Electric Field Distribution Measurement of Microstrip Antennas and Arrays Using Electro-Optic Sampling

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Abstract—**This paper proposes an electric field distribution measurement method for microwave integrated circuit arrays that uses Electro-optic sampling (EOS). The electric fields of a microstrip patch antenna are measured by EOS and compared with the theoretical results calculated by the spectral domain approach. Good agreement between measurement and theory is found. An array antenna composed of two microstrip patches is also assessed by the EOS method and the expected results are experimentally verified. The EOS proposed in this paper is promising to evaluate the electric field distribution of individual antenna elements in large scaled integrated array antennas.**

I. Introduction

RECENTLY, VARIOUS planar antennas for the high frequency band have been intensively investigated for phased array applications [1]. Much attention has given to monolithic integrated phased array antennas in the millimeter-wave frequency bands [2]. These integrated array antennas have been characterized by conventional far field pattern measurement. However, this method cannot evaluate the individual and mutual-coupling characteristics of array antenna elements. Active circuits integrated on the same wafer are usually characterized by a different measurement system such as an on-wafer probe station. If the same measurement system could be used for both the active circuits and radiation elements integrated on one wafer, the time taken for designing, fabricating, and validating wafer-scale integrated circuits could be shortened significantly.

This paper proposes an electro-optic sampling (EOS) method for measuring the electric field distribution of integrated arrays. EOS was first introduced to measure internal-node waveforms on high-speed electronic integrated circuits such as digital signal-processing LSI's [3]. It can also measure the analog performance of MMIC's and active devices up to millimeter-wave frequencies [4]. Recently, the electric field distributions on monolithic integrated slot antennas and coplanar transmission lines have been successively measured by EOS [5], [6]. However, the measurement results have not yet been compared against accurate theoretical results. The field distribution of integrated array elements has not been studied by EOS measurement.

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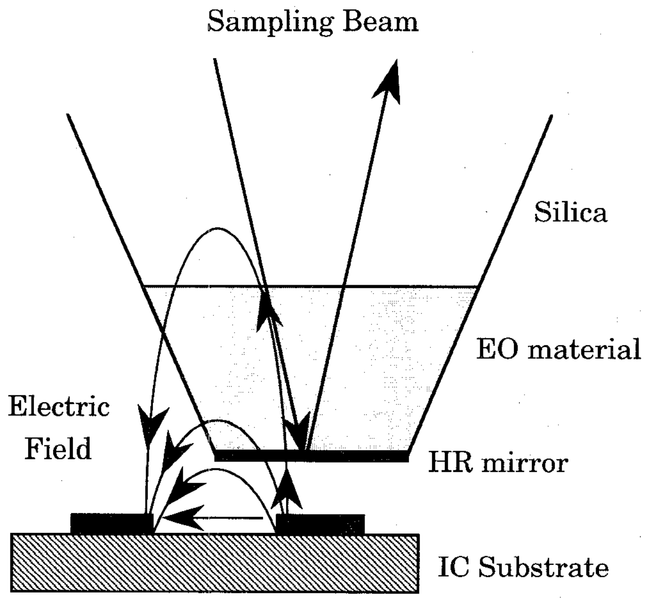

Fig. 1. EO probe tip configuration.

This paper compares, for the first time, the electric field distribution of a microstrip patch antenna measured by EOS with theoretical results calculated by the spectral domain approach, and good agreement is demonstrated. Furthermore, the electric field distribution of a two microstrip patch array is measured by EOS, which confirms that EOS can evaluate not only the individual characteristics of array antennas, but also the mutual coupling between antenna elements.

II. Electro-Optic Sampling System for Electric Field Measurement

Fig. 1 shows the schematic structure of the EO probe tip [7]. The probe tip is formed by depositing a 100-μm-thick layer of EO material on a fused silica support. The tip is then formed into a truncated cone with a tip diameter of 100 μm. A high-reflectivity (HR) mirror is formed on the bottom surface of the EO material. Fig. 2 illustrates a schematic block diagram of the EOS measurement system [8]. The beam from a laser diode (LD) is reflected from the HR mirror and captured by detection optics. In the EO material, the coupled electric field from the element under test changes the polarization of the laser beam. When the beam passes through the polarizing beam splitter (PBS), the change in polarization is converted into a change

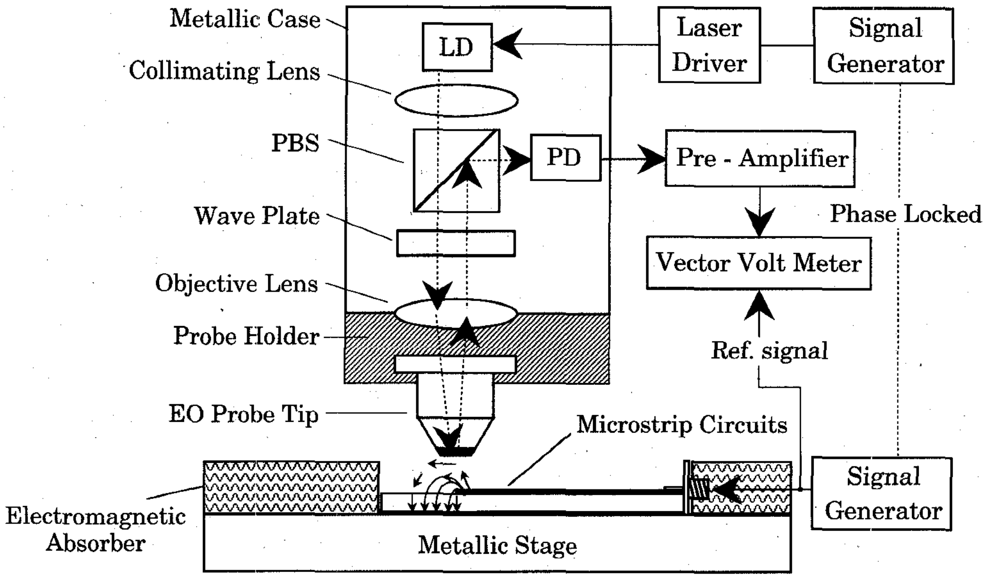

Fig. 2. EOS system configuration.

in beam intensity which is detected by a photodetector (PD). Finally, the electro-optically modulated signal (EO signal) is passed to a signal acquisition circuit, a vector volt meter. The microwave phase distribution is also measured to compare with reference signals divided from antenna feed signals.

The EOS system mentioned above was developed for digitally measuring the internal-node waveforms propagating in high-speed electronic signal-processing LSI's. Since the EO probe generally detects the leakage of weak electric fields whose amplitude is proportional to that of the digital waveforms, the EO probe is very sensitive to variations in the electric field. This means that when the EOS method is used to measure microwave fields on planar integrated circuits, undesired microwave signals, i.e. reflection power from obstacles such as probe holders and stages, must be suppressed to realize precise measurement. To this end, the following improvements were made to the conventional EOS:

1) The probe holder, which was made of metal, consists of a nylon resin whose dielectric constant is about 4.
2) Electromagnetic absorbers are used to cover the stage and other metal surfaces including coaxial connectors.

Therefore, the modified EOS system can measure the surface electric field distribution of microwave integrated antennas and circuits without affecting their performance.

III. Electric Field Distribution of Microstrip Patch Antenna

Fig. 3 shows the layout of the microstrip patch antenna circuit fabricated on an alumina substrate whose size and dielectric constant are 50×50×0.635 mm and 9.7, respectively. The microstrip conductors are 5 μm thick. The patch width W and length U are 8.12 and 5.51 mm, respectively. The dominant resonant frequency is designed to be 8.0 GHz. This patch antenna is matched to 50-ohm by a quarter-wave microstrip-line transformer. In this section, the electric field distribution of the dominant resonant mode measured by the

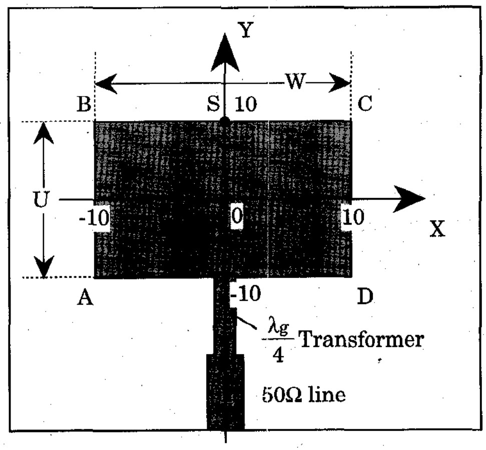

Fig. 3. Measured microstrip patch antenna configuration.

EOS method will be compared with the theoretical electric field distribution calculated by the spectral domain approach.

A. Theoretical Field Distribution by Spectral Domain Approach

The spectral domain approach was used to calculate the theoretical surface electric field of the above microstrip patch antenna. The patch model used for the calculation does not include the feed line to simplify the calculation. The metal thickness is assumed to be zero. The spectral domain approach discussed in [9], [10] was extended to handle two-dimensional cases. The unknown current densities are expanded in terms of known sets of basis functions which are given by

$$i_x(x,y) = \sum_{j=1}^{N_x}\sum_{k=1}^{N_y} a_{jk}\xi_{xj}(x)\eta_{xk}(y) \tag{1}$$

$$i_y(x,y) = \sum_{j=1}^{N_x}\sum_{k=1}^{N_y} b_{jk}\xi_{yj}(x)\eta_{jk}(y) \tag{2}$$

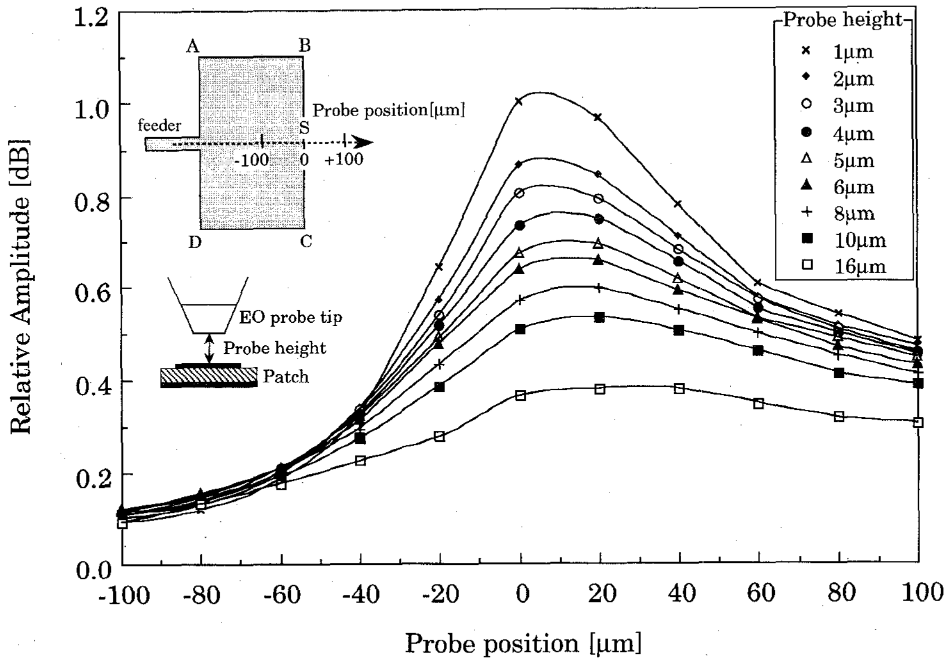

Fig. 4. Detected field strength as functions of probe position and height.

where a_{jk} and b_{jk} are unknown coefficients. Substituting (1) and (2) into the electric field integral equation and applying Galerkin's method, a set of simultaneous equations for the unknown coefficients is obtained. The basis functions used in this paper are given by

$$\xi_{xj}(x) = U_{2j}\left\{\frac{2x}{W}\right\} \tag{3}$$

$$\xi_{yj}(x) = \frac{T_{2(j-1)}\left\{\frac{2x}{W}\right\}}{\sqrt{1-\left\{\frac{2x}{W}\right\}^2}} \tag{4}$$

$$\eta_{xk}(y) = \frac{T_{2k-1}\left\{\frac{2y}{U}\right\}}{\sqrt{1-\left\{\frac{2y}{U}\right\}^2}} \tag{5}$$

$$\eta_{yk}(y) = U_{2j-1}\left\{\frac{2y}{U}\right\} \tag{6}$$

where T and U are Chebyshev's polynomials of the first and second kind, respectively. Our calculation uses N_x =2 and N_y =2. Numerical results will be shown with the measured results.

B. Experimental Field Distribution by EOS

Electric fields E_x and E_y were measured by the EOS method using a KTP probe. KTP is the representative EO material and offers maximum sensitivity against transverse electric fields. First, the probe at point S, whose position is depicted in Fig. 4, was moved along the dotted line to define the measurement position. The experimental results of the normalized amplitude E_y along the dotted line are also shown in Fig. 4. On the horizontal axis, the positive and negative values correspond to the probe position above the alumina dielectric and microstrip conductor portions, respectively. The probe height was a parameter. Although the amplitude of E_y is proportional to probe height, the maximum E_y is attained at position S; the most sensitive probe position is the edge of the microstrip conductor. With respect to probe height, clearance of a few μm is necessary to avoid unexpected touching and subsequent damage. The probe height was set at 3 μm and the transverse electric fields along the microstrip patch edges were measured.

Fig. 5(a) shows the normalized amplitude of the E_y field, where the solid lines indicate the theoretical results calculated by the spectral domain approach, and the circles and triangles show the E_y field along microstrip edges BC and AD, respectively. Fig. 5(b) also shows the normalized amplitude of the E_y field along microstrip edges CD (circles) and AB (triangles). The E_x field distribution was also measured using the same KTP probe. The only difference between E_y and E_x measurement is the probe direction which has the maximum sensitivity in each direction. Fig. 6 shows both theoretical and experimental results for the E_x field.

As shown in Figs. 5 and 6, the measured results agree well with the experimental ones. In Fig. 5(a), the measured E_y field at edge AD, to which the microstrip feeder line is connected, differs from the theoretical one, because the theoretical patch model did not include the feeder line. A relatively large difference between the theoretical and experimental results is observed in the E_x field along microstrip edges CB and AD, as shown in Fig. 6(b). This is caused by imperfect isolation of the probe sensitivity in each direction. The measured results can be improved by using high isolation probes. During the measurement, the return loss of the microstrip patch was also

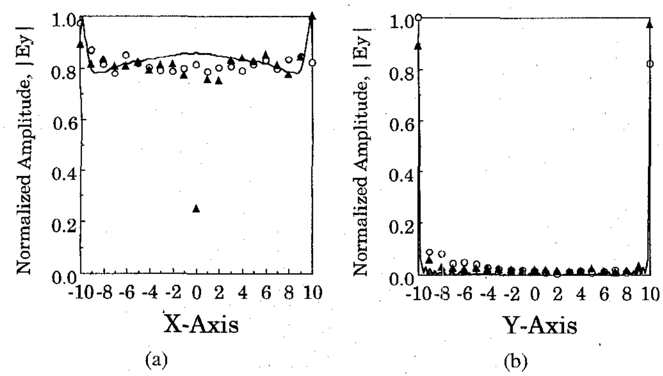

Fig. 5. E_y field distribution. (a) Normalized amplitude along sides BC and AD. (b) Normalized amplitude along sides CD and AB.

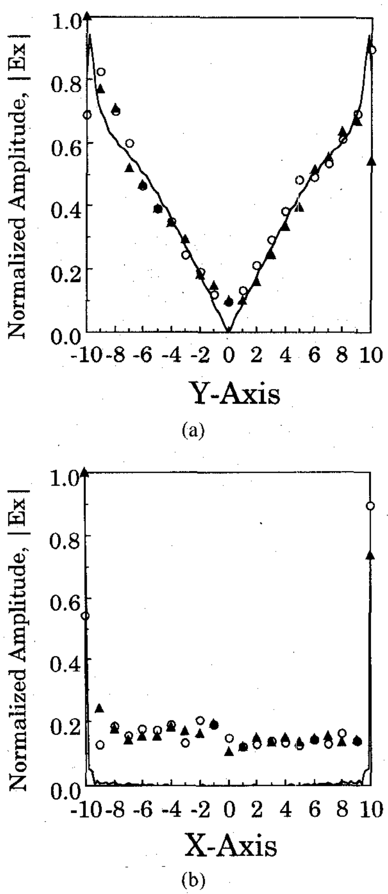

Fig. 6. E_x field distribution. (a) Normalized amplitude along sides CD and AB. (b) Normalized amplitude along sides BC and AD.

monitored using a Network Analyzer. The return loss greater than 20 dB was observed in the experiment. Therefore, EOS can characterize the surface electric fields of microwave planar circuits precisely.

IV. Field Distribution Measurement of Patch Array Antenna

Fig. 7 shows the pattern layout of the measured microstrip patch array fabricated on an alumina substrate. Patch width W, length U, resonant frequency, and element pitch d are 8.21 and 5.56 mm, 8.03 GHz, and 10 mm (about 0.27 $\times$ resonant wavelengths), respectively. In Fig. 7, the numbers on the X and Y axes show coordinates of the measurement points. The E_z field of the microstrip array was measured by the EOS method using a GaAs probe which is a representative EO material offering excellent sensitivity against vertical electric fields. The EO probe height was set at 5 μm.

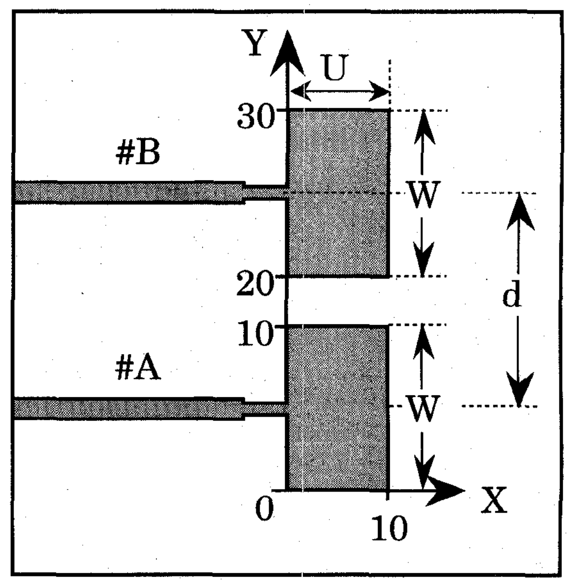

Fig. 7. Pattern layout of dual microstrip patch array.

Figs. 8 and 9 show the measured E_z-field distribution when the two microstrip patches (#A and #B) were excited under phase differences of 0 and 40 degrees, respectively. In Fig. 9, the phase delay of the patch #B is 40 degrees. Figs. 8(a) and 9(a) show the normalized amplitude distribution of the E_z field, and Figs. 8(b) and 9(b) show the relative phase distribution of the E_z field on the edges of the two microstrip patches. In these figures, the plots between $Y = 10$ and $Y = 20$ are compressed, because the variation of the E_z field in this area is extremely small.

The amplitude, as well as phase distribution, of the E_z field in microstrip patches #A and #B is symmetrical as long as the two microstrip patches are excited in phase, as shown in Fig. 8. In Fig. 9, the measured phase of microstrip patch #B is delayed approximately 40 degrees, because microstrip patch #B was excited by a delayed microwave signal. This means that the radiation pattern from the microstrip patch array can be adjusted by the phase of the input microwave signals. Furthermore, it is observed that the amplitude of patch #B is larger than that of patch #A due to the mutual coupling effect. The opposite behavior is also observed if the phase of the input microwaves is reversed. As a result, it was experimentally verified that the surface electric field of patch arrays can be changed by the phase distribution of the microwave signals input. Although the above results are well known in the field of phased arrays, the feasibility of independent electric field measurement of individual array elements excited simultaneously has been successfully demonstrated using the EOS method for the first time. Additionally, since EOS can measure the performance of active devices, it will be a powerful measurement system for wafer-scale integrated planar phased array antennas.

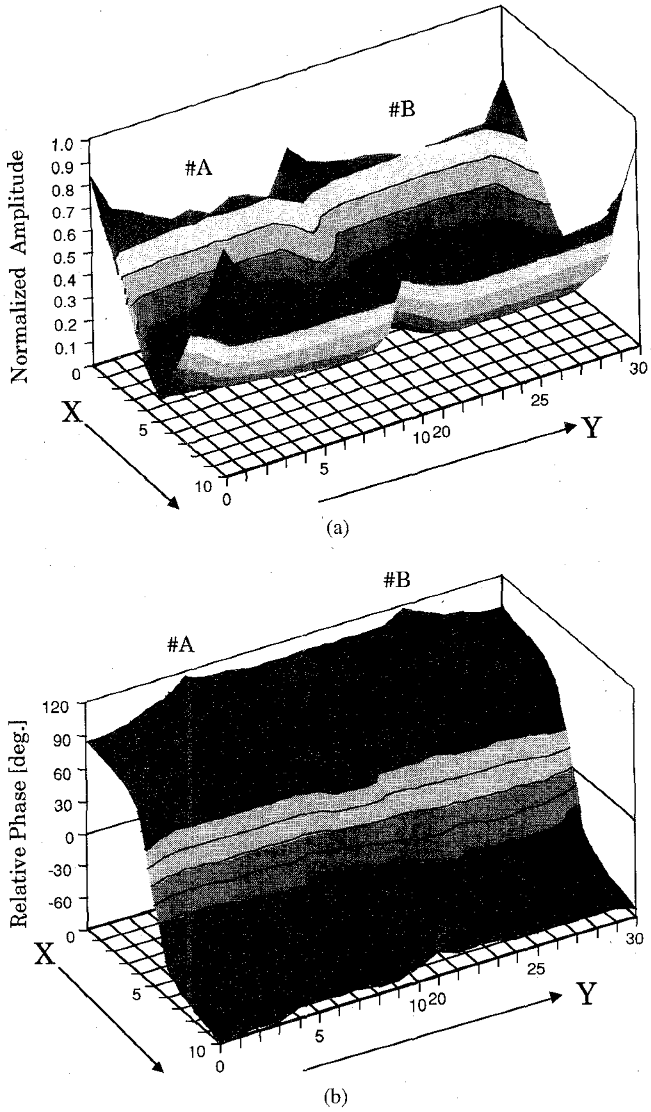

Fig. 8. Measured E_z field distribution with no phase difference. (a) Normalized amplitude distribution. (b) Relative phase distribution.

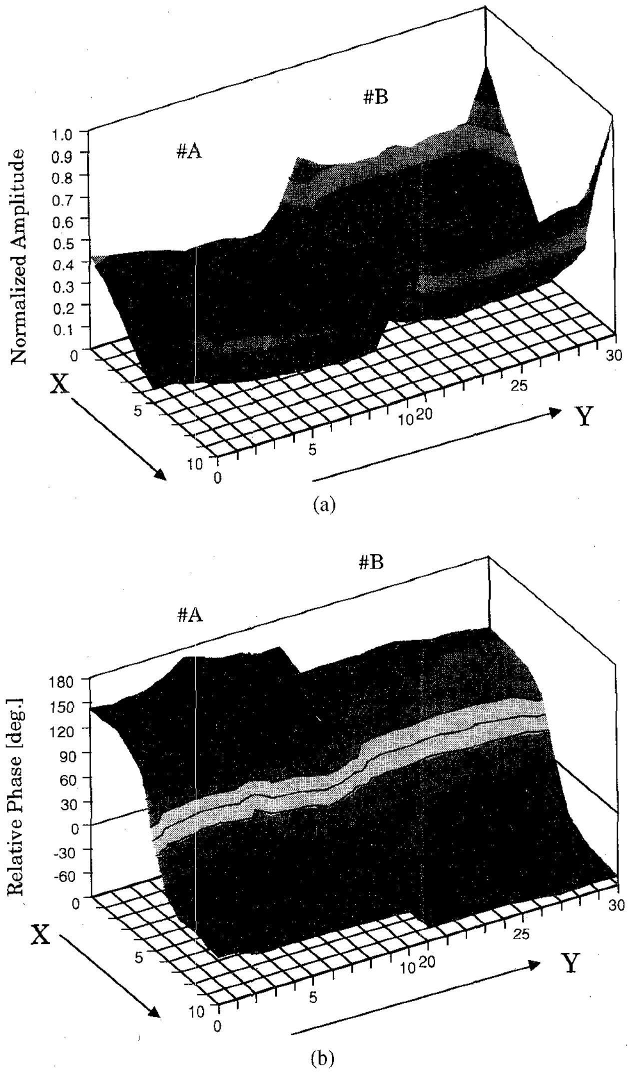

Fig. 9. Measured E_z field distribution with the phase difference of 40 degrees. (a) Normalized amplitude distribution. (b) Relative phase distribution.

V. Conclusion

A novel measurement technique using the EOS method has been successfully used to measure the surface electric fields of microwave integrated arrays. The validity of the proposed method is first verified by a comparison of the exact theoretical results calculated by the spectral domain approach. Second, the electric field distribution of a dual microstrip patch array was characterized by EOS. The advantages of the proposed EOS method are as follows:

1) It can accurately characterize array elements as well as active circuits integrated on the same wafer.
2) Complicated circuit structures which cannot be theoretically calculated can be directly measured.
3) The individual characteristics of array antenna elements can be evaluated in addition to the mutual coupling between elements.
4) All expected and unexpected electromagnetic effects between microwave components will be evaluated.
5) Extension of method to millimeter-wave bands is feasible because of its ultra-high-speed performance whose response speed is above 100 GHz [11].

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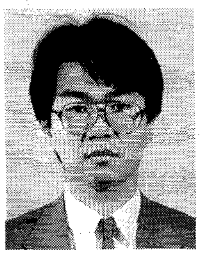

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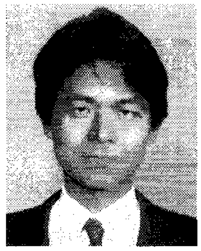

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