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A Compact Low-loss Magic-T using Microstrip-Slotline Transitions

Kongpop U-yen[1], Edward J. Wollack[1], Samuel H. Moseley[1], John Papapolymerou[2] and Joy Laskar[2]

[1]NASA Goddard Space Flight Center, Greenbelt, Maryland, 20771, USA
[2]Georgia Institute of Technology, Atlanta, Georgia, 30332, USA

***Abstract* — The design of a compact low-loss magic-T is proposed. The planar magic-T incorporates the compact microstrip-slotline tee junction and small microstrip-slotline transition area to reduce slotline radiation. The experimental results show that the magic-T produces broadband in-phase and out-of-phase power combiner/divider responses, has an average in-band insertion loss of 0.3 dB and small in-band phase and amplitude imbalance of less than ± 1.6° and ± 0.3 dB, respectively.**

***Index Terms* — Microstrip circuits, passive circuits, power combiners, power dividers, slotline transitions.**

I. INTRODUCTION

Planar magic-Ts are used in microwave integrated circuits to split or combine in-phase and out-of-phase signals. Applications include balanced-mixers, discriminators, interferometers, and beam-forming networks. Desirable properties of a magic-T include: wide bandwidth phase and amplitude balance, low insertion loss, high isolation, compact size, and fabrication simplicity.

Several techniques have been developed to provide broadband response to a magic-T. Co-planar waveguide (CPW) or microstrip (MS) to slotline (SL) mode conversion techniques [1]-[4] are widely incorporated in a magic-T to produce a broadband out-of-phase power combiner or divider such that the slotline transmission becomes the main part of these magic-Ts. Since a slotline has less field confinement than a microstrip or a CPW, slotline radiation can cause high insertion loss in these magic-Ts. In addition, the magic-T constructed from CPW transmission lines requires the bonding process for air bridges which increases fabrication complexity. Although aperture coupled magic-Ts [5] have a small slot area, they require three metal layers.

In this paper, we propose a magic-T design that incorporates a MS-SL tee junction and a MS-SL transition using minimum size SL terminations such that the magic-T is compact and has less slotline radiation loss than the previously propose magic-Ts [1]-[4]. Finally, the hardware prototype magic-T operating at 10 GHz is developed to evaluate the magic-T's performance.

II. MAGIC-T CONFIGURATIONS AND POWER COMBINING/DIVIDING SCHEME

The proposed magic-T, shown in Fig. 1, consists of the quarter-wavelength (λ/4) microstrip lines with the characteristic impedances of Z_1, Z_2 and Z_t. The Z_1 line with the length of L_1 is used to transform the characteristic impedance Z_0 at port 1 or port 2 to a slotline impedance (Z_s) at the center of the structure. Z_2 and Z_t lines (with the length of L_2 and L_t, respectively) are used for transforming impedance from slotline impedance to Z_0 at the sum port (port H) and at the difference port (port E), respectively. The magic-T also consists of a slotline Z_s with the length of L_s. One end of the Z_t line is terminated with a microstrip stepped impedance open-end (SIO) stub to produce a broadband virtual ground for the MS-SL transition. The SIO stub consists of the microstrip lines with the characteristic impedances of Z_{t1} and Z_{t2} and the associated electrical lengths of θ_{t1} and θ_{t2}, respectively. Z_{t1} and Z_{t2} have the physical widths and lengths of W_{t1} and W_{t2}, and L_{t1} and L_{t2}, respectively.

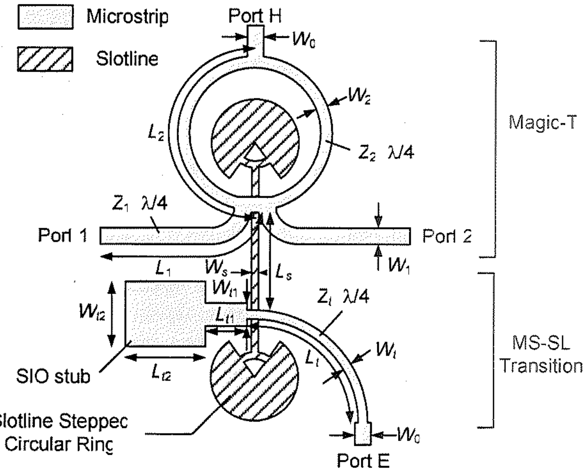

Fig. 1. The proposed 10 GHz magic-T with microstrip ports on the 0.25 mm-thick Duroid 6010 substrate. Dimensions: 5 mm × 6.2 mm.

Both ends of the slotline Z_s are terminated with the slotline stepped circular ring (SCR) [6] to provide broadband and low-loss MS-SL transition and to allow out-of-phase combining at MS-SL tee junction along *A-B* in Fig. 2(a). The signals from port 1 and port 2 are combined out-of-phase at the MS-SL tee junction along *A-B* plane and combined in-phase at the port H as shown in Fig. 2(a) and (b), respectively.

In the odd mode, the signals from port 1 and port 2 are out-of-phase. This creates a microstrip virtual ground plane along the y-axis of the magic-T. The slotline SCR connected to the slotline Z_{sl} also allows the MS-SL mode conversion to occurs as demonstrated by the electric-field (E-field) and current directions around the *A-B* cross section as shown in Fig 2(a).

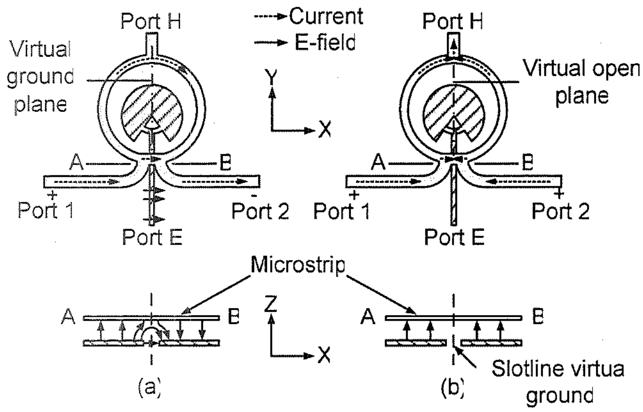

Fig. 2. (a) The odd-mode and (b) the even-mode electric field and the current flow in the magic-T.

In the even mode, the signals from port 1 and port 2 are in-phase, thus creating a microstrip virtual open along the y-axis of the magic-T as shown in Fig. 2(b). E-fields in the slotline at the A-B cross section are canceled thus creating a slotline virtual ground that prevents the signal flow to or from port *E*.

III. Circuit Model

In order to match the impedance of all four ports of the magic-T, the magic-T is analyzed at the center frequency in odd-mode and even-mode circuits up to the MS-SL tee junction.

In the odd mode, as shown in Fig. 3(a), the λ/4-line Z_1 is used to transform the input characteristic impedance Z_0 at port 1 to the desired value of $Z_s/2$. The slotline SCR has no effect on the circuit at the center frequency since it is a virtual open at that frequency. Therefore, Z_1 can be derived as follows:

$$Z_1 = \sqrt{n_t^{2} \frac{Z_s}{2} \cdot Z_0} \tag{1}$$

where n_t is the MS-SL transformer ratio [6]. The λ/4-line Z_2 is used to transform the grounded-end at port H to a virtual open at Z_s. The practical value of Z_2 is set by the impedance matching in the even-mode analysis.

In the even mode, as shown in Fig. 3(b), the input impedance Z_0 at port 1 is transformed to the in-phase port impedance of $2Z_0$. Since the line Z_1 is used to transform impedance Z_0 to $Z_s/2$ in odd-mode, the line Z_2 must be used to transform the odd-mode impedance of $Z_s/2$ to $2Z_0$. Therefore, Z_2 can be computed as follows:

$$Z_2 = \sqrt{2Z_0 \cdot n_t^{2} \frac{Z_s}{2}} = \sqrt{2} Z_1 . \tag{2}$$

The isolation between port 1 and port 2 and the return loss of port 1 and port 2 are derived in term of Γ_{+-} and Γ_{++} defined in Fig. 3(a) and 3(b), respectively, as follows

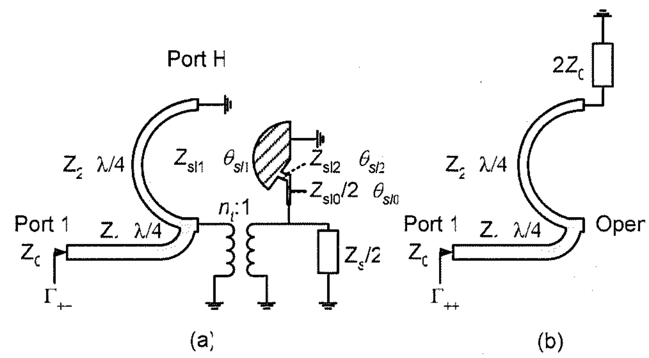

Fig. 3. (a) The odd-mode and (b) the even-mode equivalent circuit of the compact magic-T.

$$\text{Isolation} = -20\log\left(\frac{|\Gamma_{++} - \Gamma_{+-}|}{2}\right) \tag{3}$$

$$\text{Return loss} = -20\log\left(\frac{|\Gamma_{++} + \Gamma_{+-}|}{2}\right). \tag{4}$$

The magic-T is designed on a 0.25 mm-thick Duroid 6010 substrate with the dielectric constant of 10.2. The slotline is 0.1 mm wide, which is the minimum width allowable in this fabrication process. This corresponds to the Z_s value of 72.8 Ohm. Given Z_0= 50 Ohm and n_t =1, from (1) and (2), we obtain Z_1 and Z_2 of 42.7 Ohm and 60.4 Ohm, respectively.

Using the circuit model in Fig 3(a) and (b), and the parameters at 10 GHz in Table I, the frequency response of the magic-T can be determined up to the tee junction as shown in Fig. 4. This magic-T provides better broadband out-of-phase combining response than the in-phase combining response. The in-phase combining bandwidth is limited by the two impedance transformation sections in Z_1 and Z_2 used to transform Z_0 at port 1 to $2Z_0$ at port H in even mode. Moreover, the Z_2 value needs to satisfy the odd-mode matching condition.

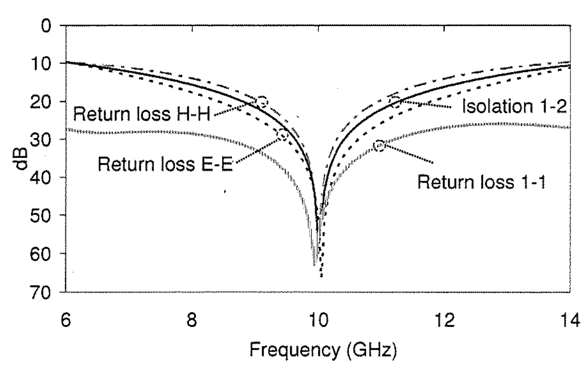

Fig. 4. The magic-T's frequency responses of the return loss and isolation using odd and even-mode circuit models.

IV. SLOTLINE SCR TERMINATIONS IN THE PROPOSED MAGIC-T

A SL termination is used at the MS-SL tee junction to provide a slotline virtual open and allow mode conversion in the out-of-phase combiner. It is also used in the MS-SL transition at port E. A slotline SCR termination, developed in our previous work [6] was selected for use in this magic-T due to its compact size. The slotline SCR termination minimizes the effect of parasitic in the slotline on the Z_2 lines and reduces the loss due to slotline radiation.

This slotline SCR termination can be modeled as stepped impedance transmission lines as shown in Fig. 3(a). Its equivalent circuit parameters and its physical parameters are provided in Table I and Table II, respectively. The full circuit model at 10 GHz shows a good agreement with electromagnetic (EM) simulation result as shown in Fig. 5.

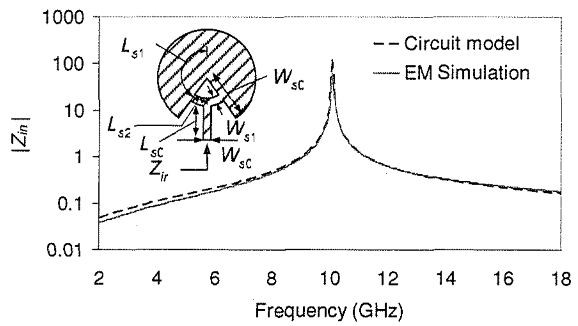

Fig. 5. The input impedance of the slotline SCR in the compact magic-T using the parameters provided in Table II.

TABLE I
THE MAGIC-T CIRCUIT DESIGN PARAMETERS AT 10 GHz

Microstrip line section	Slotline section
Z_1=42.7 Ω, Z_2=60.33 Ω, Z_{t1}=40 Ω θ_{t1}=23.3°, θ_{t2}=46.6°, Z_{t2}=20 Ω	Z_s=72.8 Ω, Z_{s0}=72.8 Ω, Z_{s2}=72.8 Ω, θ_{s0}=13.57°, θ_{s2}=6.2°, Z_{s1} =163.4 Ω, θ_{s1}=34.95°, θ_s=113.3°

TABLE II
THE PHYSICAL PARAMETERS OF THE COMPACT MAGIC-T IN MILLIMETERS

Microstirp line section	Slotline section
L_1=2.62, W_1=0.26, L_2=1.83, W_2=0.14, L_f=2.80, W_f=0.16, L_{t1}=0.68, W_{t1}=0.37, L_{t2}=1.30, W_{t2}=1.05	L_s=1.92, W_s=0.10, L_{s0}=0.58, W_{s0}=0.10, L_{s1}=0.23, W_{s1}=0.10, L_{s2}=0.91, W_{s2}=0.71

VI. HARDWARE AND EXPERIMENTAL RESULTS

The magic-T is fabricated on a 0.25 mm-thick Duroid 6010 substrate. The physical dimensions shown in Fig. 1 are computed based on the circuit parameters in Table I and their values are shown in Table II. The method of moments simulation is performed using Ansoft designer software [7]. Since the lines L_1 and L_2 are close to the slotline and the slotline SCR, they have less electric-field to the ground plane. Therefore L_1 and L_2 are compensated for this effect and they are slightly longer than a λ/4 microstrip line at 10 GHz.

The photograph of the top and the bottom side of the proposed magic-T is shown in Fig 6(a) and (b), respectively. Each port is connected to a 2.4 mm end-launch connector. Using thru-reflect-line calibration, these connections are de-embedded up to the reference plane shown in Fig. 6(a). The measurement is performed using the HP8510c network analyzer. The magic-T's in-phase and out-of-phase 3-dB power diving/combining loss are less than 0.2 dB and 1 dB from 8 GHz to 12 GHz, respectively, as shown in Fig. 7. The return loss frequency responses in Fig. 8 and Fig. 9 are narrower than those predicted by the circuit model due to strong parasitic around the MS-SL tee junction, which requires additional transmission length L_1 and L_2 compensations. The magic-T isolation response shown Fig. 10 is in good agreement with the simulation results. The magic-T provides the minimum isolation of 31 dB in the pass band from 2 GHz to 17 GHz.

The amplitude imbalance of the magic-T is less than 0.3 dB from 2 GHz to 16 GHz as shown in Fig. 11(a). The phase imbalance of the port H and port E are less than ±1.5° and ±1.6°, respectively as shown in Fig. 11(b). The magic-T's isolation is limited by the accuracy of the measurement, non-ideal finite ground plane, and fabrication misalignment.

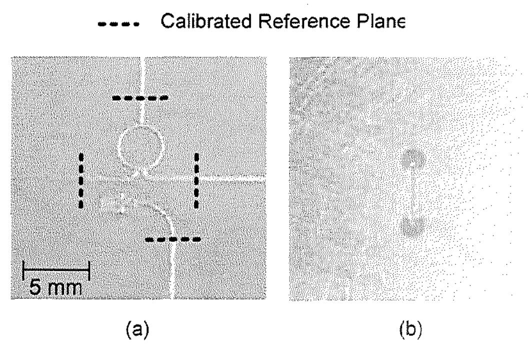

Fig. 6. The photograph of (a) the top view and (b) the bottom view of the magic-T on 0.25 mm-thick Duroid 6010 substrate.

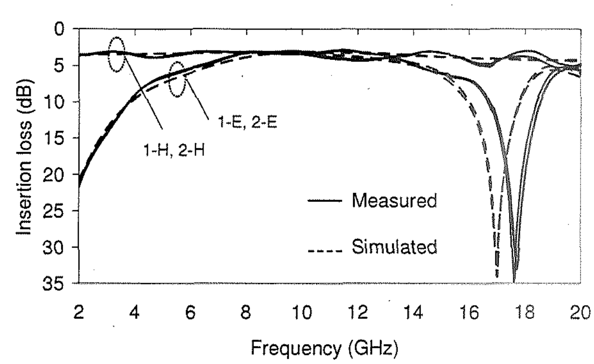

Fig. 7. The measured and simulated frequency responses of the in-phase and the out-of-phase power dividing of the magic-T.

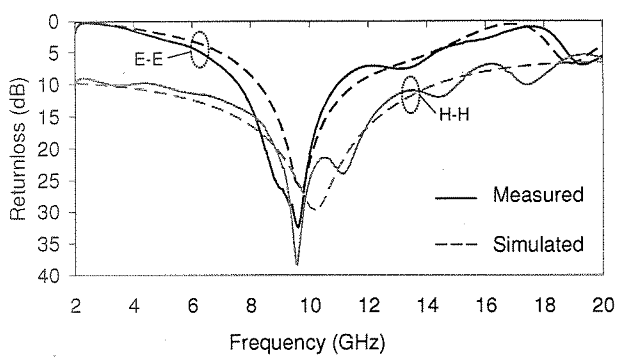

Fig. 8. The measured and simulated frequency responses of the return loss at port E and port H of the magic-T.

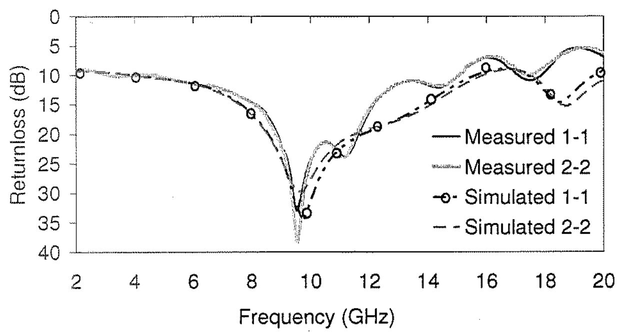

Fig. 9. The measured and simulated frequency responses of the return loss at port 1 and port 2 of the magic-T.

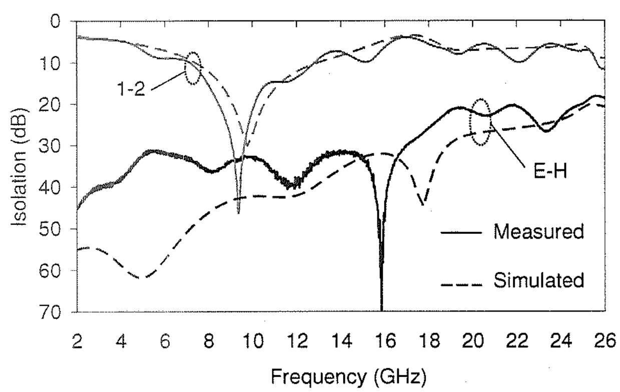

Fig. 10. The measured and simulated frequency responses of port 1-2 and port E-H isolation of the magic-T.

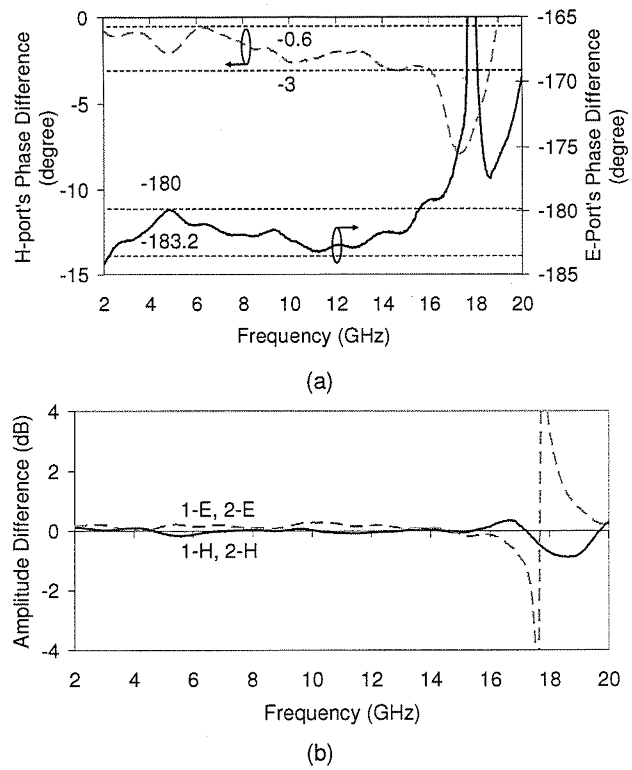

Fig. 11. The measured frequency responses of the magic-T: (a) amplitude imbalance and (b) phase imbalance.

VII. Conclusion

A new magic-T configuration using MS-SL transitions was developed. The effort to reduce slotline radiation in the magic-T design is presented for the first time. As a result, the magic-T produces low-loss broadband response with little amplitude and phase imbalance. Moreover, the design is less than two-third the size of those in [2] and [3]. It is also less difficult to fabricate than [1], [3]-[5] since the proposed magic-T requires no via hole or air bridges and use only two metal layers.

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