigma L)$$

$$\begin{bmatrix} \left[\frac{\sigma}{\kappa_{12}} + i\left(\frac{\delta - i\alpha}{\kappa_{12}}\right)\tanh(\sigma L)\right]e^{i\beta L} & i\,e^{-i\phi}\tanh(\sigma L)\,e^{i\beta L} \\ -i\,e^{i\phi}\tanh(\sigma L)\,e^{-i\beta L} & \left[\frac{\sigma}{\kappa_{12}} - i\left(\frac{\delta - i\alpha}{\kappa_{12}}\right)\tanh(\sigma L)\right]e^{i\beta L} \end{bmatrix} \tag{1}$$

where $\sigma = [\kappa_{12}^2 - (\delta - i\,\delta)^2]^{1/2}$, κ_{12} = grating mutual coupling parameter = 0.0091 + 0.48(h/λ) for the 64° YX $LiNbO_3$ substrate, δ = detuning parameter = $2\pi(f - f_0)/v + \kappa_{11}$, κ_{11} = grating self-coupling parameter = 0.052 + 0.18 (h/λ) + 1.4(h/λ)^2 for the 64° YX $LiLbO_3$ substrate, α = grating attenuation coefficient, f = frequency, f_0 = center frequency of the IDT pattern, v = SAW velocity, L = length of the reflector grating, β = wave number, h = electrode thickness, λ = SAW wavelenght, and θ = phase angle.

The transmission matrix T of an IDT is also found by manipulating the well known admittance matrix based on a Mason equivalent circuit model. Using the results of Smith, et al. [5], and including an effective series electrode resistance R, T is given by

$$T = \begin{bmatrix} (1+t_0)e^{i\theta_t} & -t_0 & s\,t_{13} \\ t_0 & (1-t_0)e^{-i\theta_t} & s\,t_{13}e^{-i\theta_t} \\ t_{13} & -t_{13}e^{-i\theta_t} & s\,t_{33} \end{bmatrix} \tag{2}$$

where $s = (-1)^{N_t}$, $t_0 = \frac{G_r(R_s + Z_c)}{1 + i\,\theta_c}$, $t_{13} = \frac{\sqrt{2 G_r Z_c}}{1 + i\,\theta_c}e^{i\theta_t/2}$, $t_{33} = 1 - \frac{2i\,\theta_c}{1 + i\,\theta_c}$, N_t = number of electrodes in the transducer, G_r = transducer radiation conductance, R_s = combined IDT metal and lead resistance, Z_c = load resistance or source resistance, $\theta_c = (\omega C_T + B_r)(R_s + Z_c)$, ω = angular frequency, B_r = transducer radiation susceptance, $\theta_t = N_t \Lambda \delta$, Λ = reflector repetition period, $\theta_c = (\omega C_T + B_r)$, and C_T = total IDT capacitance.

The 2 × 2 transmission matrix of the transmission line between each of the active elements, IDT's and reflector gratings, is in such a simple form as

$$P = \begin{bmatrix} e^{i\beta L_d} & 0 \\ 0 & e^{i\beta L_d} \end{bmatrix} \tag{3}$$

where L_d is the length of the transmission line.

These transmission matrices provide the means to calculate the properties of a cascaded structure of gratings and transmission lines. Once the transmission matrices are set up, the external transmission through a SAW resonator is found by matrix multiplication. Modification of the structure in Fig. 1 can be easily simulated by manipulation of the matrices. The transmission matrices derived in this paper reflect all the theories suggested by C. K. Campbell [2], and C. S. Hartmann [7]. That is, the elements of the matrices are properly updated to include SAW velocity dispersion, SAW attenuation increase due to scattering, radiation of bulk waves, and SAW reflectivity change at the reflector gratings.

3. New type double mode SAW resonator filters

The structure in Fig. 1 in four pole configuration, two channels in cascade, is simulated with the above mentioned transmission matrices, and the theoretical and experimental results are shown in Fig. 2. The Fig. 2(b) is the measurement result of the device fabricated following all the configurations of Fig. 1. for this comparison. The middle input IDT has eighteen finger pairs, and the two outer IDT's hae eleven finger pairs, respectively. Each reflector grating has seventy five fingers. All the other specifications follow those of Ref. 1. There is a close agreement between the two results with some discrepancy below the passband. As shown, the structure in Fig. 1 offers device operation with wide fractional bandwidth capabilities, low insertion loss, and flat passband response. However, it has the serious shortcoming that out-of-band rejection above the passband is quite poor. It means that in order to meet the specifications required by mobile telecommunication systems, the number of poles in cascade should be increased, which leads to more complicated device structures, difficulties in photolithography, larger device size, and so on. Hence new structures of double mode SAW resonator filters are developed with the transmission matrices. The development is made with the philosophy that several IDT's, reflector gratings, or transmission lines are added to or subtracted from the basic structure in Fig. 1 so that the goal of better out-of-band rejection is attained without sacrificing all the other performances. Simple addition of more reflectors or IDT's may induce harmful effects. Hence, the optimum combination of the reflectors and IDT's is sought to reach the goal. In addition, the effect of many design factors is investigated and their optimum values are determined. We have checked the effects of the nine design design factors: the number of reflectors, width of the reflectors, open or short states of the reflectors, reflector finger metallization ratio, spacing between the reflector fingers, number of IDT fingers, IDT apodization pattern, separation between the IDT and the reflector grating, and electrode thickness. Based on the results, fairly many new configurations have been attempted and several successful modifications are presented.

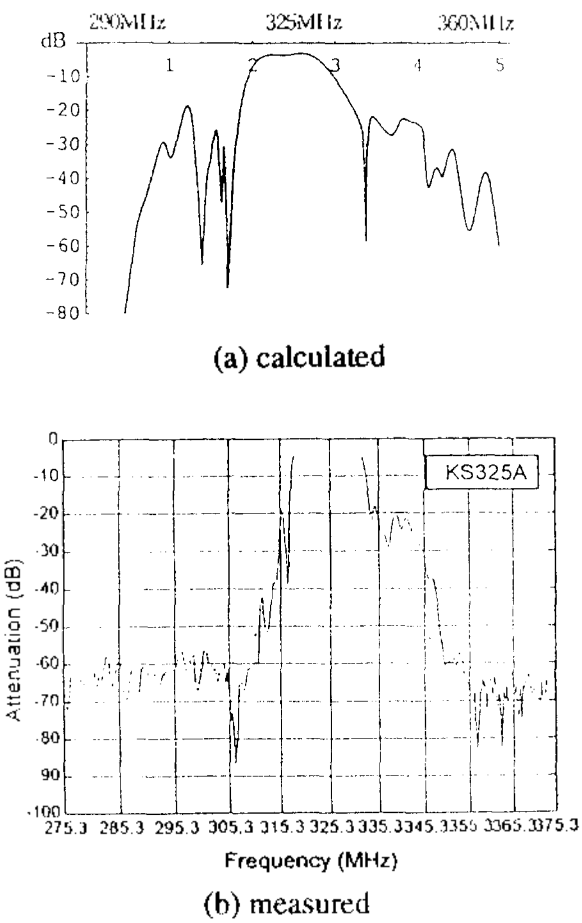


Figure 2. Frequency responses of the conventional double mode SAW resonator filters in Fig. 1, (a)calculated, (b) measured.

The first modification is the insertion of a quarter wave transmission line into the middle of each reflector grating. The configuration is otherwise the same as those in Fig. 1. Figure 3 shows the structure with the quarter wave transmission line insertion. According to P. S. Cross, et al

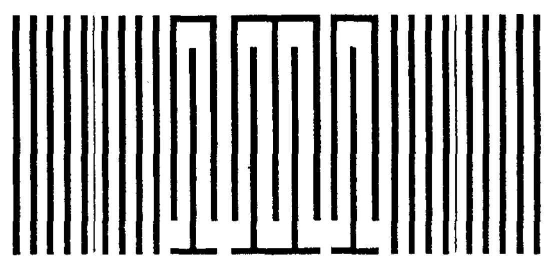


Figure 3. Structure of double mode SAW resonator filter with the insertion of a quarter wave transmission line in the middle of each reflector grating.

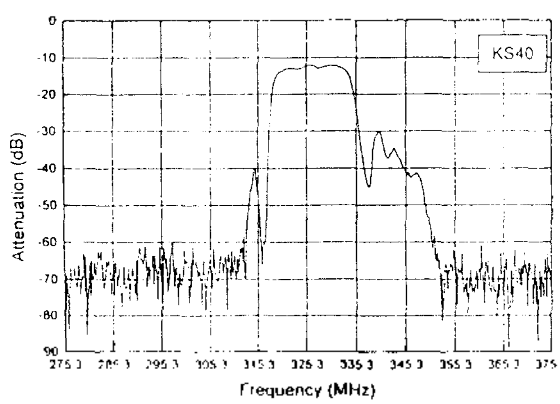


Figure 4. Experimental frequency responses of the SAW resonator filter in Fig. 3.

[5], this kind of modification leads to operating bandwidth increase and sidelobe magnitude decrease of the device. Experimental results are shown in Fig. 4. Increased insertion loss is due to the impedance mismatching between the SAW filter and the measurement instrument, not to the filter performance. In comparison with Fig. 2, overall performance is quite similar to each other. However, at right below and above the passband, significant reduction of the sidelobe is observed. Below the passband, that reduction amounts to about -10dB. Bandwidth of -3dB reduction is increased by 6% in comparison with Fig. 2(b).

Second modification is the addition of an IDT to the outer side of each existing reflector grating, as shown in Fig. 5. The reflector grating has twenty fingers and each of the new outer IDT's has three finger pairs. The problem with the basic structure of Fig. 3 is that we have to have a fairly large number of fingers in the reflector grating in order to get sufficient reflection. For high frequency devices such as those working at 900 MHz and above, device size may not matter so much. However, for devices such as 325 MHz filters for pagers, smaller size is of great importance because it is directly related to its mass productivity. For reduction of the device size, the number of reflector fingers should be reduced, which results in poorer performance of the device, i.e., a larger insertion loss. Hence, for smaller devices, some better idea must be employed. The point of devising the new structure in Fig. 5 is that, with a smaller number of reflector fingers, the remaining unreflected SAW can be intercepted by the new IDT's. The intercepted SAW energy is transferred to the second resonator channel, where the newly IDT's work as additional SAW generators. With fewer reflector fingers, the level of SAW energy confinement within the resonator pattern may get poorer. However, part of the unreflected energy is intercepted by the new IDT's, and is utilized to regenerate SAW at the lower channel. Regenerated SAW can compensate for some of the energy lost due to the insufficiency of reflector fingers. Figure 6 shows the frequency responses of the new structure. Much improvement is observed around the passband, quite much reduction of the sidelobe at just below the main lobe. However, a fairly large side lobe occurs in the region where the response used be flat. This undesirable sidelobe generation is supposed to be due to the insufficiency of reflector fingers. Further, the problem with this structure is that in the second resonator channel, each of the newly added IDT's have to lose half of its radiated energy due to its bidirectionality.

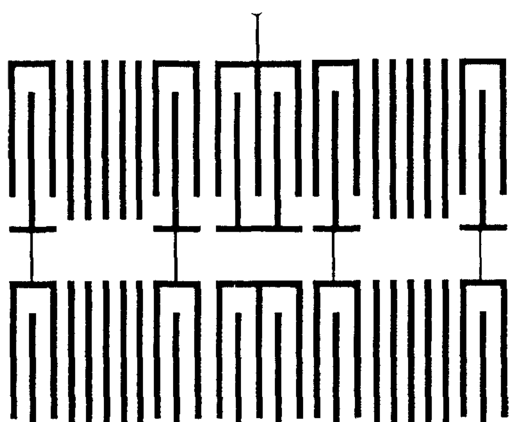
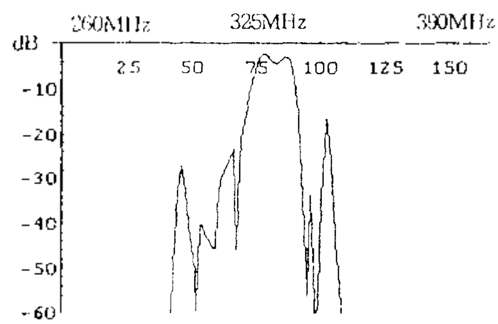
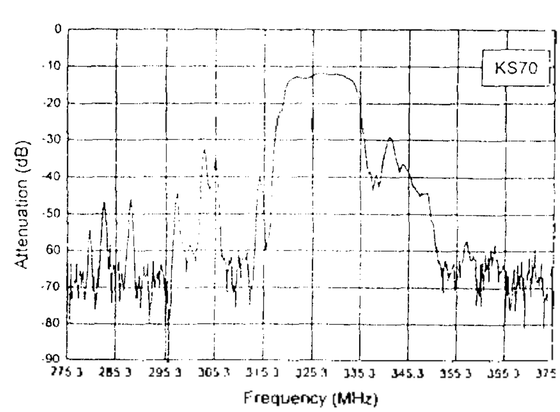


Figure 5. Structure of a double mode SAW resonator filter with the addition of a IDT to outer side of each existing reflector grating.



(a) calculated



(b) measured

Figure 6. Frequency responses of the SAW resonator filter in Fig. 5. (a) calculated, (b) measured.

Compromise for this problem is made by adding one more reflector grating next to each of the new IDT's as shown in Fig. 7. The newly added reflector has ten fingers. The structure is, in some sense, similar to the interdigitated IDT(IIDT) configuration consisting of a series of IDT's alternately connected to the electrical input and output ports [8]. The structure in Fig. 7 results form the addition of a set of a reflector grating and an IDT to the basic structure. In this configuration, more and more set of them continue to be added. In the IIDT design, each IDT works as either input or output transducer alternately. In the structure of Fig. 7, only the central IDT receives the external electrical energy. Figure 8 is the photograph of the device with the pattern in Fig. 7, while Fig. 9 is the results from the analysis of Fig. 7 structure. Compared with Fig. 6, the magnitude of the sidelobes is much reduced. In comparison with the results in Fig. 4, some enhancement is observed above the passband, about -5dB. If we increase the number of fingers in the outermost reflector grating, more reduction of the sidelobes is expected. The structure in Fig. 7 sizes about 75% of that in Fig. 3. Hence, these results confirm that the goal of more sidelobe reduction with smaller device size has been reached with the new pattern in Fig. 7.

The results of Figs. 6 and 9 were obtained after optimization of various design factors mentioned above. Of the nine factors investigated in this paper, most of them turned out to have the same values as those in Refs. 1 and 2. However, for Fig. 9, the effect of two factors-the number of IDT fingers and the number of reflector fingers-is new and is presented here. The number of IDT fingers does not have much effect on the passband shape of the filter. However, as the number increases for fixed reflector gratings, the magnitude of sidelobes increases gradually. Figure 10 shows the change of sidelobe magnitude with IDT finger numbers. On the other hand, as the number of reflector fingers increases, the passband gets more and more flat, and the insertion loss gets smaller

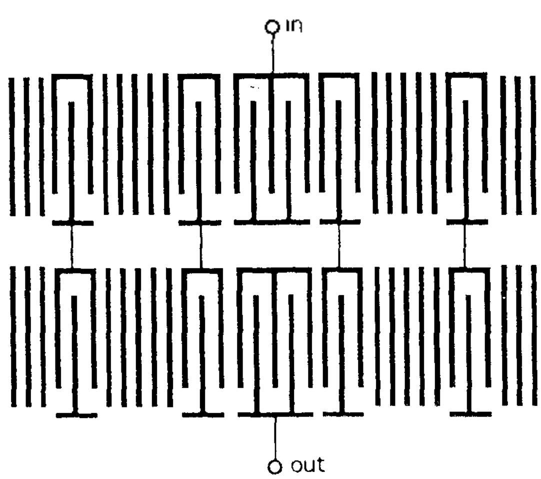


Figure 7. Structure of a double mode SAW resonator filter with the addition of one more set of a reflector grating and an IDT to outer side of each existing reflector grating.

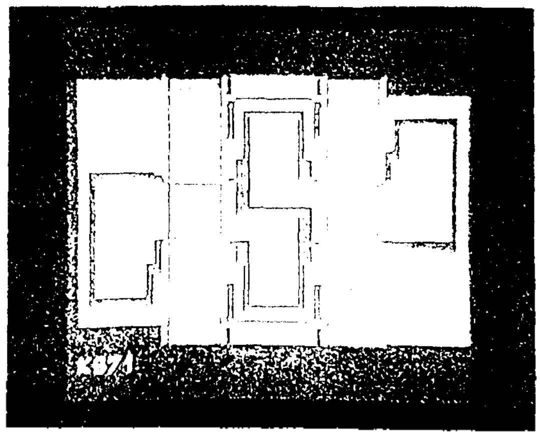


Figure 8. Photograph of a fabricated double mode SAW resonator filter with the pattern in Fig. 7.

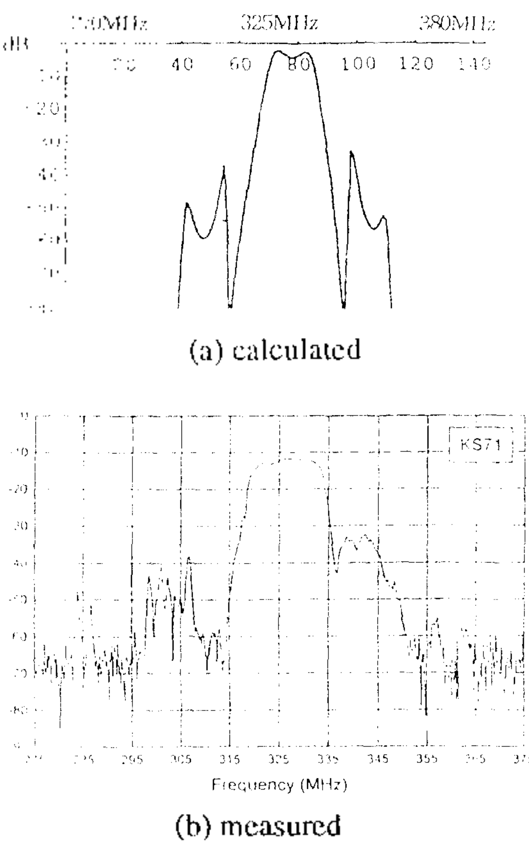


Figure 9. Frequency responses of the SAW resonator filter structure in Fig. 7. (a) calculated, (b) measured.

and smaller. However, as expected [1], above a certain number of reflector fingers, this effect is saturated, and no more improvement is observed. The saturation number is ten for the configuration in Fig. 7.

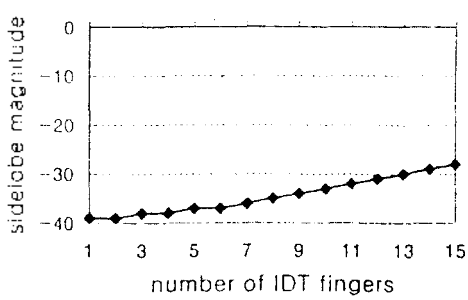


Figure 10. Change of sidelobe magnitude with the number of IDT fingers.

Ⅳ. Conclusion

In order to overcome the shortcomings of conventional double mode SAW resonator filters, we attempted to develop new structure of the filter with better out-of-band rejection characteristics while keeping all the beauties of the conventional structures. It was further attempted to reduce the planar size of the structure so that mass productivity of low frequency devices could be improved. The new structure was designed with the COM (Coupling Of Modes) theory. Based on the conventional double mode filter structure, several IDT's and reflector gratings were added to or subtracted from it. As results of the investigation, several new double mode SAW resonator filter structures were developed. Some of the structures had 10dB more out-of-band rejection characteristics than the conventional type with 25% smaller device size. Good agreement was demonstrated between the analytical results and the experimental results for an illustrative 325 MHz four pole resonator filter on 64° YX $LiNbO_3$.

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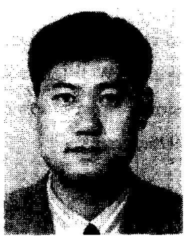

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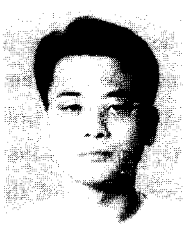

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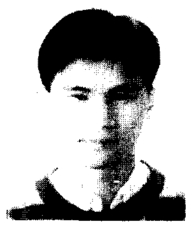

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