Dual FET Active Patch Elements for Spatial Power Combiners

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Abstract—**A novel dual-FET active patch antenna element and arrays for quasi-optical power combining are described. The circuit uses two FET's that symmetrically load a split patch antenna. The configuration of the devices decreases H-plane cross-polarization dramatically. The power combining was achieved by injection locking through mutual coupling. An equivalent isotropic radiation power of 0.88 W for a 2-element dual-FET patch antenna array has been obtained. For a 2×2 array, an equivalent isotropic radiated power of 2.99 W was achieved. The circuit is planar and amenable to monolithic circuits.**

I. INTRODUCTION

SOLID-STATE oscillators have limited output power in the microwave and millimeter-wave region. In order to obtain higher power, it is desirable to combine the power generated from many solid-state oscillators. Many power-combining techniques have been demonstrated in the microwave and millimeter-wave frequency range [1]. Most of these techniques have serious limitations due to size and moding problems. They become impractical at millimeter-wave frequencies as the waveguide dimensions become very small.

Recently, a planar quasi-optical approach has been suggested by Mink [2] for combining a large number of devices. The transverse dimensions of quasi-optical systems can be quite large, which accommodates many devices without the problem of multi-frequency operation. Quasi-optical arrays depend upon the interaction of the devices for proper operation. As the power combining takes place in the free space, high combining efficiency is possible.

Currently, two major types of quasi-optical power-combining arrays have been reported. One is a grid structure loaded with transistors [3], [4]. The second approach involves arrays of weakly coupled individual oscillator elements [5]–[8]. The important figures of merit are the output power, radiation pattern, antenna efficiency, combining efficiency, and packing density.

This paper reports the design and performance of a novel active antenna with two FET's integrated directly on one patch. The circuit forms an element for spatial or quasi-optical combiners. The configuration of the devices decreases H-plane cross-polarization dramatically. These active antennas were successfully combined to form two-element and 2×2 arrays. Injection locking through mutual coupling was accomplished, and good power combining efficiency was achieved. The new structure is completely planar, and there is no need for drilling holes through the substrate for bias. Because the circuit is in the same plane, it is suitable for monolithic implementation.

II. DESIGN OF DUAL-FET ACTIVE RADIATING ELEMENT

Several different FET active patch antennas have appeared in the literature. One circuit uses the patch as a feedback resonator and as a radiator [9]. Another circuit uses a gap between the gate and the drain to form feedback, with the source leads grounded through the substrate [7]. The patch antenna and oscillator circuit can be separated, usually in a different plane [5]. The patch antenna is useful because it is simple to fabricate, can easily accommodate devices, has high antenna efficiency, and serves as a resonant stabilization element in the oscillator circuit. However, active patch antennas with the device integrated directly on the patch antenna suffer high cross-polarization [7].

This paper reports power combining using novel dual-FET active patch antennas in which each antenna element is symmetrically loaded with two FET's. The use of dual devices in a patch was first reported by York and Compton [10] with improved radiation characteristics using two Gunn diodes mounted inside a single patch. The actual current distribution on the patch with a single device is quite different from that of a deviceless patch. An excess of higher-order current modes will be generated on the patch because of the discontinuity. These higher-order modes are partially responsible for the high cross-polarization. Also, asymmetry in the device location will further exacerbate this problem by exciting current modes with odd symmetry. The dual-FET active patch circuit overcomes these problems and can be easily built with an excellent radiation pattern [11].

The dual-FET active patch antenna is shown in Fig. 1. The gaps between the source and drain and between the source and the gate form a feedback circuit to make the device unstable. The patch serves both as a resonator in the feedback loop for the FET oscillator and as a radiating element. Different from the Dual-Gunn Diodes patch antenna, where the two diodes are symmetrical on the resonant dimension, the FET's are symmetrical on the nonresonant dimension. As the FET's operate in an in-phase mode, oppositely directed higher-order mode currents on the patch will cancel out in the H-plane far field. The H-plane cross-polarization is thus reduced with this configuration. The design of the patch antenna was based on equations given by Bahl and Bhartia [12] and Lo *et al.*

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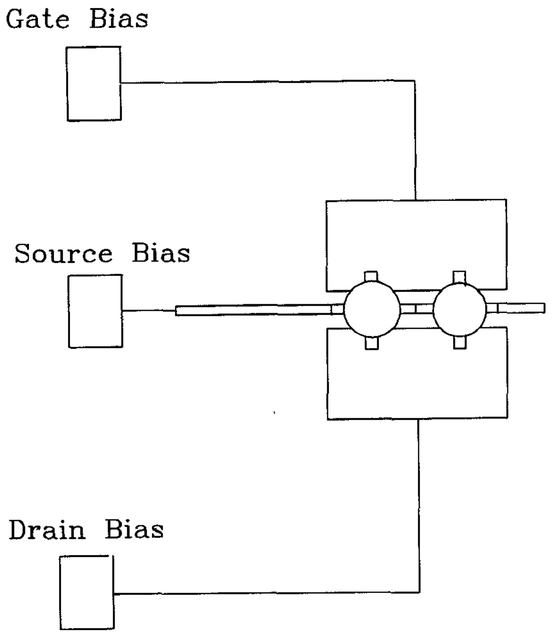

Fig. 1. Circuit configuration of a dual-FET active patch antenna.

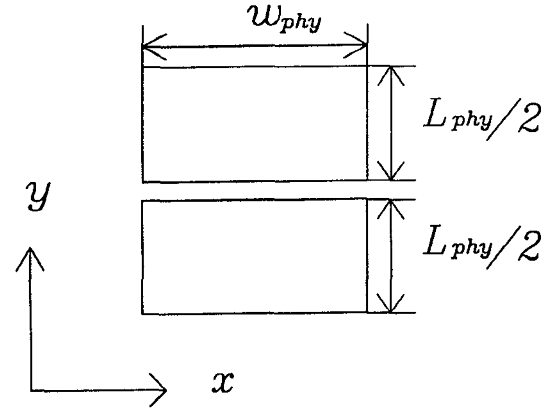

Fig. 2. Dimensions of patch antenna.

[13]. The relation between resonant frequency f_{mn} (GHz) and the patch electrical dimensions W and L (cm) are given by [13]. The mn mode numbers are associated with the x and y directions. The dominant radiating mode is $m = 0$ and $n = 1$. Due to the fringing field effect, the actual physical dimensions are smaller. The modified dimensions (L_{phy}, W_{phy}) shown in Fig. 2 can be calculated by the equations given in [12]. As an approximation, the design was based on the theory for a patch without the gap and devices.

The patch has an overall size of 10 by 10 mm that is divided into two halves separated by a 2-mm gap. The main difference from the conventional patch antenna is that the dual-FET patch has no ground plane on the substrate. Instead, a reflecting mirror that has dimensions of 90 by 200 mm was placed approximately 0.5 mm behind the circuit. The output power and frequency of a dual-FET active patch antenna varied with the position of the reflecting mirror. All circuits, including the single-patch antenna and two- and four-element arrays, were constructed on RT/duroid 5870 substrate with a thickness of 62 mils. As the mirror was put very close to the substrate, the design method described above gives a good approximation.

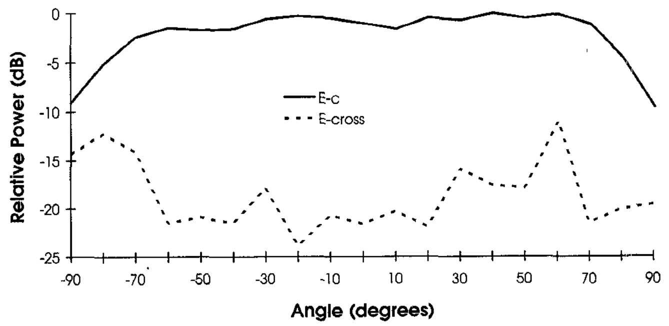

Fig. 3. E-plane pattern of the dual-FET active patch antenna.

The experimental resonant frequency for the active patch antenna is 8.1 GHz, whereas the theoretically resonant frequency for the passive antenna is 8.26 GHz.

III. RESULTS FOR A SINGLE DUAL-FET ACTIVE PATCH ANTENNA

A standard horn antenna with a gain of G_1 was used to measure the power output from a dual-FET active patch antenna. The standard horn antenna was placed a distance R from the active antenna. The received power P_r was measured using a power meter. The output power of the active antenna P_0 was calculated using the Friis transmission equation:

$$P_0 = P_r \left(\frac{4\pi R}{\lambda_0}\right)^2 \frac{1}{G_1 G_2} \tag{1}$$

where

$\lambda_0 =$ the wavelength in free space
$G_2 =$ the gain of dual-FET active patch antenna

If the active antenna gain is unknown, the Equivalent Isotropic Radiated Power $(EIRP)$ defined below should be used.

$$EIRP = P_r \left(\frac{4\pi R}{\lambda_0}\right)^2 \frac{1}{G_1}. \tag{2}$$

The devices used were Fujitsu FHX35LG general purpose FET's. The rated output power of the FET is 25 mW at 12 GHz. A clean spectrum output power of 47 mW was observed at 8.1 GHz for a dual-FET active patch antenna element. The output power is about twice the output of the single FET active patch antenna. In the power calculation, it is assumed that the patch has an antenna gain of 6 dB. This output power corresponds to an equivalent isotropic radiated power of 0.188 W. Figs. 3 and 4 show the E- and H-plane patterns for the dual-FET patch antenna. The cross-polarization is 12 dB down from the co-polarization radiation, which is much better than the single FET patch.

IV. RESULTS FOR TWO-ELEMENT DUAL-FET ACTIVE PATCH ANTENNA ARRAY

Mutual coupling between the oscillator elements will have an effect on the injection locking behavior of the array. The single element described in the previous section was used to form a 2-element array as shown in Fig. 5. Spacing

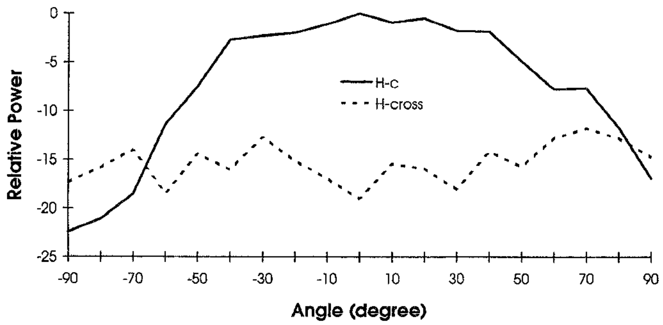

Fig. 4. H-plane pattern of the dual-FET active patch antenna.

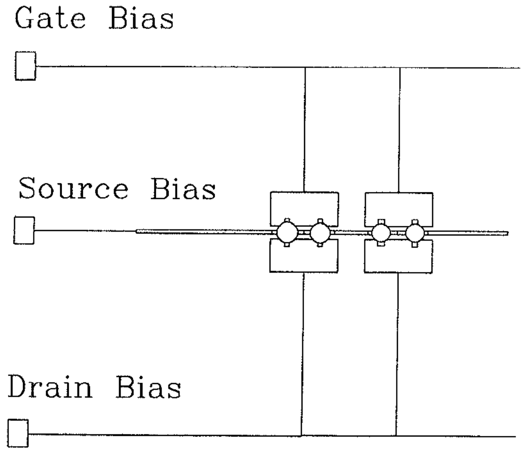

Fig. 5. Two-element active patch antenna array.

between the elements is approximately $\lambda_0/2$. It is necessary for the individual oscillators to have nearly identical oscillation frequencies, which can be obtained by using separate power supplies and changing the bias voltage of each element. However, providing individual bias to all the elements of a large array containing several hundred devices is impractical.

A dielectric slab can be placed in front of the array to overcome these problems. The slab and the mirror form a Fabry–Perot resonator as shown in Fig. 6. The dual-FET active array was operated by connecting the bias lines from the elements to a single power supply. The dielectric constant of the slab was 10.5. The dielectric slab not only can influence the coupling between the elements and thereby facilitate phase-coherent operation, but also the position of the slab can influence the output power and thus increase the gain of the array.

An $EIRP$ of 0.88 W was achieved at 7.62 GHz. Here the $EIRP$ is used since a dielectric slab was placed in front of the active antenna array and the active antenna gain was difficult to estimate. The E- and H-plane patterns of the two-element array are shown in Figs. 7 and 8, respectively. The cross-polarization was 15 dB down from the peak power in both the E- and H-plane. The spectrum of the two-element array is shown in Fig. 9.

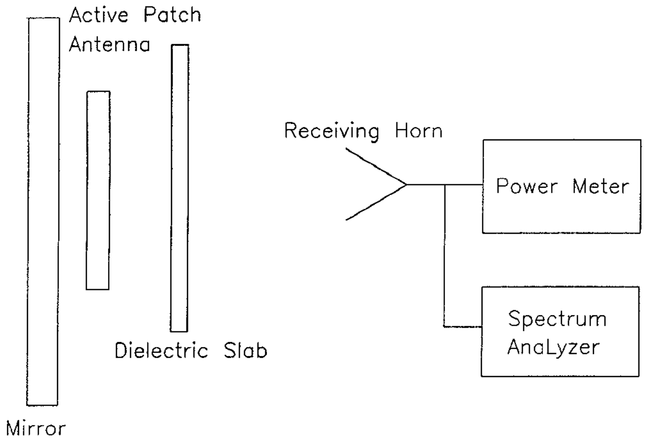

Fig. 6. Quasi-optical power-combining measurement setup.

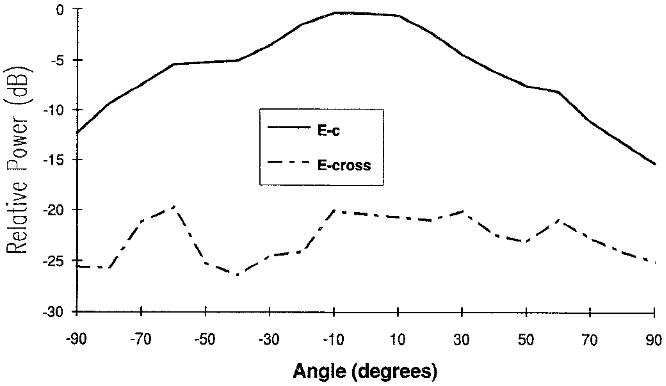

Fig. 7. E-plane pattern of the two-element dual-FET active patch antenna array.

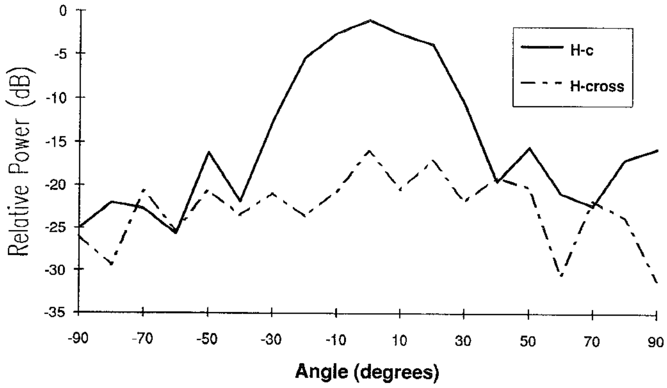

Fig. 8. H-plane pattern of the two-element dual-FET active patch antenna array.

V. DESIGN AND RESULTS FOR FOUR-ELEMENT DUAL-FET ACTIVE PATCH ANTENNA ARRAY

A 2×2 array was also built and tested. The individual elements were designed as described above. Due to variances in individual FET parameters, it was difficult to make the oscillators—which used a common power supply—to oscillate at the same frequency. Small frequency tuning could be achieved by adjusting the position of the dielectric slab and the position of the reflecting mirror. For dual-FET active antenna array design, it is important to choose FET's with similar parameters. Also, symmetry in the device location is important. Therefore, monolithic fabrication of large dual-FET active antenna arrays is desirable.

The design and operation of the 2×2 active antenna array are described below. Let the coupling coefficient be-

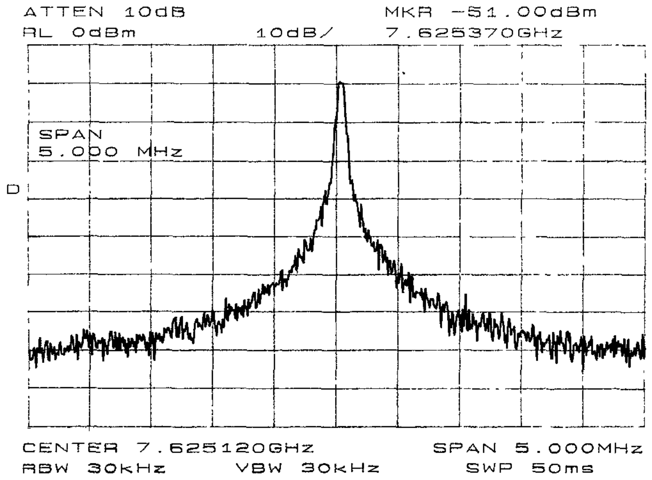

Fig. 9. Spectrum of the two-element dual-FET active patch antenna array.

tween elements mn and ij be written as \mbi $\mathbf{C}_{mn,ij} = C_{mn,ij}\exp(-j\Phi_{mn,ij})$, where $C_{mn,ij} \ll 1$.

The relative phase in the steady-state of the 2×2 symmetric array can be written as [14]:

$$s = s_{11}\left[1 - \frac{C_a}{2Q}\left(\sin(\Delta_1 - \Phi_a) + \sin(\Delta_2 - \Phi_a) + \frac{C_b}{C_a}\sin(\Delta_3 - \Phi_b)\right)\right] \tag{3}$$

$$s = s_{12}\left[1 - \frac{C_a}{2Q}\left(-\sin(\Delta_1 + \Phi_a) + \frac{C_b}{C_a}\sin(\Delta_2 - \Delta_1 - \Phi_b) + \sin(\Delta_3 - \Delta_1 - \Phi_a)\right)\right] \tag{4}$$

$$s = s_{21}\left[1 - \frac{C_a}{2Q}\left(-\sin(\Delta_2 + \Phi_a) + \frac{C_b}{C_a}\sin(\Delta_1 - \Delta_2 - \Phi_b) + \sin(\Delta_3 - \Delta_2 - \Phi_a)\right)\right] \tag{5}$$

$$s = s_{22}\left[1 - \frac{C_a}{2Q}\left(-\frac{C_b}{C_a}\sin(\Delta_3 + \Phi_b) + \sin(\Delta_1 - \Delta_3 - \Phi_a) + \sin(\Delta_2 - \Delta_3 - \Phi_a)\right)\right] \tag{6}$$

where $\Delta_1 = \varphi_{11} - \varphi_{12}$, $\Delta_2 = \varphi_{11} - \varphi_{21}$, $\Delta_3 = \varphi_{11} - \varphi_{22}$

$\mathbf{A}_{11} = A\exp(-j\varphi_{11})$, $\mathbf{A}_{12} = A\exp(-j\varphi_{12})$,

$\mathbf{A}_{21} = A\exp(-j\varphi_{21})$, $\mathbf{A}_{22} = A\exp(-j\varphi_{22})$,

$Q = Q_{11} = Q_{12} = Q_{21} = Q_{22}$,

$A = A_{11} = A_{12} = A_{21} = A_{22}$,

$\mathbf{C}_a = \mathbf{C}_{11,12} = \mathbf{C}_{11,21} = C_a\exp(-j\Phi_a)$,

$\mathbf{C}_b = \mathbf{C}_{11,22} = \mathbf{C}_{22,11} = C_b\exp(-j\Phi_b)$.

A = free running amplitude of the ijth oscillator

φ_{ij} = free running phase of the ijth oscillator

Q_{ij} = external Q of the ijth oscillator circuit

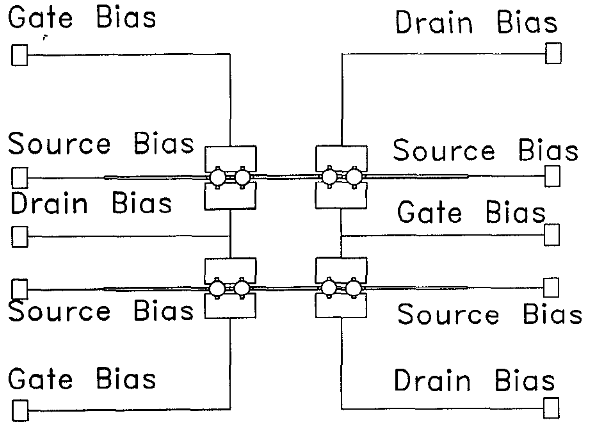

Fig. 10. Four-element active patch antenna array.

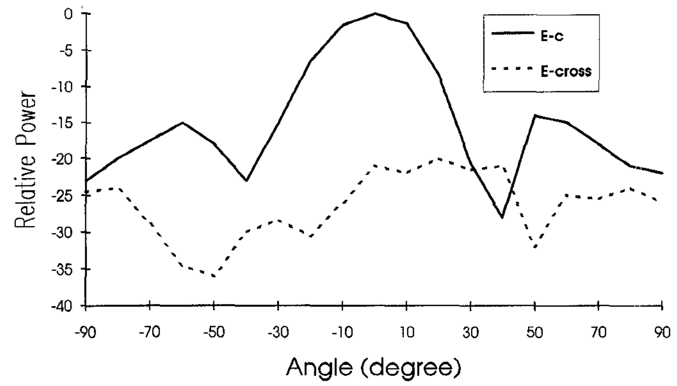

Fig. 11. E-plane pattern of the four-element dual-FET active patch antenna array.

$s_{ij} = j\omega_{ij}$, free running complex frequency of the ijth oscillator

$s = j\omega$, complex frequency of an injection locked array

* denotes complex conjugate.

Suppose these elements operating at the same frequency, for coherent combining ($s_{11} = s_{12} = s_{21} = s_{22}$) and from (3)–(6), it is required that $\Delta_1 = n\pi$, $\Delta_2 = m\pi$, and $\Delta_3 = k\pi$, where $n, m, k = 0, \pm 1, \pm 2, \cdots$. Mode stability for these modes can be analyzed using a perturbation method. In order to get a sum antenna pattern from the quasi-optical array, the relative phase is very important. The above analysis shows that the phase difference between two neighboring elements should be equal to multiples of π. A relative phase of π was selected for our design since it provided better stability.

Fig. 10 shows the circuit arrangement of the 2×2 active array. The right phase relation was achieved by reversely connecting the FET's. For the 2×2 array, an equivalent isotropic radiated power of 2.99 W was achieved at 8.94 GHz. The combining efficiency is about 85%. (100% combining efficiency corresponds to 0.88 W×4. The 0.88 W is from a 2×1 array, and 4 is due to the fact that both the active antenna gain and the output power are double.) Figs. 11 and 12 show the E- and H-plane radiation patterns. The cross polarization is 20 dB down in both E and H plane. The frequency change is due to the coupling between the elements.

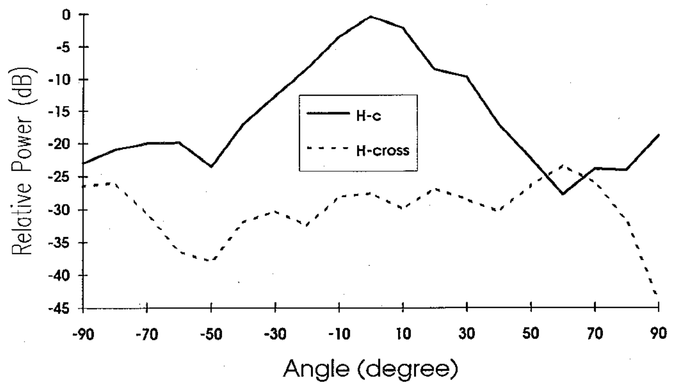

Fig. 12. H-plane pattern of the four-element dual-FET active patch antenna array.

VI. CONCLUSION

This paper has presented a novel dual-FET active patch antenna element and arrays. The additional FET improves the radiation characteristics of the active antenna and increases the power output. Two and four elements of these dual-FET's were successfully combined with good power-combining efficiency. By changing the position of the dielectric slab and the reflecting mirror, the output power of the dual-FET active antenna array can be optimized. This circuit should have many applications in low-cost transmitters for microwave and millimeter-wave frequencies. Since the circuit is in the same plane, it is suitable for monolithic implementation.

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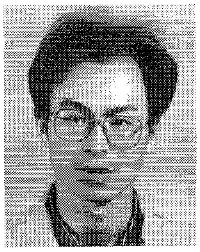

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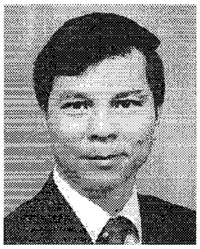

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