Mode Filter for High-Power Microwaves

Michio Otsuka and Masashi Shimizu

***Abstract*—A new type resistive-wall mode filter in which the axisymmetric modes, e.g., the TE_{01} and TE_{02} modes, pass almost without attenuation and the nonaxisymmetric modes, e.g., the TE_{11} and TM_{11} modes, attenuate has been developed for 28 GHz high-power microwaves. Pyrolytic graphite having an anisotropic resistivity was installed in the mode filter so that the normal direction to the deposition surface of the pyrolytic graphite was in the axial direction of the mode filter. The inner diameter of the mode filter was 30 mm and its length, 100 mm. Mode attenuation and return losses in the mode filter were measured for the TE_{01}, TE_{02}, TE_{11}, and TM_{11} modes using a scalar network analyzer with mode converters that convert from the rectangular TE_{10} mode to the circular modes. Measured attenuation was 2.4 ± 0.3 dB for the TE_{11} mode, 5.5 ± 0.2 dB for the TM_{11} mode, and $0.0 + 0.2$ dB for the TE_{01} and TE_{02} modes at 28 GHz. Return losses were in the range of -20 to -25 dB for each mode.**

I. Introduction

A number of electron cyclotron heating (ECH) experiments have been carried out and others are planned for fusion devices. In these experiments, high-power microwaves generated in the gyrotron are used. In an ECH system, highly oversized circular waveguides are used as transmission lines to reduce transmission loss. The major transmission modes in these waveguides are the TE_{01} and TE_{02} modes because these are the major output modes of the gyrotron and have low transmission losses. However, a number of undesired modes, for example the TE_{11}, TE_{12}, and TM_{11} modes, are generated at bends or at discontinuities along the waveguide because of mode conversion from TE_{01} and TE_{02}. These undesired modes cause breakdowns in waveguides and/or arcings on vacuum windows used in the ECH transmission lines owing to the strong electric fields in the normal direction to the waveguide wall compared with those for circularly symmetric modes, e.g., TE_{01} and TE_{02}. Therefore, mode filters which pass the TE_{01} and TE_{02} modes and attenuate the undesired modes, e.g., TE_{11}, TE_{12}, and TM_{11} modes, are necessary for high-power microwave transmission lines.

Several mode filters have been developed and are used in ECH transmission lines. The resistive-wall filter, the helix-waveguide filter, and the spaced-ring filter are commonly used [1]. Recently, an anisotropic wall filter having tapered corrugations on the waveguide wall has been developed for ECH transmission lines [2]. Mode selectivity of attenuation in resistive-wall filters made of isotropic resistive materials is not good because of rather high wall resistivity, although these filters are easy to manufacture owing to their simple structure. The others cited above have good mode selectivities, but manufacturing is rather difficult because of complicated structures. Complicated structures, especially rugged-wall surfaces are unsuitable for the mode filters used in high-power microwave transmission lines because roughness of the wall surface causes breakdown in the waveguide. Therefore, a smooth wall surface, that is, a simple structure, is desired for the mode filter.

Our objective here is to develop a mode filter which has good mode selectivity and a simple structure.

Manuscript received September 20, 1986; revised October 31, 1989.
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IEEE Log Number 9101647.

II. Design of Mode Filter

The mode filter developed is a kind of resistive-wall mode filter in which pyrolytic graphite is used as the resistive material. Pyrolytic graphite has anisotropic properties because of the pyrolytic decomposition process during manufacture. That is, certain properties measured parallel to the surface of the substrate differ from values measured perpendicular to the surface. The electrical resistivity of pyrolytic graphite is one such anisotropic property. The resistivity in the direction parallel to the deposition surface is smaller by three orders of magnitude than in the normal direction. Therefore, when pyrolytic graphite is installed on the inner wall of a waveguide so that the direction normal to the surface is parallel to the waveguide axis, this waveguide will work as a mode filter in which the circular modes, e.g., the TE_{01} and TE_{02} modes, pass and the undesired modes, e.g. the TE_{11}, TE_{12}, and TM_{11} modes, attenuate because of the difference in the current distributions of those modes on the waveguide wall.

The attenuation constants, α_{nm}^E and α_{nm}^M, for the TE_{nm} and TM_{nm} modes, respectively, in a circular waveguide which has a wall material with a finite electrical resistivity, η, are expressed as follows:

$$\alpha_{nm}^E = \frac{2(\pi\epsilon_0\eta f)^{1/2}\left\{\left(\frac{f_{cnm}^E}{f}\right)^2 + \frac{n^2}{\left((k_{nm}^E)^2 - n^2\right)}\right\}}{d\left\{1-\left(\frac{f_{cnm}^E}{f}\right)^2\right\}^{1/2}} \tag{1}$$

$$\alpha_{nm}^M = \frac{2}{d}(\pi\epsilon_0\eta f)^{1/2}\left\{1-\left(\frac{f_{cnm}^M}{f}\right)^2\right\}^{-1/2} \tag{2}$$

TABLE I
ATTENUATION IN THE RESISTIVE-WALL WAVEGUIDE

	Anisotropic Resistive Wall		Isotropic Resistive Wall	
Mode	Measured (dB)	Calculated (dB)	Measured (dB)	Calculated (dB)
TE_{01}	$0.0+0.2$	3.6×10^{-2}	3.0 ± 0.2	2.7
TE_{02}	$0.0+0.2$	0.18	14.0 ± 0.3	13.6
TE_{11}	2.4 ± 0.3	2.0	6.3 ± 0.3	6.1
TM_{11}	5.5 ± 0.2	4.7	13.6 ± 0.5	14.4

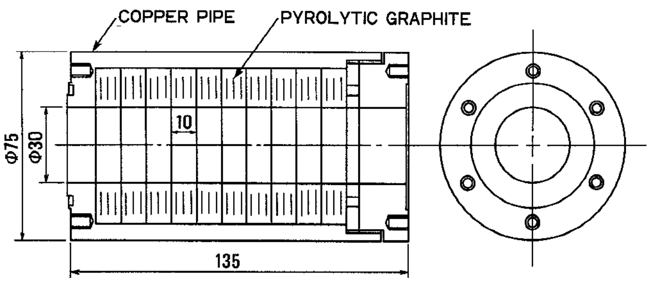

Fig. 1. Structure of the anistropic resistive-wall mode filter.

where f^E_{cnm} and f^M_{cnm} are cutoff frequencies for the TE_{nm} and TM_{nm} modes, respectively, ϵ_0 is electrical permittivity in vacuum, f is the frequency of the transmitting microwave, d is the inner diameter of the circular waveguide, and k^E_{nm} and k^M_{nm} are the mth roots of the derivative of the Bessel functions J'_n and J_n, respectively.

The attenuation per meter, α_{Lnm}, is expressed as follows:

$$\alpha_{Lnm} = 8.686\cdot\alpha_{nm} \qquad (\text{dB/m}). \qquad (3)$$

The attenuation rate in the mode filter for each mode is calculated by using (1) or (2) and substituting the inner diameter of the waveguide and the electrical resistivity of pyrolytic graphite.

The mode filter was primarily developed for the Hitachi Tokamak (HT-1) ECH system, in which a gyrotron (Varian: VGA8050, 28 GHz, 200 kW, 40 ms) is used. Thus the frequency of the transmitting microwave in the mode filter is 28 GHz. The inner diameter and the length of the mode filter are selected as 30 mm and 100 mm, respectively, in order to ensure that the attenuation rates can be measured more precisely with rather large measurement errors, e.g., 0.4–0.6 dB [3].

The electrical resistivity of the pyrolytic graphite used for the mode filter (Union Carbide Corp.: grade HPG) was measured with a four-point probe [4]. The resistivities measured in the parallel and normal directions to the surface are 1.1×10^{-5} Ω·m and 6.9×10^{-3} Ω·m at 20°C, respectively. These values are larger than those cited in the catalogue, 4.6×10^{-6} Ω·m and 5.1×10^{-3} Ω·m. The attenuation rates calculated for the TE_{01} and TE_{02} modes are 0.36 dB/m and 1.8 dB/m, respectively, with the resistivity in the normal direction (see Table I). Since pyrolytic graphite is available only in sheets with a maximum thickness of 10 mm, ten rings of this thickness were installed in circular waveguide. The inner diameter of the rings was machined after assembling to make the size deviation less than ±50 μm. The structure of the mode filter is shown in Fig. 1.

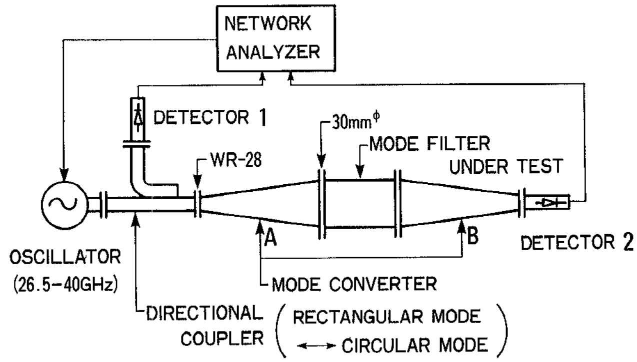

Fig. 2. Schematic of measuring equipment.

A mode filter of the same dimensions, but using the isotropic material of a high-voltage resistor, was made to allow comparison of the attenuation rates. The resistivity of this material is 6.4×10^{-2} Ω·m. The attenuation rates for the TE_{01}, TE_{02}, TE_{11}, and TM_{11} modes in this mode filter are 27.3, 136.4, 61.0, and 143.6 dB/m, respectively (see Table I).

III. MEASUREMENT OF ATTENUATION RATES IN THE MODE FILTERS

A. Measuring Procedure

Attenuation and return losses (VSWR's) in the mode filters were measured for the TE_{01}, TE_{02}, TE_{11}, and TM_{11} modes using a scalar network analyzer (Pacific Measurements (now: Wavetek Corp.) model 1038-NS20) in the frequency range of 26.5 to 31 GHz. The measuring equipment is shown in Fig. 2. Currents on the circular waveguide wall of the TE_{01} and TE_{02} modes are only in the azimuthal direction of the waveguide. The current of the TE_{11} mode, being mainly in the azimuthal direction, also has an axial component in the waveguide. In order to demonstrate the effect of the anisotropic resistivity, the attenuation of the TM_{11} mode, having currents only in the axial direction, was also measured. The circular TE_{01}, TE_{02}, and TE_{11} modes are converted from the rectangular TE_{10} mode by geometrical taper type mode converters in which the cross-sectional shape of the waveguide continuously changes from a rectangular cross section (WR-28) to a circular one (diameter: 30 mm). In these mode converters, appropriate mode filters using resistive thin films are installed to damp undesired modes. Measurements of mode purities, insertion losses, and return losses show that the undesired mode outputs are less than −22 dB compared with the desired mode output and that return losses for the TE_{10} mode are less than −24 dB for each mode converter. These values are small enough to evaluate the attenuation and return losses in the mode filters with reasonable accuracy. The measured insertion losses of the mode converters are in the range of 0.2 dB (+0.4 dB, −0.2 dB) to 2.0±0.8 dB. These rather large errors result from signal fluctuations with trapped higher modes becoming resonant between forward and backward waves in the mode converters [5].

The TM_{11} mode is converted from the rectangular TE_{10} mode by a multihole-type mode converter in which a rectangular waveguide (WR-51) is coupled with a circular waveguide (diameter: 30 mm) through many small apertures [6]. In order not to convert to the TE_{01} mode, which is degenerate with the TM_{11} mode in the circular waveguide, the broad side of the rectangular waveguide is connected to the circular waveguide. Mode discriminations of the TM_{11} mode to the TE_{01} mode of this mode converter were less than −15±2.5 dB in the frequency range of 26.5 to 31 GHz. Measured mode discriminations of the TM_{11} mode to the TE_{02} and TE_{11} modes were less than −25±2.5 dB. Measured mode coupling of the TM_{11} mode to the rectangular TE_{10} mode was −14±2.5 dB at 28 GHz and almost constant over the entire frequency range.

Return losses in the mode filters were measured from the output of detector 1 (Fig. 2) with the matched load connected to the output flange of the mode filter under test after detector 1 was normalized by shorting mode converter A at its output flange. Insertion losses (attenuation) in the mode filters were measured from the output of detector 2 after it was normalized without the mode filter under test.

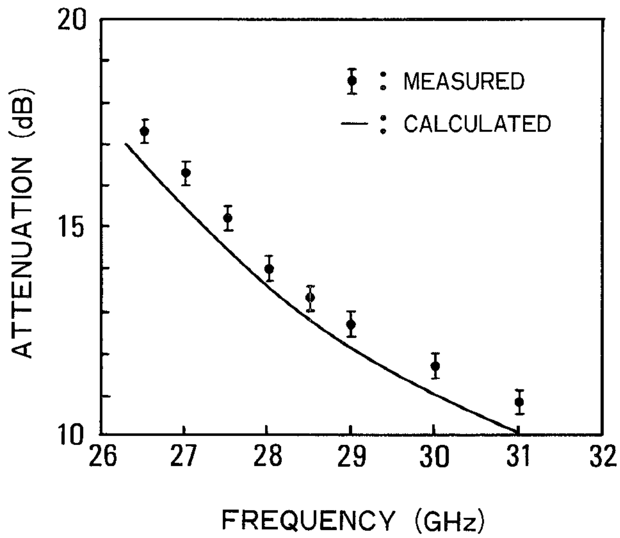

Fig. 3. Attenuation of the TE_{02} mode in the isotropic resistive-wall waveguide.

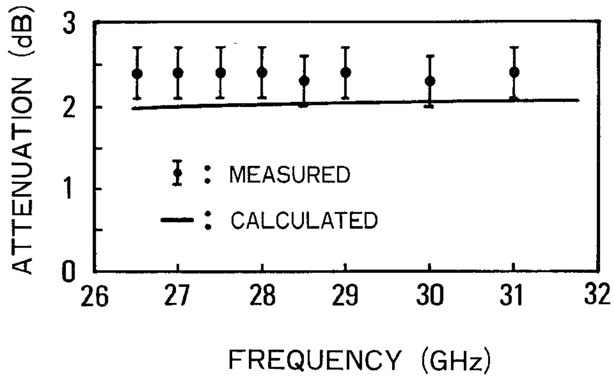

Fig. 4. Attenuation of the TE_{11} mode in the anisotropic resistive-wall mode filter.

B. Measured Results and Discussion

1) Attenuation: Fig. 3 shows the measured and calculated attenuation of the TE_{02} mode in the isotropic resistive-wall waveguide. Though the trend for frequency dependence of the measured values is in good agreement with calculations, the measured values are 0.4–0.8 dB larger than the calculated ones. Error resulting from manufacturing deviations is estimated to be about 0.1–0.2 dB. Return losses in the waveguide are less than −20 dB and the mode conversion losses in the waveguide, which are measured by changing the output mode converter so that it is different from the input one, are less than −20 dB for all other modes, in this case the TE_{01}, TE_{11}, and TM_{11} modes. These losses result in a maximum measurement error of the attenuation of 0.1–0.3 dB. This leaves a difference between the measured values and calculated ones of 0.1–0.3 dB. This difference is assumed to be caused by mode conversion to other modes, e.g. the TM_{12} mode, which is degenerate with the TE_{02} mode. The differences between the measured attenuation and the calculated one for the other three modes are also 0.2–0.8 dB. From these measurements, it is considered that the theoretical equations (1) and (2) for the attenuation can be applied to estimate the attenuation in the resistive-wall waveguide.

The measured and calculated attenuations of the TE_{11} mode in the anisotropic resistive-wall waveguide in which the pyrolytic graphite is installed is shown in Fig. 4. The measured values are 0.2–0.4 dB larger than the calculated ones, although the trend for the frequency dependence of the measured values is in good agreement with the calculated one. The return losses in the mode filter are less than −25 dB and the mode conversion losses to other modes, the TE_{01}, TE_{02}, and TM_{11} modes, are each less than −25 to −30 dB in the frequency range of 26.5–31 GHz. These losses are too small to cause a 0.2–0.4 dB difference between the measured and calculated values.

The attenuations of the TE_{01} and TE_{02} modes are both 0.0+0.2 dB over the entire frequency range. In the case of the TM_{11} mode, the difference between the measured and calculated values is similar to the case of the TE_{11} mode. Although the trend for frequency dependence of the attenuation is in good agreement, the measured val-

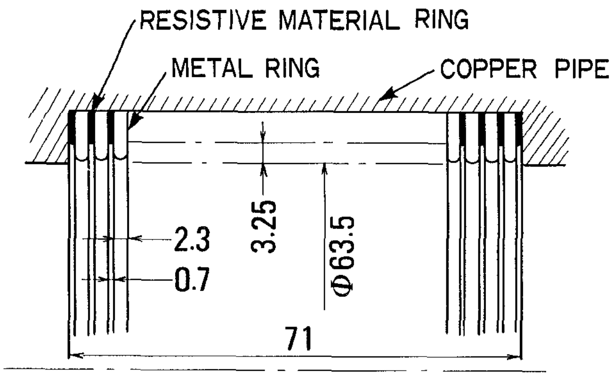

Fig. 5. Structure of the spaced-ring mode filter used in the HT-1 ECH system.

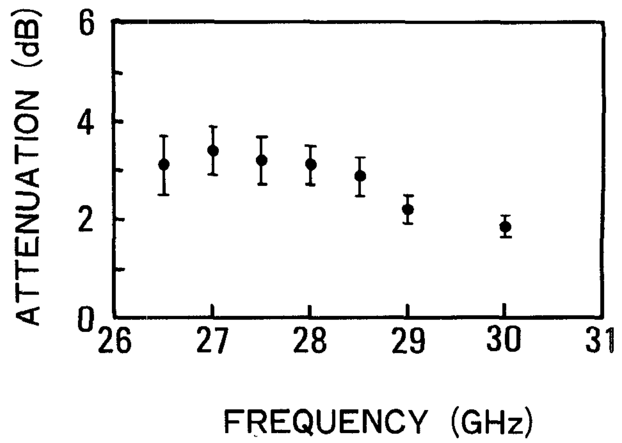

Fig. 6. Measured attenuation of the TE_{11} mode in the spaced-ring mode filter.

ues are 0.4–0.8 dB larger than the calculated ones. Measurement of the contact resistance between pyrolytic graphite rings shows that this resistance is too small to cause the difference. One cause for this difference is the mode conversion loss from the TE_{11} mode to the higher order modes, e.g., the TE_{12} mode and the TM_{12} mode. Another is that the theoretical equations for the attenuation cannot be applied to mode attenuation in the anisotropic resistive-wall waveguide. It is not clear now what is responsible for this difference. The important result, however, is that the attenuation of the TE_{11} mode whose current direction on the waveguide wall is also in the azimuthal direction can be roughly estimated using the resistivity of the axial direction in (1).

The measured and calculated attenuations of four modes at 28 GHz in the anisotropic and isotropic resistive-wall waveguide are summarized in Table I. In the anisotropic resistive-wall waveguide in which the pyrolytic graphite rings are installed, the TE_{01} and TE_{02} modes propagate practically without attenuation. On the other hand, the TE_{11} and TM_{11} modes attenuate. Thus, this waveguide is satisfactory as a mode filter because of its high mode selectivity. The isotropic resistive-wall waveguide, on the other hand, is not suitable because of its poor mode selectivity, as indicated in Table I.

In order to compare the mode attenuation rates with those in anisotropic resistive-wall mode filter, the attenuation rates in the spaced-ring mode filter presently used in the HT-1 ECH system were measured. The structure of this mode filter is shown in Fig. 5. In this mode filter, resistive rings and metal rings are alternately installed. The dimensions of these rings depend on the frequency of the wave propagating in the mode filter. The mode filter shown in Fig. 5 is designed for a wave having a frequency of 28 GHz. The inner diameter of the metal rings is 63.5 mm, this being the diameter of the output waveguide of the gyrotron. The attenuations of the TE_{01} and TE_{02} modes in this mode filter are both $0.0+0.2$ dB in the frequency range of 26.5 to 31 GHz. The attenuation rate of the TE_{11} mode at 28 GHz is 3.1 ± 0.4 dB per 71 mm, i.e., 44 dB/m. Fig. 6 shows the frequency dependence of the attenuation. The attenuation decreases to about 2 dB in the high-frequency region. The calculated attenuation rate of the TE_{11} mode in the anisotropic resistive-wall mode filter with an inner diameter of 63.5 mm is 8.6 dB/m at 28 GHz, which is 43% of the attenuation rate for the mode filter with a diameter of 30 mm. This attenuation rate is one fifth that of the spaced-ring mode filter. Although the attenuation rate in the anisotropic resistive-wall mode filter is smaller than that in the spaced-ring mode filter, the former can be lengthened more easily than the latter because of its simpler structure. Furthermore, application of the spaced-ring mode filter to higher frequency waves is difficult because of its construction dimensions; in particular, the spaces between metal rings which would need to become narrower, and such a narrow space would lead to breakdown for high-power microwaves. Another advantage of the anisotropic resistive-wall mode filter is the ease with which it can be cooled because the heat conductivity in the direction parallel to the substrate of the pyrolytic graphite is on the same order as that of copper.

2) Return Losses: Return losses of the anisotropic resistive-wall mode filter are in the range of -20 to -25 dB for the TE_{01}, TE_{02}, TE_{11}, and TM_{11} modes. These return losses correspond to VSWR's of 1.1–1.2, which are small enough to be used in high-power ECH systems.

IV. Conclusion

A circular waveguide mode filter (the anisotropic resistive-wall mode filter) in which the axisymmetric modes, e.g., the TE_{01} and TE_{02} modes, propagate without attenuation and the nonaxisymmetric modes, e.g., the TE_{11} and TM_{11} modes, attenuate has been developed for 28 GHz high-power microwave. Ten pyrolytic graphite rings with an inner diameter of 30 mm and a thickness of 10 mm were installed in a cylindrical pipe made of copper in such a way that the normal direction to the surface of the pyrolytic graphite substrate is in the axial direction of the waveguide. Total length of mode filter is 10 cm. In order to compare the attenuation characteristics, an isotropic resistive-wall waveguide which has the same dimensions as the anisotropic resistive-wall mode filter was also made.

The attenuation and the return losses for the TE_{01}, TE_{02}, TE_{11}, and TM_{11} modes in these waveguides were measured using a scalar network analyzer in the frequency range of 26.5 to 31 GHz and were compared with those in the spaced-ring mode filter with a diameter of 63.5 mm used in the Hitachi Tokamak Electron Cyclotron Heating System. Measured results were as follows:

1) The attenuations of the TE_{01} and TE_{02} modes in the anisotropic resistive-wall mode filter were 0.0+0.2 dB over the entire frequency range. The attenuation rates for the TE_{11} and TM_{11} modes at 28 GHz were 2.4 ± 0.3 dB (24 dB/m) and 5.5 ± 0.2 dB (55 dB/m), respectively. These results show that in this mode filter the axisymmetric modes propagate without attenuation and the nonaxisymmetric modes are damped because of the anisotropic resistance of the pyrolytic graphite.
2) The measured attenuation of the TE_{11} and TM_{11} modes in this mode filter were 0.4–0.8 dB larger than the calculated ones, although the trends for frequency dependence were in good agreement with each other. The cause of this discrepancy was not clear. The mode conversion losses to higher order modes, e.g., the TE_{12} and TM_{12} modes, were deduced as responsible for this discrepancy.
3) The measured attenuation rates of the TE_{01}, TE_{02}, TE_{11}, and TM_{11} modes in the isotropic resistive-wall waveguide were 0.2–0.8 dB larger than the calculated ones. The theoretical equations for the attenuation rates are considered to be applicable to the resistive-wall waveguide.
4) The attenuation rates of the TE_{11} mode, whose current direction on the waveguide wall is mainly in the azimuthal direction but has axial currents as well, could be estimated using the resistivity of the pyrolytic graphite in the axial direction of the waveguide.
5) The attenuation rate in the spaced-ring mode filter with a diameter of 63.5 mm was 44 dB/m for the TE_{11} mode at 28 GHz and was five times larger than that in the anisotropic wall mode filter with the same diameter. This result need not present a practical problem because the anisotropic resistive-wall mode filter can be lengthened more easily than the spaced-ring mode filter. Furthermore, the anisotropic resistive-wall mode filter would be more suitable for high-frequency microwaves than the spaced-ring mode filter because the space between metal rings in the latter would become narrower for higher frequency microwaves and such a narrow space would lead to breakdown at the metal rings.
6) Return losses of the TE_{01}, TE_{02}, TE_{11} and TM_{11} modes in the anisotropic resistive-wall mode filter were in the range of -20 to -25 dB and were small enough to be used in high-power microwave transmission lines.

Acknowledgment

The authors would like to thank Dr. S. Yamada, Dr. N. Ozaki, Dr. T. Kobayashi, and Dr. M. Nishi for their continuing encouragement and support throughout this work.

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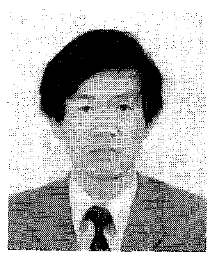

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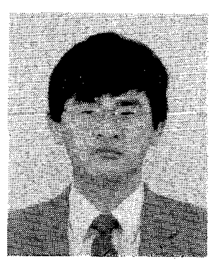

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