# A Coupled-Line Type Waveguide Bandpass Filter using Normalized Impedance Concept

Jun-Seok Park[1] · Young-Tae Kim[2] · Sun-Hyeong Kim[2] · Jae-Bong Lim[1] · Hong-Goo Cho[1]

## Abstract

In this paper, a coupled-line type waveguide bandpass filter is newly proposed. The proposed bandpass filter configuration consists of magnetically coupled waveguide cavities. In order to show the background of the proposed waveguide bandpass filter, the general coupled line TEM bandpass filter theory, which means the coupled line filter with arbitrary coupled line length and impedance level, will be briefly introduced. Calculations for the even- and odd-mode wave impedance of a coupled line waveguide structure are achieved based on the normalized impedance concept for a broad-side coupled waveguides by using vector finite element method(VFEM) calculation. Measured result of an implemented coupled-line type waveguide filter is presented.

***Key words*** : Waveguide Bandpass Filter, Normalized Impedance Concept, Vector Finite Element Method.

## Ⅰ. Introduction

Waveguide components such as filters, couplers, combiner and so on have been most widely used for various microwave and millimeter wave applications. Moreover, increasing various wireless communication systems lead to a higher level of frequency selectivity with high quality of filter performance. Demanding this high quality of waveguide filter performance have led to various design and implementing efforts to have more improved filter characteristics such as losses, attenuations, volume and so on. Especially, in case of waveguide filters overall size of waveguide section is one of limitations to several applications. Many recent works have reported and outlined the design theories and implementing technology such as multi-mode waveguide filters to overcome several problems and limitations[1],[2]. Despite of many advantages, multi-mode waveguide filters have difficulties such as a complicate design procedure and poor loss characteristics due to degradation of unloaded quality factor of a degenerated mode, which is required to implement multi-mode performance. In this paper, "a coupled-line type" waveguide bandpass filter is newly proposed. Configuration and equivalent circuit of the presented waveguide filter are based on TEM-mode coupled line filter, which has arbitrary coupled line length and resonator impedance. In case of a conventional direct-coupled waveguide filter, electromagnetic coupling between resonators is implemented by longitudinal direction. Thus, the over all length of conventional waveguide filters intensively depends on the number of resonator. On the other hand, the proposed waveguide filter has parallel-coupled resonator configurations, which gives rise to mainly magnetic couplings between cavities. The parallel-coupled configuration of presented filter provides reduction in overall length of waveguide filter. Furthermore, the magnetic coupling due to the parallel-coupled line configuration can improve the spurious characteristics of waveguide bandpass filter. In this paper, we present an experimental data of the implementation of the proposed 6-section coupled-line type waveguide bandpass filter, as well as normalized impedance concept using directly propagation constant to extract exact design parameters, which mean the even- and odd-mode impedance for coupled waveguide structure.

## Ⅱ. Parallel Coupled-Line Type Filter with Arbitrary Coupled Length and Impedance

Fig. 1 shows the proposed parallel coupled-line type

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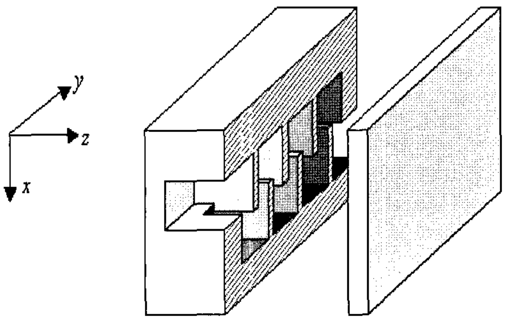



Fig. 1. Proposed parallel coupled-line type waveguide bandpass filter configuration.

waveguide bandpass filter configuration. The proposed parallel coupled-line type waveguide bandpass filter is composed of shorted waveguide cavities with coupling sections located in broad wall of waveguide. Each shorted waveguide cavity has a half-guided wavelength at the center frequency. Meanwhile, the length of coupling section should be less than quarter-wavelength at the center frequency because those non-adjacent cavities are separated by finite thick E-wall as shown in Fig. 1. Thus, the proposed coupled-line type waveguide bandpass filter has non-quarter-wavelength coupled sections with identical resonator impedance values. The coupling scheme is based on the aperture in broad wall of a waveguide, which is excited by y-directed electric dipole and x-and z-directed magnetic dipoles[3].

The equivalent circuit of the proposed waveguide bandpass filter can be represented by a parallel coupled-line bandpass filter with arbitrary coupled-line length and impedance levels. In order to explain the filtering phenomena of the proposed coupled-line type waveguide bandpass filter, it requires the synthesis procedure for a parallel coupled-line section with arbitrary coupled-line length and characteristic impedance based on TEM-mode as shown in Fig. 2. Fig. 2 (a) shows the equivalent TEM-mode resonator with non-quarter wavelength coupled-sections for an coupled-line type waveguide cavity section. The resonator section shown in Fig. 2(a) has either an uniform characteristic impedance or not. Meanwhile, Fig. 2(b) shows the equivalent inverter model for non-quarter wavelength coupled-section, as well as the equivalent resonator model. In case of the proposed waveguide bandpass filter, the characteristic impedance of the resonator is uniform. Then the reactance of a resonator

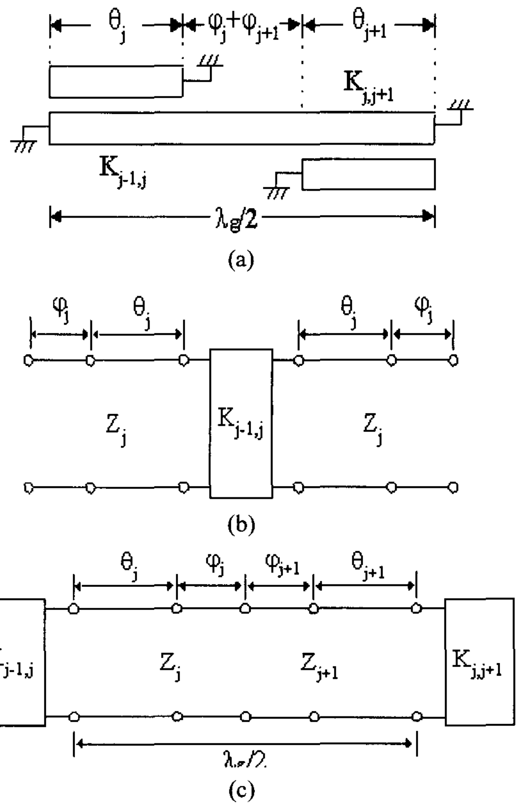



Fig. 2. Parallel coupled-line sections with arbitrary coupled-line length and characteristic impedance.
(a) TEM-mode parallel coupled-line resonator model with two coupled-section
(b) Equivalent inverter model for a coupled-line section
(c) Equivalent resonator model with inverters

is given by

$$jB_{rj} = jZ_j \tan(\theta_j + \beta_j) \quad (1)$$

where,

$$\beta_j = \tan^{-1}\left( Z_{j+1}/Z_j \tan(\theta_{j+1} + \alpha_j) \right)$$

and

$$\alpha_j = \tan^{-1}\left( Z_{j+2}/Z_{j+1} \tan\theta_{j+2} \right)$$

Furthermore, based on the reactance of a resonator, the inverter formula can be expressed as follow

$$K_{0,1} = \frac{Z_1}{Z_A}\sqrt{\frac{\pi\omega Z_1 Z_A}{2\omega_1' g_0 \cdot g_1}} \qquad K_{j,j+1} = \frac{Z_{j+1}\pi\omega}{2\omega_1'}\sqrt{\frac{1}{g_j \cdot g_{j+1}}}$$

$$K_{n,n+1} = \frac{Z_{n+1}}{Z_B}\sqrt{\frac{\pi\omega Z_{n+1} Z_B}{2\omega_1' g_n \cdot g_{n+1}}} \quad \text{for} \quad j=2,\ 3,\cdots n-1 \tag{2}$$

where $Z_A$ and $Z_B$ mean the in- and out- terminated impedances of a bandpass filter, respectively. Also, $g_i$'s in (2) mean the element values of the prototype lowpass filter. By employing the inverter formula, we can design the parallel coupled-line waveguide bandpass filter.

The even- and odd-mode line impedance can be expressed as follow

$$Z_{0e} = \sqrt{\frac{Z_1^2\cos^2\theta_1 + K^2\sin^2\theta_1}{Z_1^2\sin^2\theta_1 - K^2\cos^2\theta_1\{4Z_1^2K^2 - \sin^2 2\theta_1(2Z_1^2K^2 + (Z_1^2+K^2))\}}}\cdot Z_1\sin\theta_1(Z_1 K + (Z_1^2+K^2))$$

$$Z_{0o} = \sqrt{\frac{Z_1^2\cos^2\theta_1 + K^2\sin^2\theta_1}{Z_1^2\sin^2\theta_1 - K^2\cos^2\theta_1\{4Z_1^2K^2 - \sin^2 2\theta_1(2Z_1^2K^2 + (Z_1^2+K^2))\}}}\cdot Z_1\sin\theta_1((Z_1^2+K^2) - Z_1 K) \tag{3}$$

## Ⅲ. Normalized Impedance using VFEM

To extract design parameters, we analysis coupled-line type waveguide by using VFEM calculation. This paper deals with VFEM eigenvalue problem[4] using electric field intensity to extract the even- and odd-mode wave impedance for a coupled-line waveguide structure.

The vector potential $E_1$. satisfies the Helmholtz equation with wave number $k_0$

$$\nabla_1\times\left(\frac{1}{\mu_r}\nabla_1\times E_1\right) - k_0^2\varepsilon_r E_1 = 0 \tag{4}$$

where $\varepsilon_r$ and $\mu_r$ are the permeability and permittivity of the microwave device, respectively. The representative variational functional for such a problem is given by

$$F(E) = \frac{1}{2}\iint_\Omega\left[(\nabla_t\times E)^* - k_0^2 E\varepsilon_r E^*\right]d\Omega \tag{5}$$

Assuming that the dependence of the fields in the z-direction is $e^{-jk_oz}$, the functional can be written in terms of the transverse and the longitudinal fields similar to ;

$$F(E) = \frac{1}{2}\iint_\Omega\Big[(\nabla_t\times E)\mu_r(\nabla_t\times E)^* - k_0^2(E_t\varepsilon_r E_z^*) + (\nabla_t E_z + jk_z E_t)\mu_r(\nabla_t E_z + jk_z E_t)^*\Big]d\Omega \tag{6}$$

where $\nabla_t$ Nt is the transverse del operator; these field components can be subsequently expanded as a summation of scalar and vector basis functions. For obtaining more accurate solutions, the second-order vector elements are applied[5].

$$e_1 k_z E_1 = \sum_{i=1}^{n} N_1^e e_{ti}^e \tag{7}$$

$$e_z = -jE_z = \sum_{i=1}^{n} N_1^e e_{zi}^e \tag{8}$$

where $n$ denotes the number of degree of freedom in each element which is 9 as shown in Fig. 3.

The element matrices are given by

$$S_{el(tt)} = \frac{1}{\mu_r}\iint_\Delta(\nabla_t\times N)\cdot(\nabla_t\times N)ds - k_0^2\varepsilon_r\iint_\Delta(N_{tm}\cdot N_m)ds \tag{9}$$

$$T_{el(tt)} = \varepsilon_r\iint_\Delta(N_{tm}\cdot N_m) \tag{10}$$

$$T_{el(tz)} = \frac{1}{\mu_r}\iint_\Delta(N_{tm}\cdot\nabla L_j)ds \tag{11}$$

$$T_{el(zt)} = \frac{1}{\mu_r}\iint_\Delta(\nabla L_i\cdot N_m)ds \tag{12}$$

$$T_{el(zz)} = \frac{1}{\mu_r}\iint_\Delta(\nabla L_i\cdot\nabla L_j)ds - k_0^2\varepsilon_r\iint_\Delta L_i L_j ds \tag{13}$$

These element matrices can be assembled over all the triangles in the cross section of the waveguide to obtain a global eigenvalue equation.

$$\begin{bmatrix} S_n & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} e_1 \\ e_z \end{bmatrix} = (-\beta^2)\begin{bmatrix} T_{tt} & T_{tz} \\ T_{zt} & T_{zz} \end{bmatrix}\begin{bmatrix} et \\ ez \end{bmatrix} \tag{14}$$

After solving the eigenvalue problem given in (14) at each frequency point, the propagation constant in the z-direction and the corresponding normalized transverse and longitudinal fields inside the structure can be obtained. Both the propagation constant and the fields are needed for the calculation of the characteristic impedance. The characteristic impedance is given by

$$Z_c = \frac{VV^*}{2P}\ ,\quad P = \sum_{i=1}^{N} P_i \tag{15}$$

where $V$ is the voltage difference, $P_i$ is the power

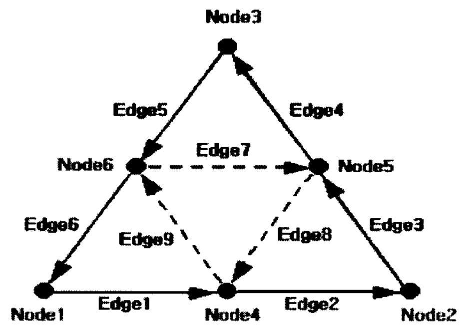



Fig. 3. The second-order triangular vector shape function.

calculated in each element, $P$ is the total power flowing in the z-direction, and $N$ is the number of finite elements in the domain of interest. The elemental power $P_i$ is given by the Poynting vector

$$Pi = \frac{1}{2}\mathrm{Re}\left[\iint_{\Delta} E_i \times H_i^* \cdot \hat{a}_z ds\right] = \frac{1}{2}\mathrm{Re}\left[\iint_{\Delta}\left(E_x H_y^* - E_y H_x^*\right) ds\right] \quad (16)$$

where the magnetic field components $H_x$ and $H_y$ are calculated directly from Maxwell's equations. Generally, the characteristic impedance using VFEM is obtained by additional calculation such as voltage difference and power calculation etc.

In order to save computing time, the normalized impedance concept using directly propagation constant is newly proposed. Calculations for the even- and odd-mode wave impedance of a coupled line waveguide structure are used to apply normalized impedance concept.

Fig. 4 shows coupled-line type waveguide bandpass filter configuration for normalized even- and odd-mode wave impedance. The characteristic impedance is defined as $Z = \omega\mu/\beta$, propagation constant ($\beta$) can be directly calculated from VFEM.

The wave impedance of the even mode $Z^e_{TE10}$ and odd mode $Z^0_{TE10}$ can respectively be obtained by propagation constant of even- and odd-mode.

$$Z^e_{TE10} = \frac{\omega\mu}{\beta^e_{TE10}} \qquad Z^o_{TE10} = \frac{\omega\mu}{\beta^o_{TE10}} \quad (17)$$

The normalized characteristic impedance of even-and-odd mode can be defined as

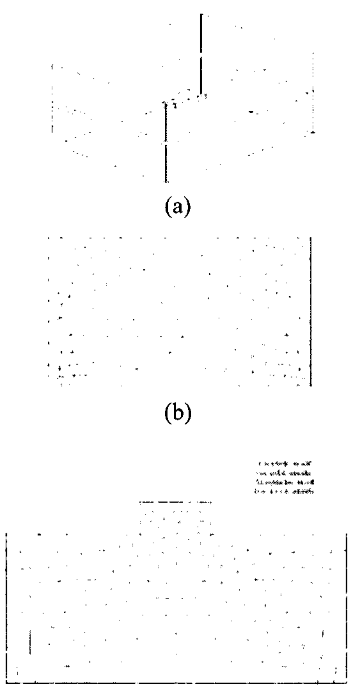
$$\bar{z}^e_{TE10} = \frac{Z^e_{TE10}}{Z_{TE10}} = \frac{\beta_{TE10}}{\beta^e_{TE10}} \qquad \bar{z}^e_{TE10} = \frac{Z^o_{TE10}}{Z_{TE10}} = \frac{\beta_{TE10}}{\beta^o_{TE10}} \quad (18)$$

To calculate characteristic impedance using 2-D VFEM analysis, we have no need to be conversion and can apply directly propagation constant, so that this method make it possible to save computing time for characteristic impedance extraction.

The coupling constant  is defined by

$$C = \frac{\bar{z}^e_{TE10} - \bar{z}^o_{TE10}}{\bar{z}^e_{TE10} + \bar{z}^o_{TE10}} \quad (19)$$

Using the concept described above to extract design parameter of coupled-line waveguide, Calculation of the design parameter is a hightly efficient and exact because of applying directly the propagation constant for calculating characteristic impedances for each mode.



(a)

(b)

(c)

Fig. 4. (a) 3-D coupled line waveguide configuration
(b) Rectangular waveguide mesh configuration for VFEM calculation
(c) 2-D waveguide mesh configuration for VF-EM calculation

## Ⅳ. Implementation and Experiments

In order to show the validity of the presented design formula for waveguide coupled-line bandpass filter, we have designed the six-section coupled-line type waveguide bandpass filter with center frequency of 20 GHz, insertion loss of 0.01 dB, bandwidth of 0.75 %.

In this paper, the six-section coupled-line type waveguide bandpass filter was designed to verify the proposed waveguide bandpass filter model. Fig. 5 depicts the schematic layout of the proposed parallel coupled-line type waveguide bandpass filter. Design results for the given specifications are shown in table 1. The coupled-line sections are chosen to be less than quarter-wavelength because that finite thick E-wall for isolations of non-adjacent cavities requires 1.5 millimeters thick. Having determined the waveguide dimension, the waveguide dimensions according to coupling coefficient are calculated by equation (19) using normalized impedance concept. To compare the

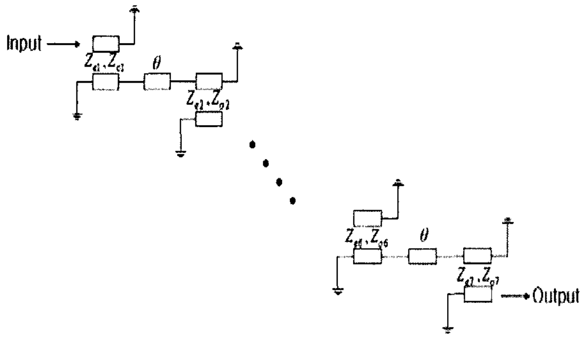



Fig. 5. Schematic of parallel coupled-line type waveguide bandpass filter.

proposed waveguide filter to double E-plane waveguide filter with excellent bandpass filter performances, we designed double E-plane waveguide filter. Fig. 7 shows the longitudinal cross section of double E-plane coupled-line type waveguide bandpass filter. It has sizes of 10.67 mm×4.3 mm×90.46 mm.

Fig. 8 shows the measurement on the fabricated coupled-line type waveguide bandpass filter. The measured results show excellent bandpass filter performances. The minimum passband insertion loss for an equal-ripple filter was approximately 2 dB with good matching performance. Insertion loss characteristic can be improved by surface coating process with an excellent conductive paste such as silver or gold. Furthermore, the measurement shows more steep attenuation performance of upper stopband than that of lower stopband frequency region. It is well known that bandpass filters designed with waveguide have poor stopband attenuation at the upper frequency region of passband because that an increasing amount of power is carried by parasitic or higher order modes across the coupling sections[6],[7]. The steeper attenuation performance at upper stopband is a notable advantage of the proposed coupled-line type waveguide bandpass filter with compact size reduction.

Fig. 9 shows photographs of the fabricated coupled-line type waveguide bandpass filter, which has sizes of

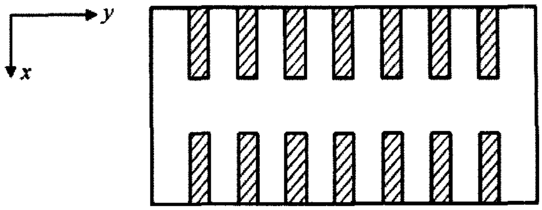



Fig. 6. The longitudinal section of a six-section coupled-line type waveguide bandpass filter.

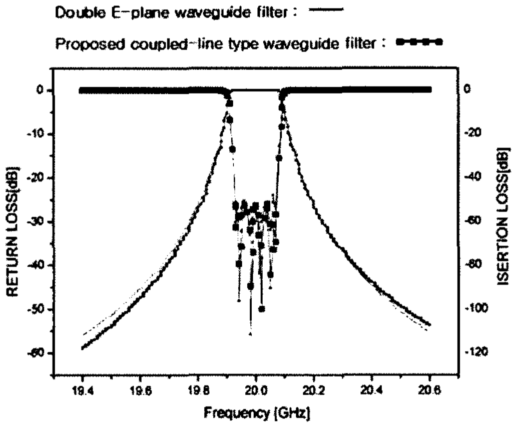



Fig. 7. Comparison of the EM-simulation of double E-plane waveguide filter and coupled-line type waveguide filter of the proposed configuration.

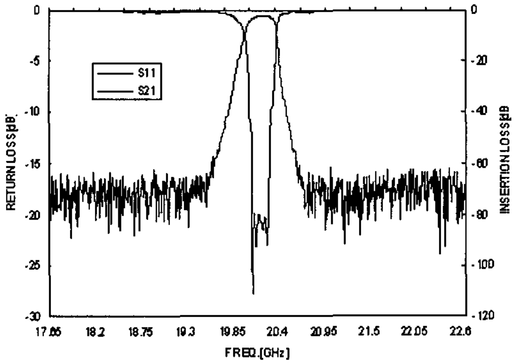
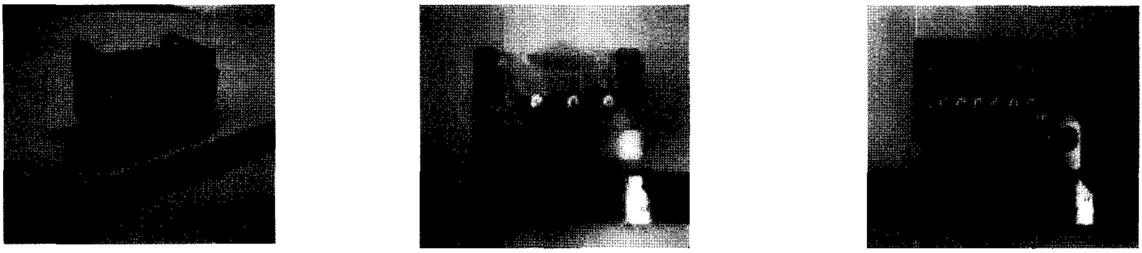



Fig. 8. Measured results of the fabricated six-section coupled-line type waveguide bandpass filter.

Table 1. Specifications of designed waveguide bandpass filter.

| Number of section (n) | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Even-mode impedance $Z_{en}$ [ohm] | 56.257 | 50.575 | 50.392 | 50.369 | 50.392 | 50.575 | 56.257 |
| Odd-mode impedance $Z_{on}$ [ohm] | 43.666 | 49.376 | 49.579 | 49.606 | 49.579 | 49.376 | 43.666 |
| Coupling coefficient | 17.99 | 38.42 | 41.79 | 42.35 | 41.79 | 38.42 | 17.99 |



(a) Front view (b) Top view (c) Side view

Fig. 9. Photograph of the fabricated six-section coupled-line type waveguide bandpass filter.

23 mm×28 mm×45 mm. Material used for the fabrication is brass. There are several screws for tuning of bandpass filter performances. The dimensions of the coupled-line sections for the required coupling values and resonant conditions of each resonator should be determined by accurate 2-D VFEM analysis to achieve the required filter characteristics. However, in order to achieve the each required values of coupling and resonant frequency, at this time several tuning screws shown in Fig. 8 were used. The screws shown in top view of the photographs are for resonance tuning of each resonators. Meanwhile, the screws shown in top view of the photographs are for resonance tuning of each resonators.

## Ⅴ. Conclusion

We have presented the new type waveguide bandpass filter, which has a parallel coupled-line configuration to achieve the required coupling. In order to explain the filtering phenomena of the proposed coupled-line type waveguide bandpass filter, the synthesis procedure for a parallel coupled-line section with arbitrary coupled-line length and characteristic impedance based on TEM-mode has been developed. To calculate the design parameters, normalized impedance concept and VFEM is applied. For demonstration, sex-section coupled-line type waveguide bandpass filter have been designed, fabricated, and measured. The measured results have been presented. It has been shown that the proposed waveguide filter has several advantages such as excellent stopband characteristic and compact size. This newly proposed filter configuration should provide an attractive solution to low-cost high-performance waveguide filters for a various microwave and millimeter-wave applications.

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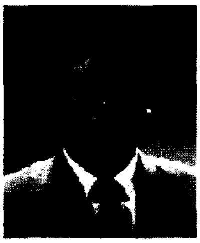

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