Novel Configurations of Planar Multilayer Magic-T Using Microstrip-Slotline Transitions

Jeong Phill Kim, *Member, IEEE,* and Wee Sang Park, *Member, IEEE*

***Abstract*—Novel configurations of microwave planar magic-T suitable for microwave integrated circuits (MICs) and monolithic MICs are described. They consist of microstrip and slotline T-junctions coupled by microstrip-slotline transitions. Since via-hole processing is not encountered, they are especially applicable to multilayer MICs. Derived equivalent network models are used efficiently for the design of the corresponding multilayer microstrip magic-T. Measured data and numerical simulations showing good amplitude and phase characteristics over an octave operating bandwidth validate the proposed configurations of planar magic-T.**

***Index Terms*—Computer-aided design, equivalent circuit, magic-T, microstrip circuits, multilayer.**

I. Introduction

The increasing complexity of microwave systems has led to the need for high-density interconnects in microwave integrated circuits (MICs) and microwave monolithic integrated circuits (MMICs) [1]. In various microwave circuit applications, magic-Ts have been used as fundamental components, such as power combiners or dividers, balanced mixers and amplifiers, frequency discriminators, and monopulse antennas.

The rat race is a well-known example of a magic-T, but its 20%$\sim$25% bandwidth limits its applications to narrow-band circuits [2]. Several designs have been developed to extend the bandwidth. One technique used a $\lambda_g/4$ coupled microstrip line section to replace the $3\lambda_g/4$ section of the conventional $3\lambda_g/2$ microstrip ring coupler [3]. Although the bandwidth has increased to approximately an octave, the difficulty of constructing the coupled microstrip line section, which requires short circuits at the ends, limits its use to lower frequencies. A double-sided MIC magic-T using coupled slotlines and microstrip-slotline transitions was proposed [4] to examine the possibility of bandwidth enhancement and the implementation of high-density integrated circuits. Even though this type of magic-T has the additional advantage of port location, via-hole or wire bonding process causes difficulty of fabrication as the frequency increases. For easy integration with active elements and broadband operation, several types of uniplanar magic-T have been suggested [5], [6]. However, the fabrication problem due to the bonding process for wire bridges limits its use.

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J. P. Kim is with the School of Electrical and Electronic Engineering, Chung-Ang University, Seoul 156-756, Korea (e-mail: phill@cau.ac.kr).

W. S. Park is with the Department of Electronic and Electrical Engineering, Pohang University of Science and Technology, Pohang, Kyungbuk 790-784, Korea (e-mail: wsp@postech.ac.kr).

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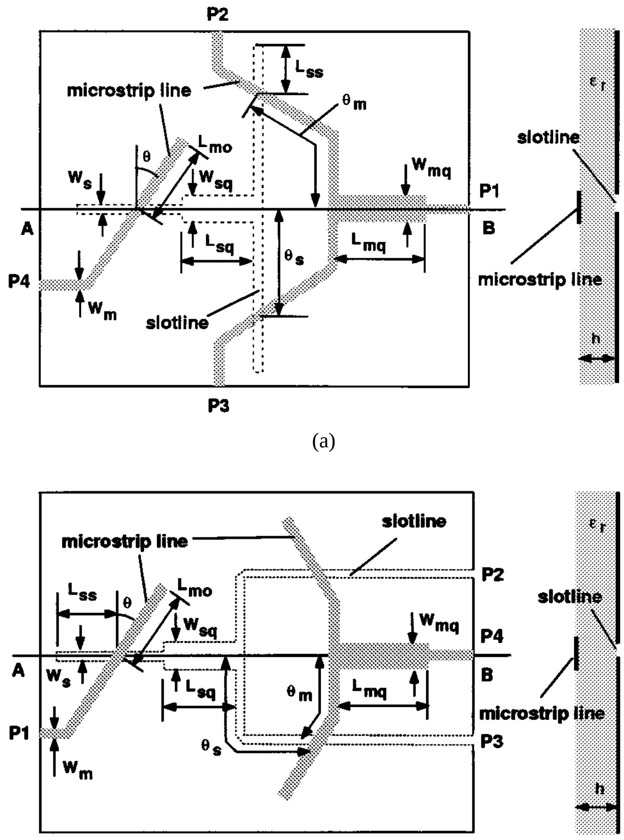

Fig. 1. Configurations of proposed magic-T. (a) Microstrip type. (b) Slotline type.

Another type of MIC magic-T was proposed in a multilayer configuration [7], [8]. This type of magic-T uses back-to-back microstrip lines coupled through the aperture in the common ground plane. Due to the electrically short slot used, the operating bandwidth tends to be narrow.

This paper proposes two configurations of broad-band multilayer planar magic-T using microstrip-slotline transitions. Equivalent networks are developed to provide a conceptual understanding of the circuit operation. The characteristics of the proposed configurations of magic-T are computed and compared with the measured data and numerical simulation results.

II. Configuration and Network Model

Fig. 1(a) and (b) shows two circuit configurations of the magic-T proposed here. A conventional microstrip T-junction is made on one side of the microstrip substrate and a slotline

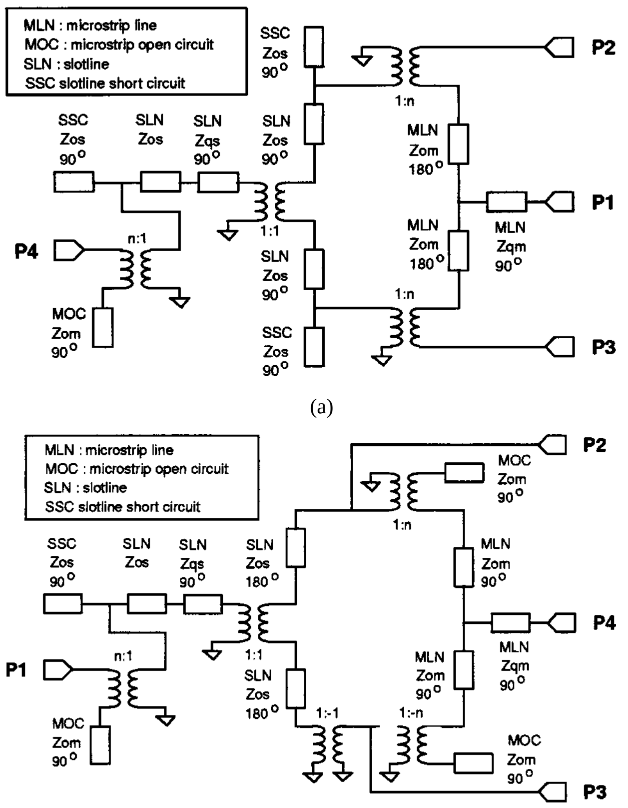

Fig. 2. Equivalent circuits of the magic-T. (a) Microstrip type. (b) Slotline type.

T-junction on the opposite side. They are electrically coupled via the microstrip-slotline transitions. Ports 1 and 4 are the sum ($\sum$) and difference (Δ) ports, respectively, and ports 2 and 3 are the remaining ports of the magic-T. They can be classified into two types (*microstrip type* and *slotline type*), as shown in Fig. 1(a) and (b), according to the type of transmission lines connected to ports 2 and 3. Microstrip and slotline quarter-wave transformers, as well as open and short stubs, are introduced for impedance matching.

The fundamental behavior can be explained by examining the corresponding equivalent circuits shown in Fig. 2(a) and (b), where the microstrip-slotline transition is modeled by an ideal transformer with a turns ratio n. Table I shows the required values of the structure's parameters for the proper operation of the magic-T at the center frequency. Z_{om} and Z_{os} denote the characteristic impedances, λ_{gm} and λ_{gs} the guide wavelengths, and Z_{qm} and Z_{qs} the characteristic impedances of the quarter-wave transformers of a microstrip line and a slotline, respectively.

Since the case of $p = 1$ and $q = 0$ in Table I is adequate for practical circuit implementation, the circuit for this case is examined further. The behavior of the slotline type is similar to that of the microstrip type in principle, therefore only the latter case will be considered. The electric field and current distributions are drawn in the slotline and microstrip line in Fig. 3(a) and (b), respectively, which enable us to have a conceptual understanding of the in-phase and out-of-phase coupling behavior.

TABLE I
REQUIRED VALUE OF STRUCTURE PARAMETERS FOR THE PROPER OPERATION OF TWO TYPES OF MAGIC-T AT THE CENTER FREQUENCY ($p = 0, 1, 2, \ldots, q = 0, 1, 2, \ldots$)

type	microstrip type	slotline type
θ_m	$p\,\pi$	$(q+1/2)\,\pi$
θ_s	$(q+1/2)\,\pi$	$p\,\pi$
Z_{qm}	$Z_{om}/\sqrt{2}$	
Z_{qs}	$\sqrt{2}\,Z_{os}$	
L_{mo}	$\le \lambda_{om}/4$	
L_{ss}	$\le \lambda_{os}/4$	
n	$\sqrt{Z_{om}/Z_{os}}$	

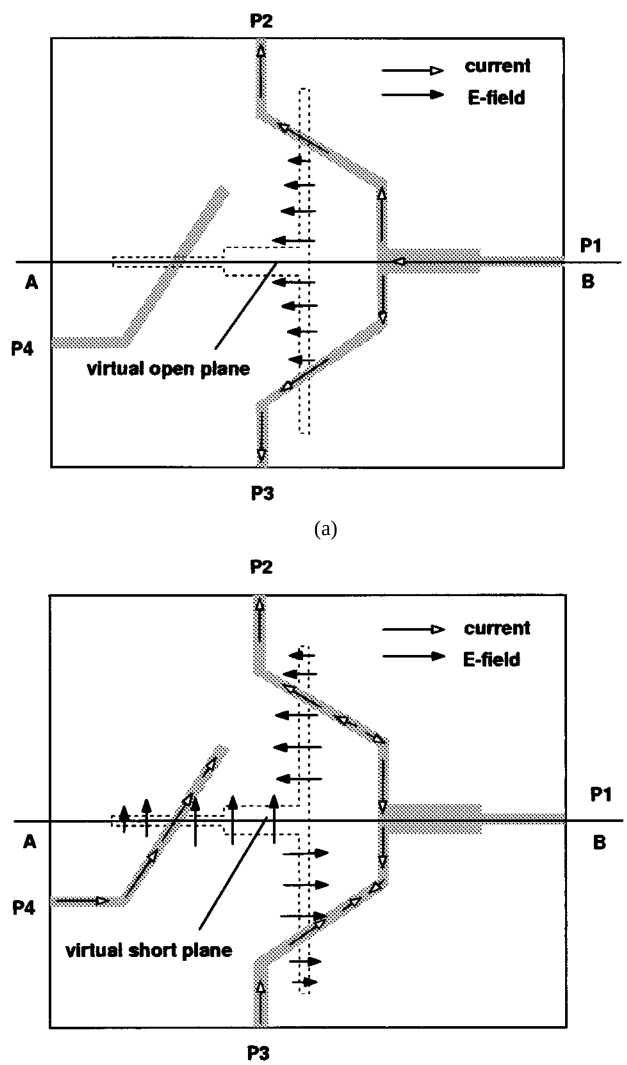

Fig. 3. Electric field and current distributions of microstrip type magic-T. (a) In-phase. (b) Out-of-phase.

As shown in Fig. 3(a), when a signal is applied to port $1(\sum)$, the symmetry plane A–B becomes a virtual open plane. The

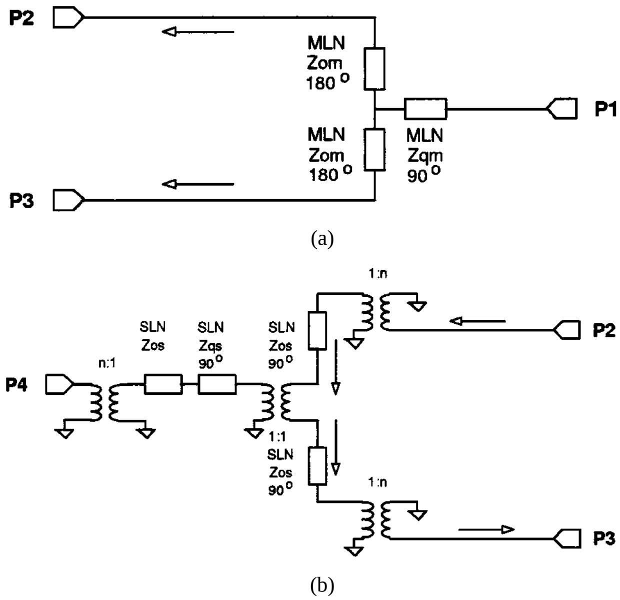

Fig. 4. Simplified circuit representations of microstrip type magic-T. (a) In-phase. (b) Out-of-phase.

equivalent circuit can, therefore, be further simplified at the center frequency as shown in Fig. 4(a). In this case, the applied input signal is evenly split into two in-phase components at ports 2 and 3, and port 4 is isolated (in-phase coupling case). Conversely, the symmetry plane becomes a virtual short plane for an input signal at port $4(\Delta)$, as shown in Fig. 3(b), and the equivalent circuit is simplified as shown in Fig. 4(b). The input signal at port 4, equally split into two components, arrives at port 2 and 3 with a phase difference of 180°, and port 1 becomes isolated (out-of-phase coupling case). If two input signals are applied at ports 2 and 3, the sum and difference of the inputs will be formed at ports $1(\sum)$ and $4(\Delta)$, respectively.

The slotline type magic-T shown in Fig. 1(b) is especially applicable to the monopulse system using a tapered slot antenna [9] as a radiator because of its simple feed structure. Fig. 2(b) shows its equivalent circuit, and the electric field and current distributions are also depicted in Fig. 5(a) and (b). The simplified equivalent circuits shown in Fig. 6(a) and (b) can be derived at the center frequency for the in-phase and out-of-phase coupling cases, respectively. The detailed coupling behavior is similar to that of the microstrip type magic-T.

These magic-T forms can also be made using a double substrate (triple-sided) configuration. For the microstrip type magic-T, a microstrip feed for port $1(\sum)$ and a microstrip T-junction can be placed on the upper surface of the top substrate, a slotline T-junction on the common ground plane, and a microstrip feed for port $4(\Delta)$ on the lower surface of the bottom substrate. This circuit configuration is useful for making multilayer MICs and MMICs. In addition, it results in the additional advantages of port location and circuit layer isolation for the sum and difference channels.

The impedance matching performance depends on the turns ratio n of the ideal transformers, and its value is determined by $n = \sqrt{Z_{om}/Z_{os}}$. The required turns ratio can be achieved by adjusting θ, the inclination angle between the microstrip line and slotline, appropriately. The related turns ratio as a function of

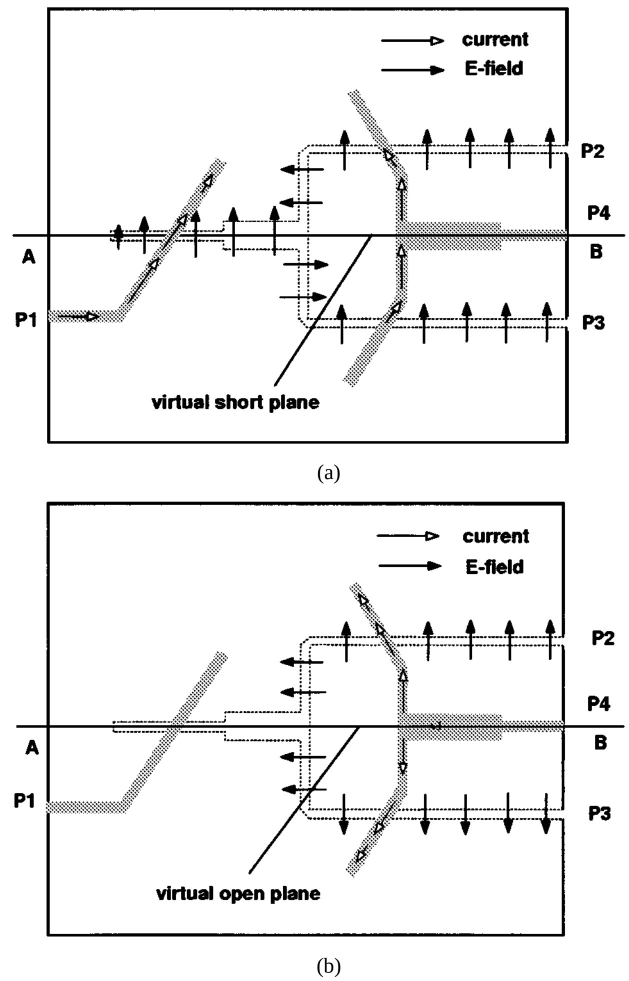

Fig. 5. Electric field and current distributions of slotline type magic-T. (a) in-phase. (b) Out-of-phase.

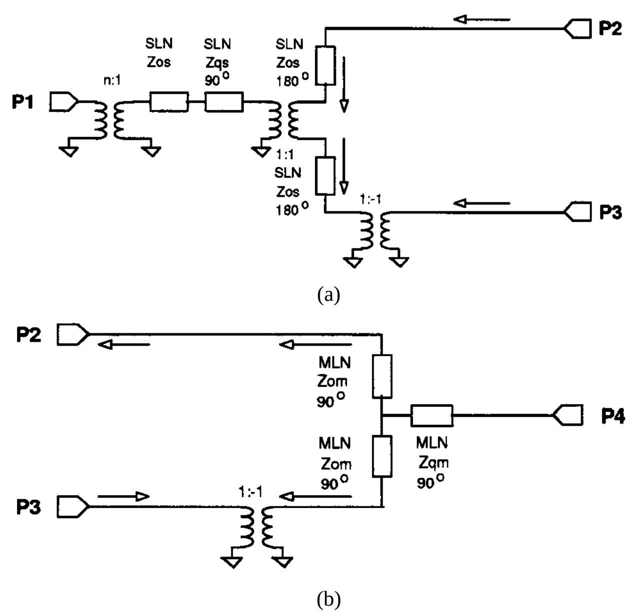

Fig. 6. Simplified circuit representations of slotline type magic-T. (a) In-phase. (b) Out-of-phase.

the inclination angle can be efficiently calculated by the method described by authors [10], [11], where the reciprocity theorem

TABLE II
DESIGN PARAMETERS OF THE MAGIC-TS

parameters	value	parameters	value
f_o	2.00 GHz	W_s	0.30 mm
ε_r	10.2	W_{sq}	1.10 mm
h	31 mils	L_{mo}	14.29 mm
θ	30°	L_{mq}	14.00 mm
W_m	0.60 mm	L_{ss}	20.13 mm
W_{mq}	1.14 mm	L_{sq}	20.06 mm

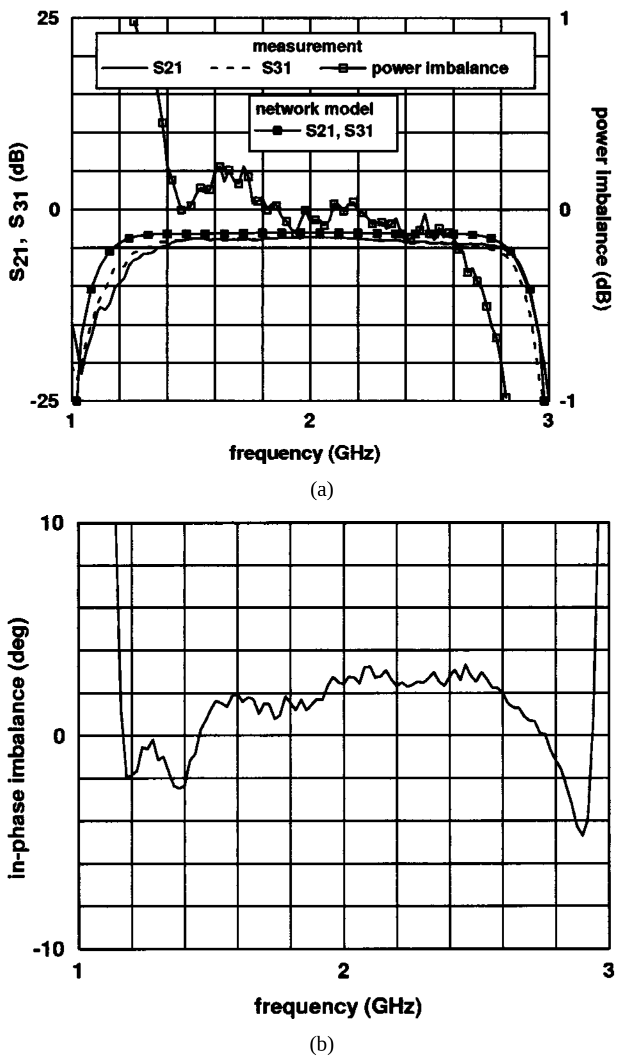

Fig. 7. Computed and measured characteristics of S_{21} and S_{31} of the microstrip type magic-T. (a) Amplitude. (b) Phase.

[12], [13] is successfully used with the spectral-domain immittance approach [14].

The characteristic impedances and propagation constants of the microstrip lines and slotlines can be calculated analytically or numerically [15]. All the characteristics of these configurations of the magic-T can then be calculated from their equivalent circuits shown in Fig. 2(a) and (b).

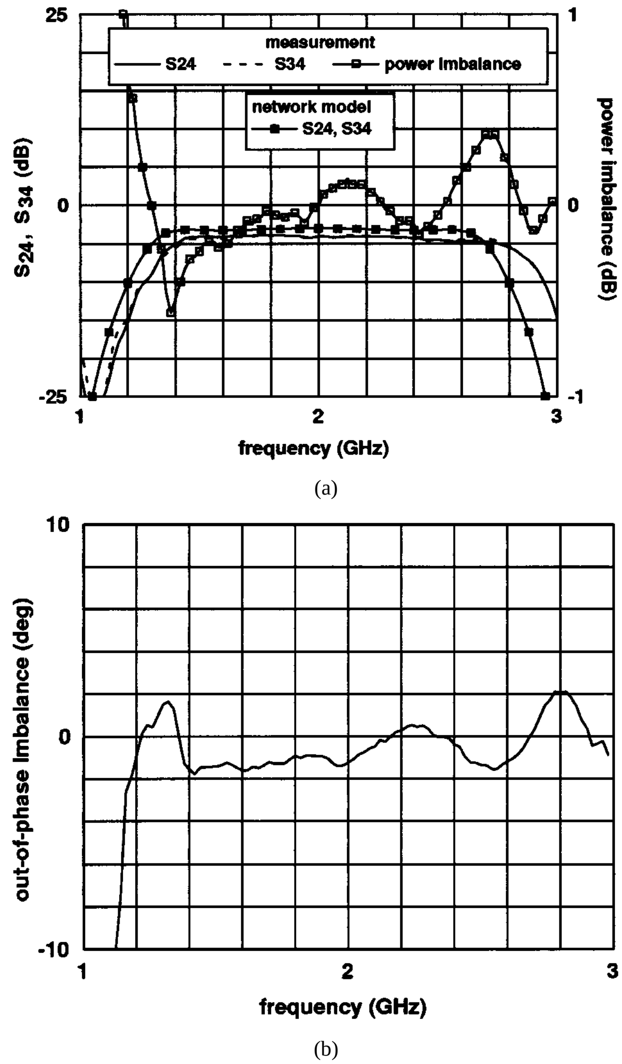

Fig. 8. Computed and measured characteristics of S_{24} and S_{34} of the microstrip type magic-T. (a) Amplitude. (b) Phase.

III. Results and Discussions

The structure parameters of the magic-T of the microstrip type and slotline type with a design frequency of 2 GHz are shown in Table II. In this case, $Z_{om} = 50\,\Omega$ and $Z_{os} = 67.4\,\Omega$. The required $n = 0.86$ can be obtained by setting the inclination angle θ equal to 30°.

A microstrip type magic-T was fabricated with these design values. For an input signal at port 1, the network model yields the relation $S_{21} = S_{31}$, which implies that the signal is evenly split into two in-phase components at ports 2 and 3. The computed characteristics of the amplitude of S_{21} and S_{31} by the network model are plotted in Fig. 7(a) together with the measured data. Good agreement is observed. Since the in-phase balancing between S_{21} and S_{31} is perfect from the network model, only the measured phase characteristics are depicted in Fig. 7(b). Fig. 8(a) shows the measured and computed characteristics of the amplitude of S_{24} and S_{34} for the input signal at port 4. In this case, the relation $S_{24} = -S_{34}$ holds from the equivalent network model. Therefore, the phase difference becomes 180° with an equal power split. The measured and computed return loss and isolation characteristics are shown in Fig. 9(a) and

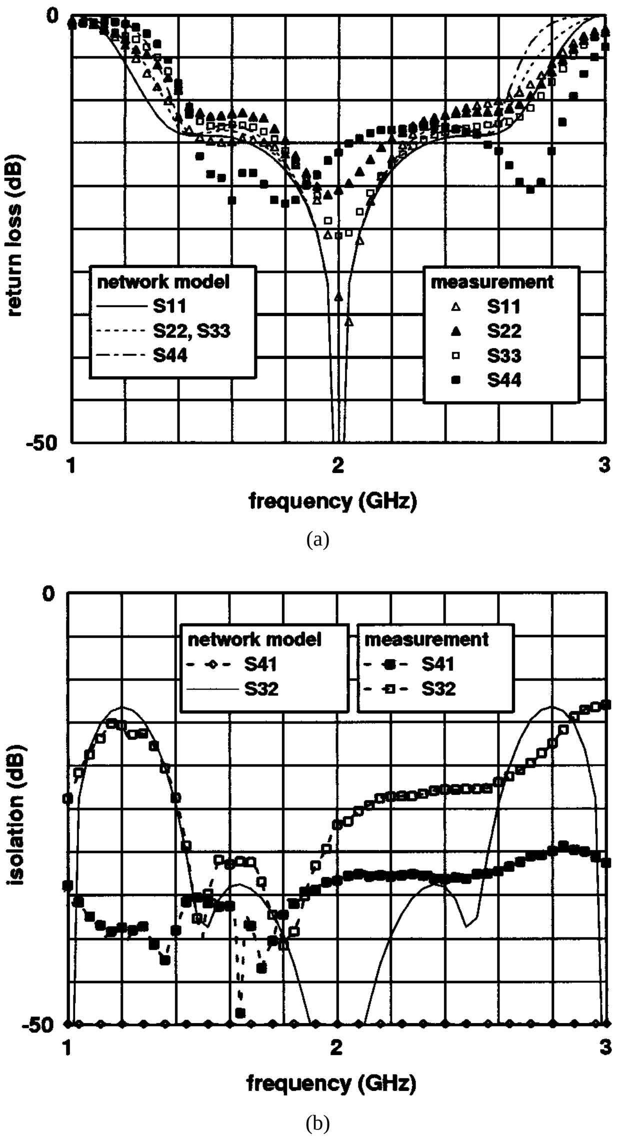

Fig. 9. Computed and measured return loss and isolation characteristics of the microstrip type magic-T. (a) Return loss. (b) Isolation.

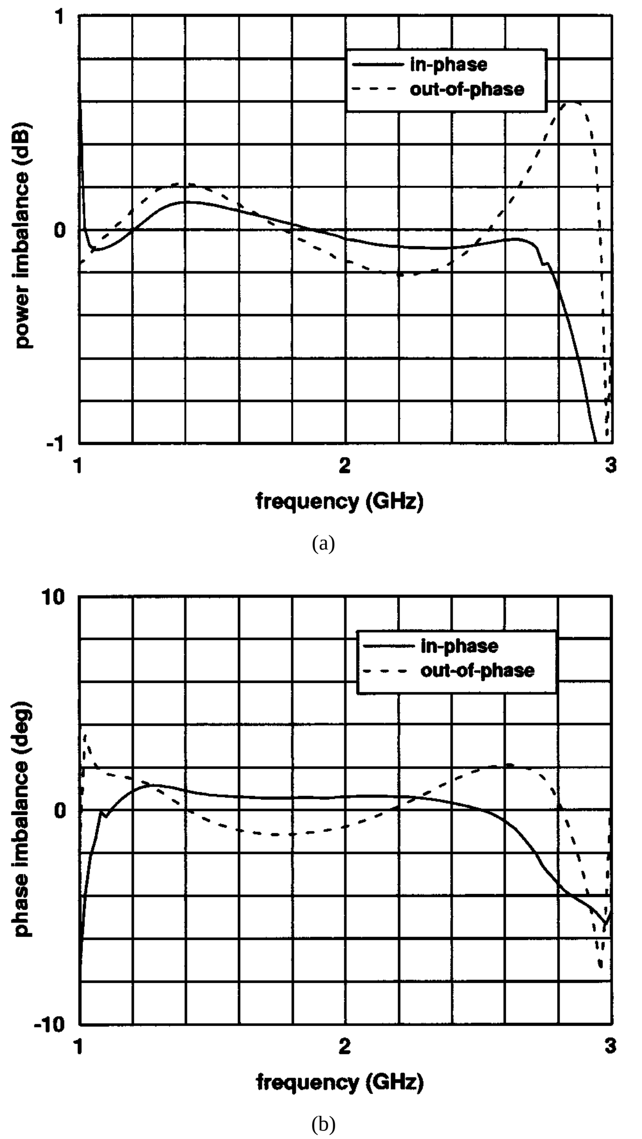

Fig. 10. Simulation results of amplitude and phase imbalancing characteristics of the slotline type magic-T. (a) Amplitude. (b) Phase.

(b). Reasonable agreement is obtained. A near one-octave bandwidth (−10-dB return loss), a 35-dB isolation between ports 1 and 4, and a 23-dB isolation between ports 2 and 3 are observed. In the frequency range of interest, the maximum amplitude imbalance is less than 0.2 dB for the in-phase and out-of-phase power coupling cases, and the maximum phase imbalance is less than 3° and 2°, respectively.

Next, a slotline type magic-T was designed. Since the characteristic impedance of the slotline is known to be frequency-dependent, it is not easy to measure the scattering parameters of the circuit. Only the simulation results based on the method of moments (MOM)[1] are therefore depicted in Figs. 10 and 11 in order to examine the operational characteristics of the magic-T. A near one-octave bandwidth was also obtained, a 40-dB isolation between ports 1 and 4, and a 21-dB isolation between ports 2 and 3 were observed. The maximum amplitude imbalance is less than 0.1 dB and 0.2 dB, and the maximum phase imbal-

[1]Advanced design system, Agilent Technologies, Palo Alto, CA 94304 USA.

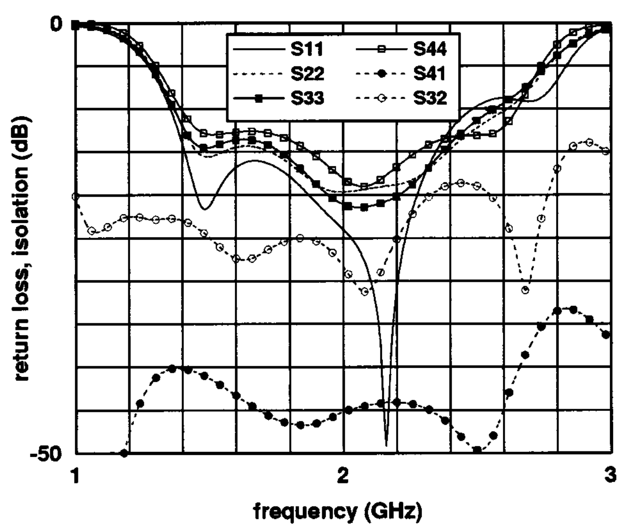

Fig. 11. Simulation results of return loss and isolation characteristics of the slotline type magic-T.

ance is less than 1° and 2°, respectively, for the in-phase and out-of-phase power coupling cases.

These excellent power and phase balances are due to the symmetrical structure of the proposed magic-T, and all the results obtained validate the proposed configurations of the magic-T and the equivalent networks developed.

IV. Conclusion

Two types of novel, easy-to-fabricate, planar magic-T using microstrip-slotline transitions have been proposed. Their equivalent networks were developed and further simplified for the in-phase and out-of-phase coupling cases. The impedance matching was accomplished by using an inclined microstrip-slotline transition. The proposed concept was applied to the design of the corresponding magic-T, and good operational characteristics over nearly a one-octave frequency band were observed. The proposed configurations and equivalent network model of the magic-T were fully validated by measurement and numerical simulation.

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Jeong Phill Kim (M'98) was born in Cheju, Korea, on November 2, 1964. He received the B.S. degree in electronic engineering from Seoul National University, Seoul, Korea, in 1988, and the M.S. and Ph.D. degrees in electrical engineering from Pohang University of Science and Technology, Pohang, Korea, in 1990 and 1998, respectively.

From 1990 to 2000, he was a Research Engineer in the Research and Development Center at LG Innotek, Korea, where he was involved with the design of antennas, transmitters, and receivers for various radar systems. Since 2001, he has been a faculty member with the School of Electrical and Electronic Engineering, Chung-Ang University, Seoul, Korea. He has made contribution to the development of material constants measurement setup using dielectric resonator. He also established efficient network models of microstrip-to-slotline transition, slot-coupled microstrip lines, microstrip-fed slot antenna, and aperture-coupled microstrip patch antenna. Using these efficient network models, he has developed various kinds of novel slot-coupled microstrip circuits such as out-of-phase power dividers, multi-slot couplers, magic-Ts, and filters. In addition, he was involved in developing 1×4 phased array antennas, where an aperture-coupled microstrip patch and a tapered slot were used as a radiator, and a microstrip meander-line on a ferrite substrate as a phase shifter. He also developed FDTD codes to simulate microwave circuits and antennas. Recently, he was involved in developing a phased array antenna with microstrip patch radiator and p-i-n-diode phase shifter, and calibrating this antenna using the rotating-element electric field vector (REV) and measurement of two elements (MTE) methods. He also designed an antenna with two fixed beams for direction-finding applications. His recent research interests include microstrip circuits and antennas, dielectric resonator antennas, numerical modeling and analysis, and microwave measurements.

Dr. Kim is a member of the IEEE Microwave Theory and Techniques and Antennas and Propagation Societies.

Wee Sang Park (M'89) was born in Korea in 1952. He received the B.S. degree in electronic engineering from Seoul National University, Seoul, Korea, in 1974, and the M.S. and Ph.D. degrees in electrical engineering from the University of Wisconsin–Madison in 1982 and 1986, respectively.

From 1986 to 1988 he taught at Wichita State University as a Visiting Assistant Professor. He joined Pohang University of Science and Technology (POSTECH), Kyungbuk, Korea, in 1988 and is currently an Associate Professor in the Department of Electronic and Electrical Engineering. Since 1995, he has been director of the Antenna Laboratory of Microwave Application Research Center at POSTECH. In 1997 he spent his sabbatical leave of one year in Prof. O. P. Gandhi's bioelectromagnetics laboratory at the University of Utah. He has been performing research in the areas of electromagnetics, microwave and antenna engineering for the last 16 years. He has authored and co-authored over 80 technical journal articles and conference papers. He has made contributions to the developments of material constant measurement methods using coaxial lines, cylindrical cavities, and dielectric resonators. He established network models for microstrip slots or slotlines for the design of microstrip patch and flared notch antennas and multilayer microstrip circuits. He developed phase shifters with ferrite meander lines and p-i-n diodes. With these components, he developed microstrip phased-array antennas and tested them with a near-field probe. He also developed FDTD codes to simulate the interaction between cellular phones and the human head and to analyze various microstrip discontinuities. His recent interest includes the measurement of SAR for portable phones and development of a bone equivalent material for human phantom.

Dr. Park is a member of the IEEE Microwave Theory and Techniques and Antennas and Propagation Societies. He is also a member of the Institute of Electronics Engineers of Korea and currently an Associate Editor for the Korea Electromagnetic Engineering Society.