A Compact and Broadband Planar Magic-T Design Using Microstrip-Slotline Transitions

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***Abstract*—In this paper, a compact wide band planar magic-T using microstrip-slotline (MS-SL) transitions is proposed. The design provides good insertion loss bandwidth along with low loss and low phase/amplitude imbalance. A complementary slotline structure and a radial stub microstrip matching technique are used in this design to achieve the desired results. It shows a simulated 1 dB insertion loss bandwidth of 5.2 GHz (68.42%) centered at 7.6 GHz and simulated E-H port isolation better than 34 dB with relatively low simulated phase and amplitude imbalances of 1° and 0.25 dB, respectively.**

Keywords—microstrip, magic-T, broadband, microstrip-slotline transition

I. INTRODUCTION

A magic tee is a 4-port circuit that is a combination of a E-plane tee and H-plane tee. It derives the term "Magic" from the characteristic power division across its 4 ports. The structure comprises of the H-plane port, also known as the Σ or sum port, and the E-plane port, also referred to as the Δ or difference port. An input signal at the sum port is split equally with the same phase whereas an input signal at the difference port is split equally with a phase difference of 180° [1-3]. Magic-Ts are widely used in monopulse comparators, beamforming systems and mixers, etc [4-6].

Traditionally, magic-T's are made using metallic structures [7-9]. In [7], a modified feed, ridged structure along with a tapered conical post is proposed which shows an enhanced bandwidth. In [8], the authors use an E-plane waveguide along with a waveguide-to-microstrip transition to realize a coplanar magic tee with 21% fractional bandwidth. A coplanar Magic-T based on the ridge and E-plane gap waveguides is presented in [9] which shows a promising impedance bandwidth and minimal insertion loss along with easy fabrication. Even though many techniques have been developed to optimize waveguide magic-T's, they tend to be bulky and have low bandwidth.

Planar magic-Ts have been growing in popularity due to their compact footprint and improved bandwidth [10-18]. A common approach in such devices is to utilize microstrip-slotline (MS-SL) transitions [11-18]. Microstrip-slotline transitions can significantly improve the bandwidth due to its orthogonal balanced and unbalanced transmission modes [19]. The usage of both layers of a planar substrate (multilayer technology) can further reduce the size of a magic-T [11].

The design proposed in [11] consists of 3 metal layers, uses MS-SL vertical transition and has shown sum-difference isolation greater than 50 dB and a bandwidth of 1.25 – 2.52 GHz (67% fractional bandwidth). In [12], the authors demonstrate multilayer planar Magic-Ts and analyze the electric field distributions of the odd and even modes of the coupled microstrip-slotline. The magic-T proposed in [13] also uses MS-SL transitions with 2 metal layers, reduced slotline radiation along with a low-loss broadband response at 10 GHz.

By using a new microstrip ring structure, the authors in [14] demonstrated an improved magic-T design that reduced the parasitic couplings at the MS-SL junction and thus improved the bandwidth, return loss and phase mismatch. In [15], authors have demonstrated two planar magic-T designs with broadband response using MS-SL transitions. The design shows isolation better than 37 dB which can be used for filtering applications. The magic-T proposed in [16] is also based on MS-SL transitions and the simulated results show a high isolation of 31 dB. In [18], the authors demonstrate a 3-layer planar magic-T with a fractional bandwidth of 40 % at 5 GHz. The reported design utilizes a radial stub instead of a rectangular one to improve the bandwidth, insertion loss and signal imbalance.

The main parameters in designing a magic – T are broadband response, low insertion loss, high isolation and fabrication simplicity. A clearly noticeable drawback in many approaches to such structures is the lack of a stable, wide band of operation. A major problem in current demonstrations is the narrow reflection and isolation responses that restricts broadband operation. In this paper, the challenge of maintaining a compact planar magic-T structure while demonstrating a wide bandwidth is tackled. Reflection coefficients and isolation losses having a flat response over the bandwidth of the device are also demonstrated in simulation. For this purpose, microstrip-slotline (MS-SL) transitions are used, consisting of radial stubs and complementary circular slotline structures.

II. MAGIC-T DESIGN

The proposed Magic-T (Fig.1) is designed on a 0.25 mm thick RT Duroid 6010 substrate with a dielectric constant of 10.2. The structure is implemented using microstrip structures with microstrip (MS) to slotline (SL) transitions employed to obtain a broadband response. Since slotlines have less field confinement than microstrips and can result in high insertion loss, the area of the slotlines is minimized to reduce radiation losses [20]. The usage of microstrip-slotline transitions reduces the insertion loss and simultaneously improves the bandwidth of the device.

Quarter-wavelength ($\lambda/4$) microstrip lines have been used to build a circular structure with two coupling arms forming the 1^{st} and 2^{nd} ports. These lines are used to transform the port impedances to the slotline impedance. The third port (H-port) is designated at the top end of the ring structure. The structure is coupled through MS-SL transitions by making use of complementary circular-shaped slots in the ground plane.

Beneath the magic-T ring structure, an impedance transforming circuit consisting of a radial stub and a stepped matching microstrip line are connected as a 4^{th} port, labelled as the E-port. A radial stub is used in place of a straight microstrip stub with radius equal to $\lambda_m/6$ [18], where λ_m is the wavelength equivalent for the microstrip stub. This provides the desired matching while also improving the bandwidth of the circuit. Stepped microstrips are used to transform impedance to achieve low loss while maintaining broad bandwidth.

The signals from ports 1 and 2 are combined in phase at the H- port which serves as the sum port. MS-SL transitions allow the signals to combine out of phase at the E- port which serves as the difference port. In the odd mode, the signals from ports 1 and 2 are out of phase, thus creating a virtual ground plane along the y-axis of the device. This allows the fields to couple to the E-port. In the even mode, the signals from port 1 and 2 are in-phase and create a virtual open along the y-axis [3]. The fields in the slotline cancel out, thus preventing signal flow to port E.

The resulting design is compact, having a low footprint of 6.24 mm x 8 mm x 0.25 mm (0.41λ x 0.53λ x 0.02λ). The parameters were designed to provide an ideal response at 7.6 GHz. The design values of the proposed structure are shown in Table 1.

The complementary circular slotline provides broadband response and improves reflection. It is shown in Fig.2. The smaller size of the slot near the E- port serves to reduce reflection while allowing for broadband response. The larger size slot in the upper section improves the bandwidth of the output. The complementary circular slotline terminations were selected in order to optimize the broadband response along with low reflections. The lower slotline was widened to lower reflections in port 4 and the complementary upper and lower slots improve the bandwidth of the device.

The MS-SL transitions allow for large port E-H isolation while resulting in good phase transitions for even and odd mode behavior.

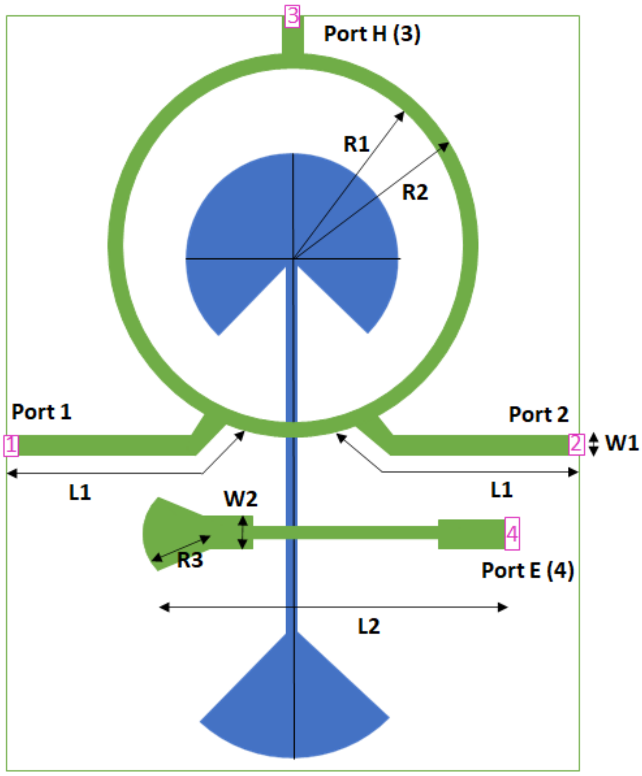

Fig 1. Proposed Magic-T using microstrip slotline transitions. Green – metal patch, , blue - slots in ground plane

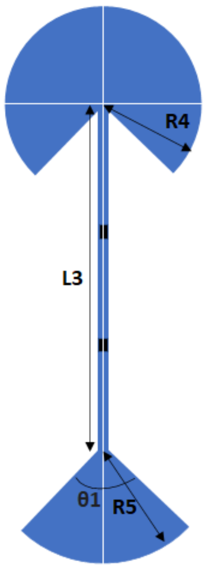

Fig 2. Complementary circular-shaped Slotline design

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TABLE I – DESIGN PARAMETERS

Dimension/Parameter	Value
R1	1.68 mm
R2	1.82 mm
R3	0.68 mm
R4	1.10 mm
R5	1.56 mm
θ_1	90^0
L1	2.47 mm
L2	4.19 mm
L3	3.53 mm
W2	0.37 mm
W1	0.26 mm

III. PARAMETRIC STUDY

In this section, the effects of changing the slot shape and size are discussed. The device is simulated using Zealand IE3D simulation software. The 1 dB insertion loss bandwidth and the reflection coefficients of the ports are the parameters considered for optimization.

Effect of slot shape

The performance of the magic-T is first analyzed by changing the shape of both the slots. Initially, both slots have the shape of a sector with an angle of 90°. The 1 dB bandwidth was found to be 3.1 GHz. After increasing the slot angle to 135°, the 1 dB bandwidth had improved to 3.5 GHz. When both slots have a semi-circular shape (angle = 180°), the 1 dB bandwidth was 4.2 GHz. It is observed that an increase in the area of the slots lead to an increase in the 1 dB bandwidth of the device. These results are illustrated in Fig.3.

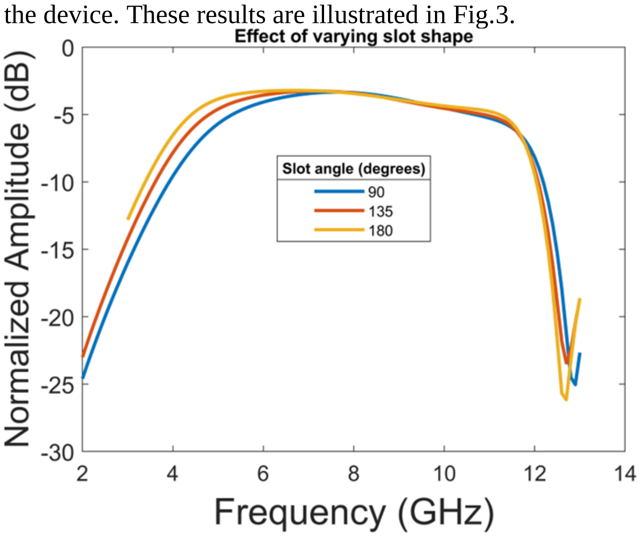

Fig.3. Effect of slot angle (both upper and lower slot) on 1 dB bandwidth

Next, the angle of the upper slot was kept at 180° and lower slot as 135° and the 1 dB bandwidth reduced to 4 GHz. When the angle of the lower slot was reduced to 90°, the 1 dB bandwidth further reduced to 3.6 GHz. However, reducing the angle of the lower slot while keeping the upper slot fixed (in a semi-circular shape) improved the reflections at ports 1,2 and 4. This is illustrated in Fig.4.

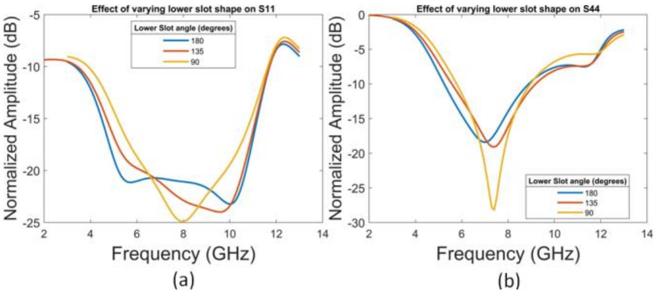

Fig.4. Effect of varying lower slot shape (or angle) while keeping upper slot as semi-circle on (a) S11 and (b) S44

By leveraging the observations that an increase in the slot area leads to an improvement in bandwidth and decreasing the angle of the lower slot improves the return losses, complementary slots were selected to optimize both bandwidth and suppression.

Effect of lower slot radius

After arriving at the complementary slot design, the radius of the lower slot is varied, and the performance is analyzed. Three values of radii are taken: 1 mm, 1.3 mm and 1.6 mm. It is observed that the bandwidth takes the values 3.7 GHz, 5.2 GHz and 5.1 GHz respectively, as illustrated in Fig.5.

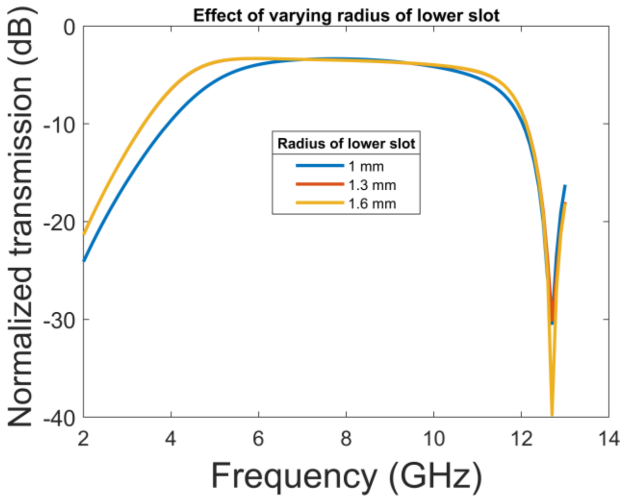

Fig.5. Effect of lower slot radius on 1 dB bandwidth

Effect of lower slot angle

The angle of the lower slot is varied from 60° to 120°. It is observed that the bandwidth of the device increases from 3.7 GHz to 5.2 GHz and then reduces to 5.1 GHz, as shown in Fig.6.

Based on the observations presented above, complementary slots are used in the proposed device. From the parametric study, it is observed that a larger slot area leads to an improved bandwidth. However, as the area of the lower slot increases, the return losses of the various ports degrade. Therefore, complementary slots are used to optimize both bandwidth and suppression. Further, the radius and sector angle of the lower slot are also varied, and the performance studied. Based on these observations, the radius and angle of the lower slot are taken as 1.3 mm and 90° respectively. The results of the proposed structure are presented in the next section.

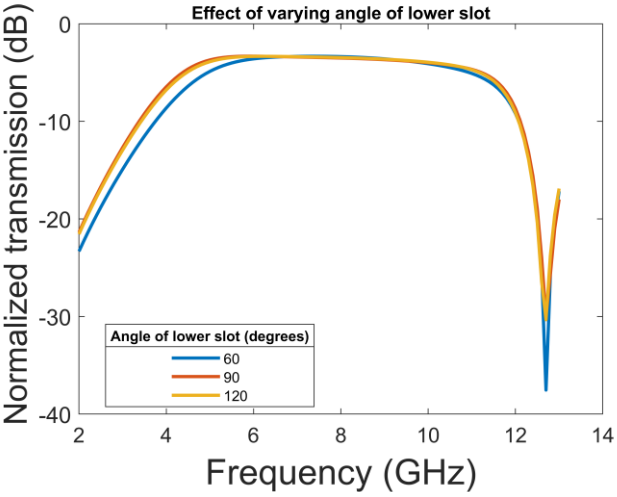

Fig.6. Effect of lower slot angle on 1 dB bandwidth

IV. Results And Analysis

The design shown in Fig. 1 was simulated in Zealand IE3D simulation software. The lengths and values were optimized for operation at 7.6 GHz. The simulation results are presented in Fig. 7, Fig. 8, Fig. 9 and Fig. 10. The complementary circular slot structure maximizes the tradeoff between bandwidth and isolation. A 1dB insertion loss bandwidth of 5.2 GHz, or 68.42% at the operating bandwidth from 4.8-10 GHz was achieved. The E-H isolation > 34 dB throughout the 1-dB bandwidth. The reflection coefficient at all ports is > 10 dB throughout the bandwidth. The amplitude and phase imbalances are less than 0.25 dB and 1° respectively.

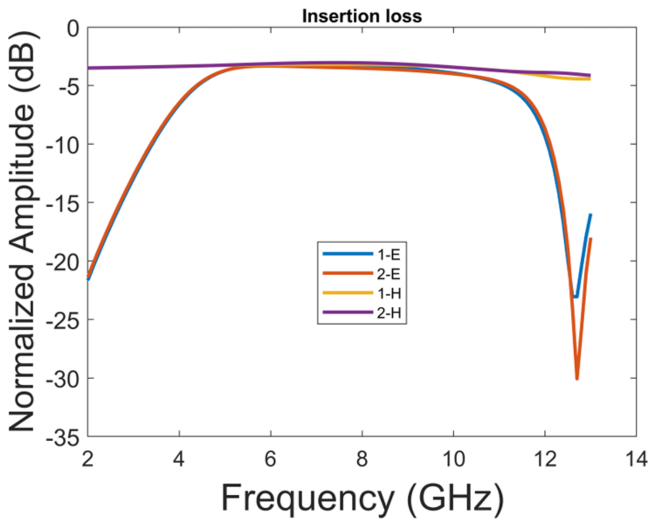

Fig 7. Power Division

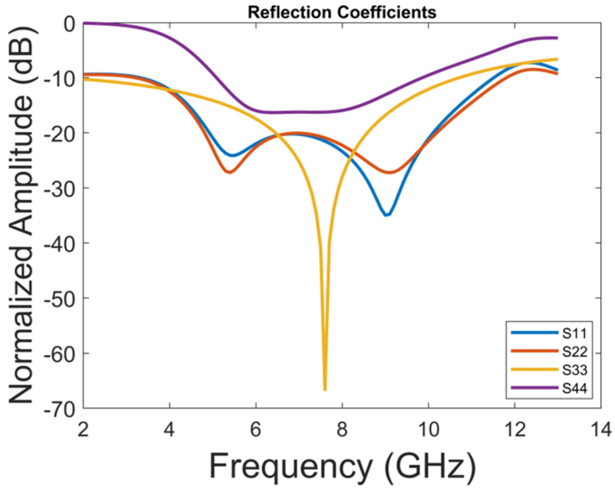

Fig 8. Reflection coefficients

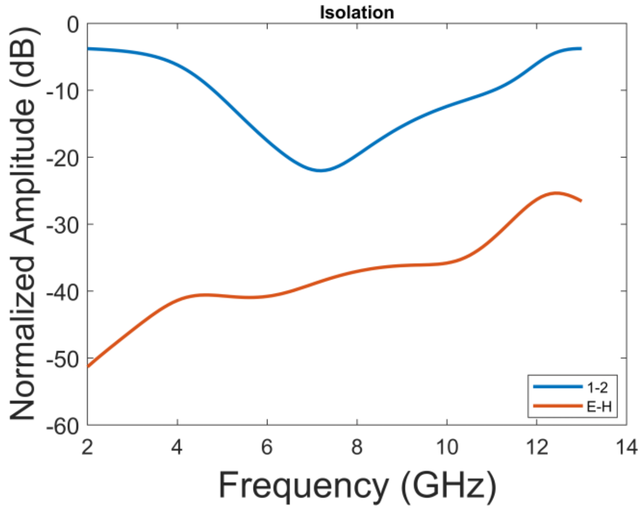

Fig 9: Isolation

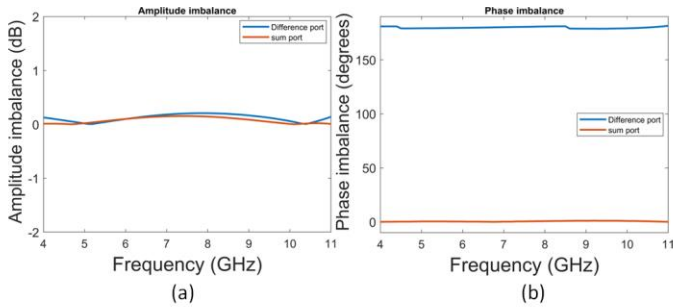

Fig 10: (a) Amplitude imbalance, and (b) Phase imbalance

From Fig.8 and Fig.9, it is observed that the suppression has a flat response over a large portion of the bandwidth and exhibits less ripples. The values of S11, S22 are > 18 dB over the 1 dB bandwidth, S33 > 12.5 dB over the 1 dB bandwidth, and S44 is > 12 dB from 5.5 – 9 GHz. Table 3 summarizes the results of the proposed design and compares it with previous designs presented in the literature. It is observed that the proposed design achieves a larger 1 dB insertion loss bandwidth compared to previous approaches. Further, a broadband response is observed with respect to return loss and isolation.

TABLE III -PARAMETER COMPARISON

Parameter	*Compact Low Loss [13]*	*Novel Planar Filtering [10]*	*Coupled Microstrip -Slotlines [112]*	*This Work*
1 dB Bandwidth	4 GHz (8-12) or 24 %	18.4 MHz (910.8 – 929.2) or 2.0%	1.27 GHz (1.25-2.52) or 67%	5.2 GHz (4.8 – 10) or **68.42%**
1-2 Isolation	>20 dB	>20 dB (at center frequency)	-	>10 dB, **>15 dB from 5.5 – 9 GHz**
E-H Isolation	>31 dB	>4 dB	>50 dB	>34 dB
Phase Imbalance	±1.6	±7	±0.4	±1°
Amplitude Imbalance (dB)	±0.3	-	±0.1	±0.25 dB
Return Losses (S11/S44)	30/>13 dB	20/<13 dB	-/>10 dB	22/>10 dB

CONCLUSION

The proposed structure has used microstrip-slotline transitions with slotline designs chosen to maximize bandwidth while maintaining losses and reflections at an acceptable level. A bandwidth of 5.2 GHz (68.42%) with 1-2 isolation of >10 dB, largest phase imbalance of 1°, maximum amplitude imbalance of 0.25 dB, and E-H isolation of >34 dB has been shown. The proposed design is compact (0.41λ x 0.53λ) with much higher bandwidth than other approaches. It uses only two metal layers and hence is simple to fabricate as well. Based on the results presented, it can be observed that the radial stub and complementary slotlines have an effect on the performance of the device. The tapering nature of the radial stub leads to an improved bandwidth and the complementary slotlines achieve a high trade-off between bandwidth and suppression. The proposed magic tee finds applications in broadband operations in defense and wireless communications.

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