손실있는 실리콘 반도체위에 제작된 전송선로의 유한차분법을 이용한 해석

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Analysis of a transmission line on Si-based lossy structure using Finite-Difference Time-Domain(FDTD) method

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요 약

MIS(도체-부도체-반도체) 구조로된 전송선로를 해석하기 위하여 기본적으로 특성임피던스와 전파상수의 추출에 기초한 일반적인 특성화 절차가 사용된다. 본논문에서는 Si와 SiO2층 사이에 0전위를 가진 도체를 일정한 간격의 주기적인 배열로 고안된 새로운 모델의 MIS구조에 대한 유한차분법을 이용한 해석방법을 제안한다. 특히 전송선로에 대한 유전체의 영향을 줄이기 위하여 0전위를 가진 주기적인 결합의 도체로 이루어진 구조가 시간영역의 신호를 통해 시험된다. Quality factor 뿐만아니라 주파수 의존적인 추출된 전송선로 파라미터와 등가회로 파라미터가 주파수 및 0전위 도체 간격의 함수로서 나타내진다. 특히 전송선로의 Quality factor가 특성임피던스 및 유효유전상수의 큰 변화없이 개선될수 있음을 볼 수 있다.

ABSTRACT

Basically, a general characterization procedure based on the extraction of the characteristic impedance and propagation constant for analyzing a single MIS(Metal- Insulator-Semiconductor) transmission line is used. In this paper, an analysis for a new substrate shielding MIS structure consisting of grounded cross-bars at the interface between Si and SiO2 layer using the Finite-Difference Time-Domain (FDTD) method is presented. In order to reduce the substrate effects on the transmission line characteristics, a shielding structure consisting of grounded cross bar lines over time-domain signal has been examined. The extracted distributed frequency-dependent transmission line parameters and corresponding equivalent circuit parameters as well as quality factor have been examined as functions of cross-bar spacing and frequency. It is shown that the quality factor of the transmission line can be improved without significant change in the characteristic impedance and effective dielectric constant.

Ⅰ. INTRODUCTION

Silicon-based technology is increasingly used for RF and microwave integrated circuits because of the distinct advantages of low cost and well developed fabrication techniques. Interconnects in silicon-based ICs can be classified as Metal-Insulator-Semiconductor (MIS) transmission lines, which consist of metal lines on semiconducting substrates, isolated by a thin SiO_2 oxide layer. The semiconducting substrate is characterized by its dielectric constant and conductivity.

In previous work Guckel et al. investigated the

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transmission properties of such structures including the analysis based on a parallel-plate waveguide approach of MIS microstrip lines[1]. In the early 1970s, Hasegawa[2] analyzed theoretically the transmission properties of microstrip lines using a parallel-plate waveguide model with a perfectly conducting line of infinite width for the MIS structure and compared them with experimental results. These works introduced the existence of three fundamental propagation modes caused by the finite resistivity of the semiconducting substrates. These modes are classified as slow-wave mode, dielectric quasi-TEM mode, and skin-effect mode. The mode that dominates depends mainly on the line geometry, the substrate resistivity, and the signal frequency.

More recently efficient and versatile methods for the characterization of low-loss MIS structures have evolved[3,4]. In 1984, Seki and Hasegawa analyzed the crosstalk and interconnection delay in the interconnection system of high-speed LSI/VLSI circuits[5,6], and G. Ghione studied a lossy quasi-TEM model for multiconductor bus lines on semi-insulating GaAs substrates and analyzed crosstalk, propagation signal delay and pulse distortion in high-speed circuits[7]. J. Gilb presented the pulse distortion and coupling of multilayer symmetric and asymmetric coupled microstrip lines using a full-wave spectral domain technique[8-10].

Microstrip structures realized on a Si-SiO2 substrate are known to be quite sensitive to the conductive properties of Si because of the particular field configuration. Goel reported a crosstalk analysis for a multi-layer multi-conductor system in the same dielectric[11].

Multi-layer multi-conductor configurations form a part of most of the high-speed circuits. Tripathi et al. reported analytical and numerical techniques for the pulse propagation characteristics such as delay, distortion, and crosstalk in multilevel interconnections associated with high-speed digital ICs including VLSI chips[12]. Chan et al. presented the propagation characteristics of waves along a periodic array of parallel signal lines in a multi-layered structure in the presence of a periodically perforated ground plane and the characterization of the discontinuities made of two orthogonally crossed strip lines on a suspended substrate[13].

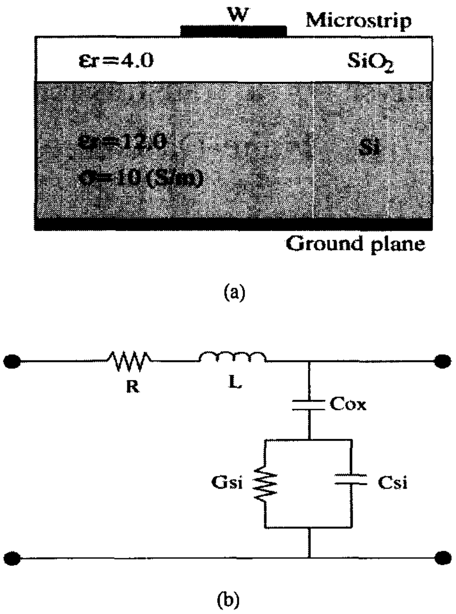


Fig. 1 (a) Single microstrip line MIS structure, and (b) its distributed equivalent circuit model

In this paper, a single MIS transmission line structure on Si-SiO2 substrates as shown in Fig. 1(a) is analyzed using the FDTD method. Then, a new substrate shielding structure consisting of grounded cross-bars is examined, and microstrip characteristics for single line over the cross-bar shielding structure is presented. The substrate-shielded microstrip structure is essentially a two-layered microstrip line with a series of cross-bar conductors at the interface between Si and SiO2 layer. The cross-bar conductors are perpendicular to the main transmission line strip conductor and are assumed to be at ground potential. A full-wave analysis of the cross-bar structure is carried out using FDTD. Equivalent circuit parameters are extracted for substrate-shielded microstrip structures from FDTD simulations, and a comparison is made with the two-layered microstrip structure without substrate shield.

Ⅱ. ANALYSIS OF A SINGLE MICROSTRIP MIS STRUCTURE

A single microstrip MIS structure and the distributed equivalent circuit model are shown in Fig. 1. It is assumed that the oxide layer is lossless and the silicon layer is lossy. The conductor loss is assumed to be zero. The characteristic impedance $Z_0(\omega)$ and the propagation constant $\gamma(\omega)$ of the signal line are obtained from the ratio of the Fourier-transformed voltage and current and the ratio of the voltages taken at two different locations. Once $\gamma(\omega)$ and $Z_0(\omega)$ are obtained, the distributed transmission line parameters for a single line $R(\omega)$, $L(\omega)$, $G(\omega)$, and $C(\omega)$ can be calculated in a similar manner as for a lossless transmission line, using the procedure described in [14]. The equations for obtaining the distributed series impedance and shunt admittance are

$$\gamma(\omega)\cdot Z_0(\omega) \equiv R(\omega)+j\omega L(\omega) \tag{1}$$

$$\frac{\gamma(\omega)}{Z_0(\omega)} \equiv G(\omega)+j\omega C(\omega) \tag{2}$$

The equivalent circuit for a small length of the structure is Fig. 1(b) which consists of series resistance $R(\omega)$ inductance $L(\omega)$, shunt capacitances $C_{ox}(\omega)$ for the oxide layer and capacitance $C_{si}(\omega)$ and conductance $G_{si}(\omega)$ for the silicon layer. It is assumed that the capacitance and the conductance for the silicon layer are related as

$$\frac{C_{si}}{G_{si}} = \frac{\varepsilon_{si}}{\sigma_{si}} \tag{3}$$

where ε_{si} and σ_{si} are the dielectric constant and conductivity of Si layer, respectively. As mentioned above, the overall admittance $Y(\omega)$ is given by

$$Y(\omega) = G(\omega)+j\omega C(\omega) \tag{4}$$

Using equations (3) and (4), the equivalent circuit parameters $C_{ox}(\omega)$, $G_{si}(\omega)$, and $C_{si}(\omega)$ for the oxide and silicon layer can be calculated as

$$G_{si}(\omega) = \frac{\sigma^2}{Re(Z(\omega))(\sigma^2+\omega^2\varepsilon^2)} \tag{5}$$

$$C_{si}(\omega) = \frac{\sigma\varepsilon}{Re(Z(\omega))(\sigma^2+\omega^2\varepsilon^2)} \tag{6}$$

$$C_{ox}(\omega) = -\frac{G_{si}^2+\omega^2 C_{si}^2}{\omega Im(Z(\omega))(G_{si}^2+\omega^2 C_{si}^2)+\omega^2 C_{si}} \tag{7}$$

where $Z(\omega) = 1/Y(\omega)$.

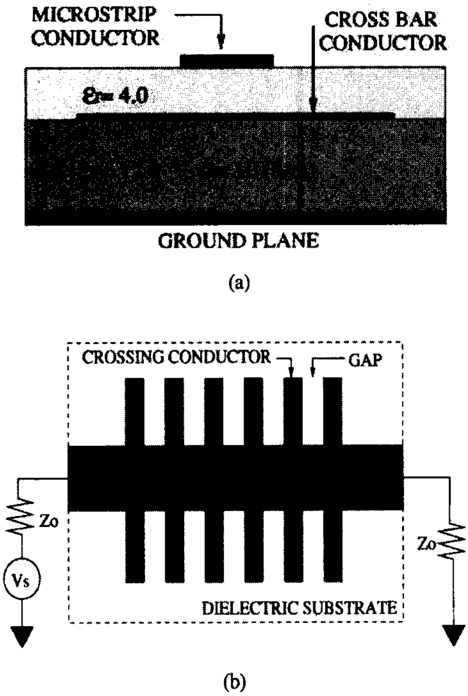
As an example, a single microstrip MIS structure is simulated using FDTD. The metal strips and the ground plane are assumed to be perfectly conducting and infinitely thin, and are defined by setting the tangential component of the electric field to zero. The conductor line is simulated on an $N_x\Delta x$ by $N_y\Delta y$ by $N_z\Delta z$ computational domain with Δx=10 μm, Δy=12.5 μm and Δz=20 μm. This corresponds to a conductor width W=5Δx of the signal line and substrate heights H1=16Δy and H2=2Δy. The width, N_x, and height, N_y, of the simulation box are chosen to be large enough to not disturb the field distributions near the strips. In all, the entire computational domain including the PML boundary of 8 cells is divided into 58 by 50 by 280 grid cells.

A time step of Δt=0.0218 ps is used and the total number of time steps is 2500. The input is excited with a Gaussian pulse with T=2.33 ps and t_0=6.98 ps.

Ⅲ. SINGLE MIS LINE WITH SUBSTRATE SHIELDING

A single line MIS structure with an embedded grounded cross bar structure for substrate shielding is shown in Fig. 4. The width and spacing of the cross bars are considered to be much smaller than the wavelength so that uniform signal propagation can be assumed along the line.

As in the case without substrate shielding, the characteristic impedance $Z_o(\omega)$ and the propagation constant $\gamma(\omega)$ of the signal line are obtained from the ratio of Fourier-transformed voltage and current and the ratio of the voltages taken at two different locations, respectively.



(a)

(b)

Fig. 4 (a) Side view and (b) top view of single microstrip MIS structure with embedded grounded cross bars for substrate shielding.

In the FDTD method, the entire computational domain is discretized into a number of cells of size Δx, Δy and Δz in x, y and z directions, respectively. Fig. 5 shows the total computational domain of the proposed cross bar structure including the Perfectly Matched Layer (PML) absorbing boundary condition.

During the FDTD simulation, the potential is set to be zero for the grid cells containing the cross bar conductors so that all cross bars behave like perfect grounded conductors. The input port of the signal line is excited with a Gaussian pulse and the voltages and currents are recorded at two different locations. The characteristic impedance of the structure is obtained from the ratio of Fourier-transformed voltage and current.

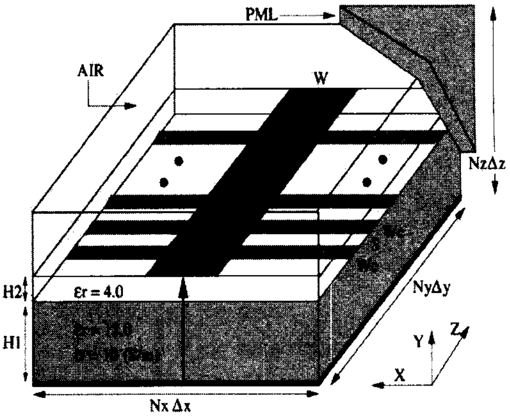


Fig. 5 Computational domain for FDTD simulation of a single MIS line with a cross bar substrate shielding structure.

The metal strips and the ground plane are assumed to be perfectly conducting and infinitely thin, and are defined by setting the tangential component of the electric field to zero. The conductor lines are simulated on an $N_x\Delta x$ by $N_y\Delta y$ by $N_z\Delta z$ computational domain with $\Delta x=10\,\mu$m, $\Delta y=12.5\,\mu$m and $\Delta z=20\,\mu$m. This corresponds to conductor width W=5Δx of the signal line, a cross bar conductor width of Wc=2Δz, a gap size between the cross bars of S=2Δz, 3Δz, 4Δz, 5Δz, and 6Δz respectively, and substrate heights H1=16Δy and H2=2Δy. The width, N_x, and height, N_y, of the simulation box are chosen to be large enough to not disturb the field distributions near the strips. The entire computational domain including the PML boundary of 8 cells is divided into 58 by 50 by 280 grid cells.

A time step of Δt=0.0218 ps is used and the total number of time steps is 2500. The input is excited with a Gaussian pulse with T=2.33 ps and t_0=6.98 ps. Figures 6 to 13 show the results of the MIS line with the cross bar structure for different spacing of the cross bar conductors for substrate conductivity σ=10 (siemens/m). Figures 6 and 7 show the frequency-dependent effective dielectric constant $\varepsilon_{eff}(\omega)$ and characteristic impedance $Z_o(\omega)$ for various gap sizes between the cross bars as well as without cross bars, respectively.

It can be seen that the effective dielectric constant and characteristic impedance are changed only slightly by the presence of the cross bar structure. The overall inductance, conductance, capacitance and attenuation constant are shown in Figures 8 to 11, respectively. It is observed that the overall conductance $G(\omega)$ is reduced with the introduction of the cross bar conductors, and the smallest conductance is achieved for the smallest gap size (S=40 μm).

Fig. 12 shows the quality factor Q= $\beta/2\alpha$ as a function of frequency and Fig. 13 gives a variation in Q as a function of normalized spacing (cross bar width/spacing) for different frequencies. It is observed that the quality factor Q improves for decreasing cross bar spacing and that the improvement is more pronounced at lower frequencies.

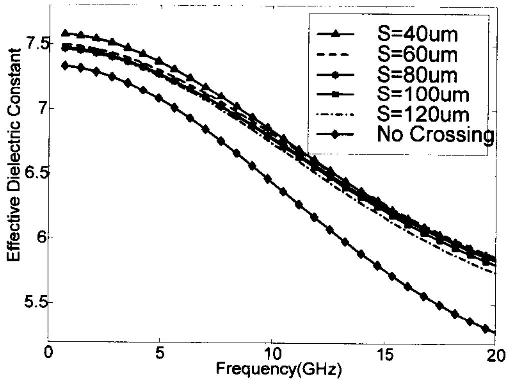


Fig. 6 Effective dielectric constant of a single MIS line with cross bars substrate shielding structure for σ =10(S/m).

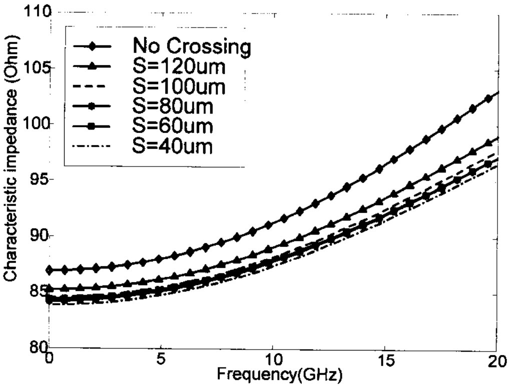


Fig. 7 Characteristic impedance of a single MIS line with cross bars substrate shielding structure for σ =10(S/m).

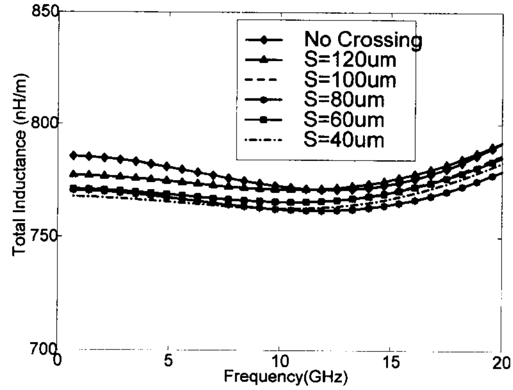


Fig. 8 Total inductance of a single MIS line with cross bars substrate shielding structure for σ=10(S/m).

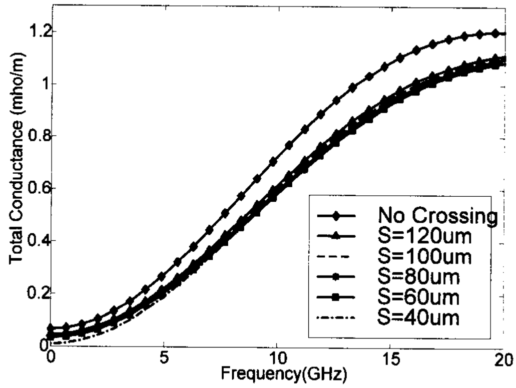


Fig. 9 Total conductance of a single MIS line with cross bars substrate shielding structure for σ=10(S/m).

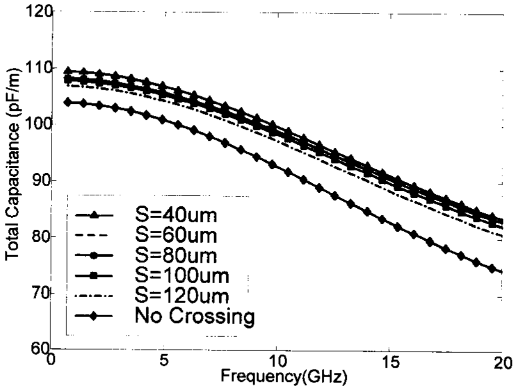


Fig. 10 Total capacitance of a single MIS line with cross bars substrate shielding structure for σ=10(S/m).

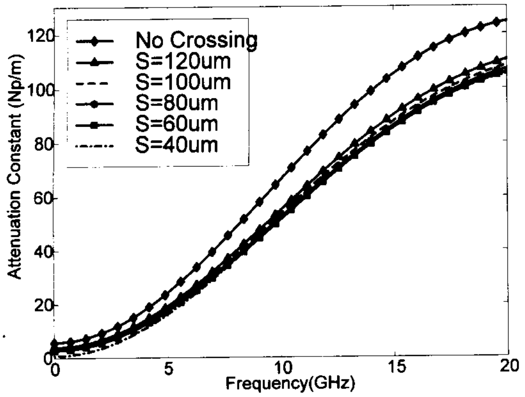


Fig. 11 Attenuation constant of a single MIS line with cross bars substrate shielding structure for σ =10(S/m)

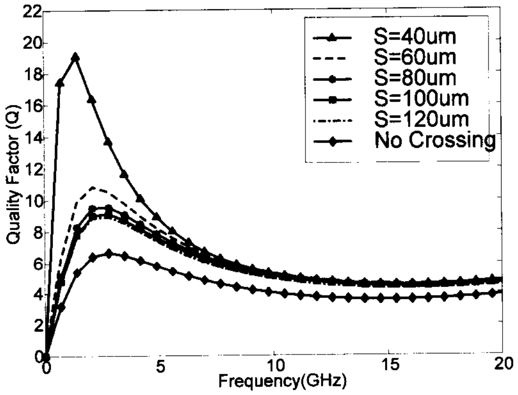


Fig. 12 Quality factor(Q) as a function of frequency of a single MIS line with cross bars substrate shielding structure for σ=10(S/m).

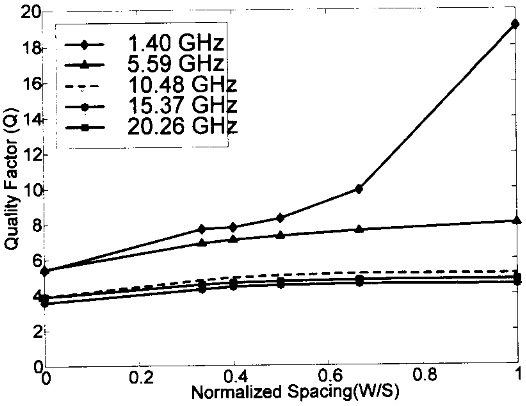


Fig. 13 Quality factor(Q) of a single MIS line with cross bars substrate shielding structure with the normalized spacing for σ=10(S/m).

Ⅳ. CONCLUDING REMARKS

In this paper, the Finite Difference Time Domain (FDTD) method has been applied to compute the propagation constants and characteristic impedances of Si-based multilayer single microstrip line MIS structures. The results show that the transmission line characteristics are strongly influenced by the lossy nature of the silicon substrate. In order to reduce the substrate effects on the transmission line characteristics, a shielding structure consisting of grounded cross bar conductor lines has been examined.

The extracted distributed transmission line parameters and corresponding equivalent circuit parameters as well as quality factor have been examined as a function of spacing of the crossbar lines. It was found that the quality factor of the transmission lines can be improved without significant change in the characteristic impdance and effective dielectric constant.

REFERENCES

[1] H. Guckel and I. Palocz, "A parallel-plate waveguide approach to micro-miniaturized, planar transmission lines for integrated circuits," IEEE Trans. MTT, vol. 15, pp. 468-476, Aug. 1967.

[2] H. Hasegawa and H. Yanai, "Properties of microstrip line on Si-SiO2 system," IEEE Trans. MTT, vol. 19, pp. 869-881, Nov. 1971.

[3] V. Tripathi and R. Bucolo, "A simple network analog approach for the quais-static characteristics of general lossy, anisotropic, layered structures," IEEE Trans. MTT, vol. 33, pp. 1458-1464, Dec. 1985.

[4] M. Abushaaban and S. Scanlan, "Modal circuit decomposition of lossy multiconductor transmission lines," IEEE Trans. MTT, vol. 44, pp. 1046-1057, July 1996.

[5] S. Seki and H. Hasegawa, "Analysis of crosstalk in very high-speed LSI/VLSI's using a coupled multiconductor MIS microstrip line

model," IEEE Trans. MTT, vol. 32, pp. 1715-1720, Dec. 1984.

[6] H. Hasegawa and S. Seki, "Analysis of interconnection delay on very high speed LSI/VLSI chips using an MIS microstrip line model," IEEE Trans. MTT, vol. 32, pp. 1721-1727, Dec. 1984.

[7] G. Ghione and G. Vecchi, "Modeling of multiconductor buses and analysis of crosstalk, propagation delay, and pulse distortion in high-speed GaAs logic circuits," IEEE Trans. MTT, vol. 37, pp. 445-456, Mar. 1989.

[8] J. Gilb and C. Balanis, "Pulse distortion on multilayer coupled microstrip lines," IEEE Trans. MTT, vol. 37, pp. 1620-1628, Oct. 1989.

[9] J. Gilb and C. Balanis, "Transient analysis of distortion and coupling in lossy coupled microstrips," IEEE Trans. MTT, vol. 38, pp. 1894-1899, Dec. 1990.

[10] J. Gilb and C. Balanis, "Asymmetric multiconductor low-coupling structures for high-speed, high-density digital interconnects," IEEE Trans. MTT, vol. 39, pp. 2100-2106, Dec. 1991.

[11] A. Goel and Y. Huang, "Modeling of crosstalk among the GaAs-based VLSI interconnections," Proceedings of the IEE, vol. 136, pp. 361-368, Dec. 1989.

[12] V. Tripathi and R. Bucolo, "Analysis and modeling of multilevel parallel and crossing interconnection lines," IEEE Trans. ED, vol. 34, pp. 650-658, Mar. 1987.

[13] C. Chan and R. Mittra, "The propagation characteristics of signal lines embedded in a multilayered structure in the presence of a periodically perforated ground plane," IEEE Trans. MTT, vol. 36, pp. 968-975, June 1988.

[14] Y. Kim and V.K. Tripathi, "Extraction of multiple coupled line parameters using FDTD simulation," IEE Proc. Micro. Antennas and Prop., vol. 146, pp. 443-446, Dec. 1999.

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