Double-sided parallel-strip line based broadband magic-T

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Abstract. A broadband magic-T based on double-sided parallel-strip line (DSPSL) and microstrip-coplanar waveguide (CPW) transition is presented and demonstrated. The DSPSL magic-T has broad bandwidth and low phase imbalance at the sum (H) and difference (E) ports. The equivalent circuits of the proposed multilayer circuit magic-T and transition between microstrip and CPW are derived. The experimental results show that the 4GHz magic-T provides more than 68% of 1dB operating bandwidth with the average in-band insertion loss of less than 0.7dB. It also has phase and amplitude imbalance of less than 4°and 0.65 dB, respectively. This magic-T was designed as DSPLS difference inputting of port E and two sides microstrip circuit outputting of port 2 and 3, and its structure is suitable for multilayer microwave integration circuit, especially LTCC multilayer circuit.

Keywords: transmission line; impedance matching; equivalent circuit; magic-T.

1 Coupled-line directional coupler principle

When two CPWs are brought in close proximity their electromagnetic fields interact and power is coupled from one CPW to the other. In [1] three examples of coupled CPW structures, the edge coupled CPW, the edge coupled grounded CPW, and the broadside coupled CPW are shown. The propagation along these CPW structures is described by two normal modes, namely the even and the odd modes. In [2] the normal modes of coupled CPW were explained in detail, and where ever possible in this book analytical expressions were presented to compute the even-mode and odd-mode effective dielectric constants and characteristic impedances. These characteristics are essential for designing directional couplers.

In weakly coupled lines, the distance of separation between the two lines is large, and hence the wave propagates with a velocity approximately the same as that on a single line. In this situation the even-mode and odd-mode phase velocities are assumed to be equal [1] and expressed as

$$v_{ph(\text{even})} = v_{ph(odd)} = v_{ph} = \frac{c}{\sqrt{\varepsilon_{eff}}} \tag{1}$$

and

$$\lambda_g = \frac{v_{ph}}{f} \tag{2}$$

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where
$c =$ velocity of light in free space
$\varepsilon_{eff} =$ effective dielectric constant
$\lambda_g =$ guide wavelength
$f =$ frequency.

In addition, for maximum coupling the length L of the coupled section is $\lambda_g / 4$. The following two relations [2] also hold good:

$$Z_0^2 = Z_{0,e} Z_{0,o} \tag{3}$$

and

$$K = \frac{Z_{0,e} - Z_{0,o}}{Z_{0,e} + Z_{0,o}} \tag{4}$$

where
$Z_0 =$ characteristic impedance of the feed line
$Z_{0,e}$ and $Z_{0,o} =$ even-mode and odd-mode characteristic impedance
$K =$ voltage coupling coefficient.

Last, it is worth mentioning that under the preceding conditions there will be no reflection at the input port of the coupler and also the coupler will have infinite directivity [2].

In the case of tightly coupled lines, the even-mode and odd-mode phase velocities are unequal [3], and so the length L of the coupled section is determined from the expression

$$L = \frac{\pi}{\beta_e + \beta_o} \tag{5}$$

where β_e and β_o are the even-mode and odd-mode propagation constants. For this case the coupler will not have infinite directivity.

2 Standard 3-dB Magic-T

In Figure 1 a magic-T [4] formed with three CPW T-junctions and a 180° reverse-phase CPW-slotline T-junction is shown. In Figure 1 port 1 and port 4 correspond to the H-arm and E-arm of a conventional waveguide magic-T. In addition the ports 1 and 4 are known as the sum (Σ) and difference (Δ) ports, respectively, as explained in [5] Ports 2 and 3 are the power dividing balanced-arms. Figure 2 shows the transmission line model of the above magic-T. In this figure the twisted transmission line represents the 180° phase reversal of the CPW-slotline T-junction. The characteristic impedance of the feed line, the CPW line and the slotline are indicated as Z_{feed}, Z_{CPW} and Z_{slot}, respectively. The guide wavelength on these lines is indicated as λ_g.
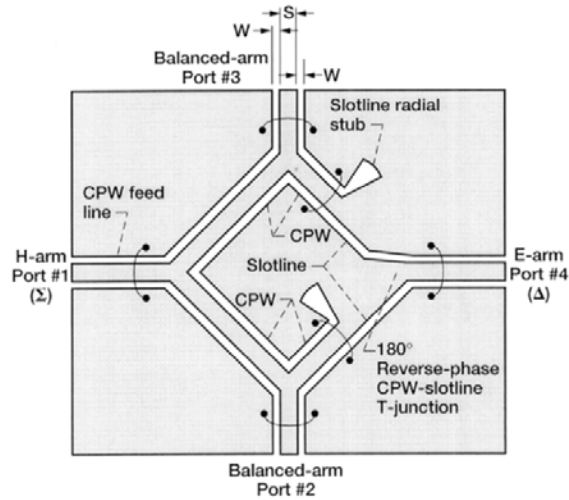
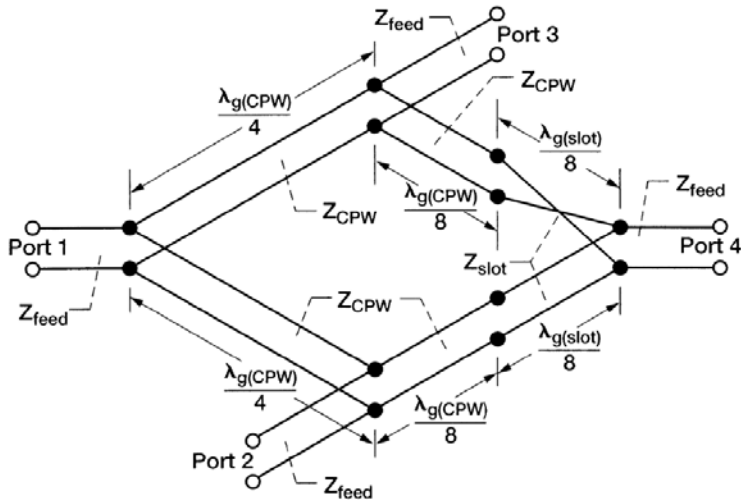**Figure 1.** Standard 3-dB Magic-T circuit configuration

Figure 2. Equivalent transmission line model

To obtain a relation between the various characteristic impedances consider a signal feed to port 1 (H-arm) of the magic-T as shown in Figure 3. The arrows indicate the direction of the electric field lines in the CPW and the slotline. The signal divides into two components and arrive in phase at ports 2 and 3. The two components arrive at port 4 (E-arm) 180° out of phase and cancel each other. In this case the plane of symmetry at the H-arm and the E-arm correspond to an open circuit (magnetic wall) and a short circuit (electric wall), respectively. The equivalent circuit of the magic-T for this excitation is shown in Figure 4.
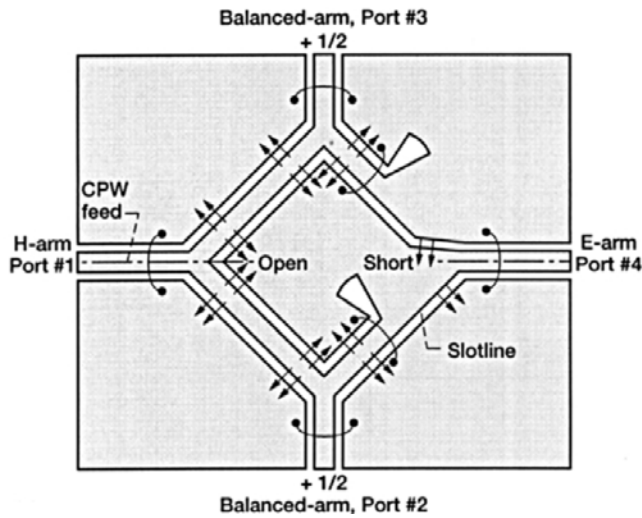
Figure 3. Electric-field distribution in-phase excitation at ports 2 and 3
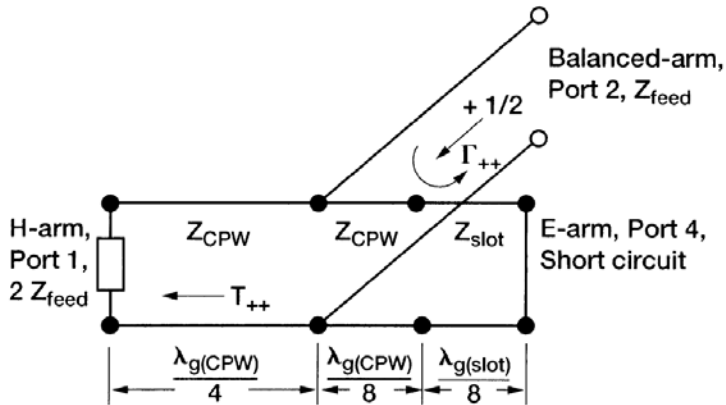

Figure 4. Simplified equivalent circuit

Next consider a signal fed to port 4 (E-arm) of the magic-T as shown in Figure 5. Once again, the signal divides into two components and arrive at ports 2 and 3 but with a 180° phase difference. The phase difference is because of the 180° reverse-phase CPW-slotline T-junction. Two components arrive at port 1 (H-arm) 180° out of phase and cancel each other. In this case the plane of symmetry at the H-arm and the E-arm correspond to a short circuit (electric wall) and an open circuit (magnetic wall), respectively. The equivalent circuit of the magic-T for this excitation is shown in Figure 6.
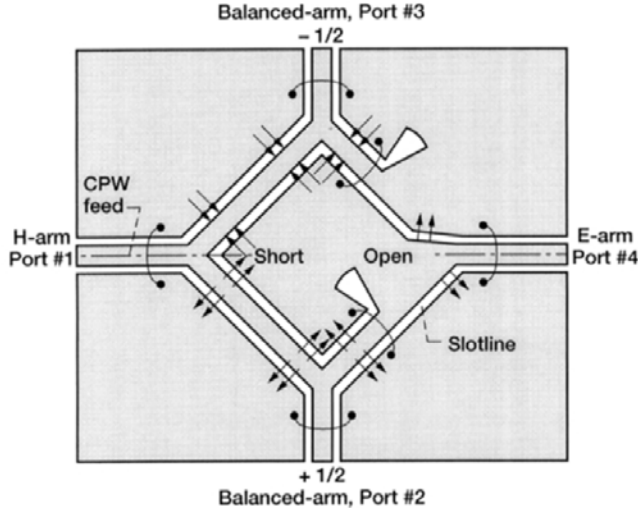
Figure 5. Electric-field distribution 180° out-of-phase excitation at ports 2 and 3
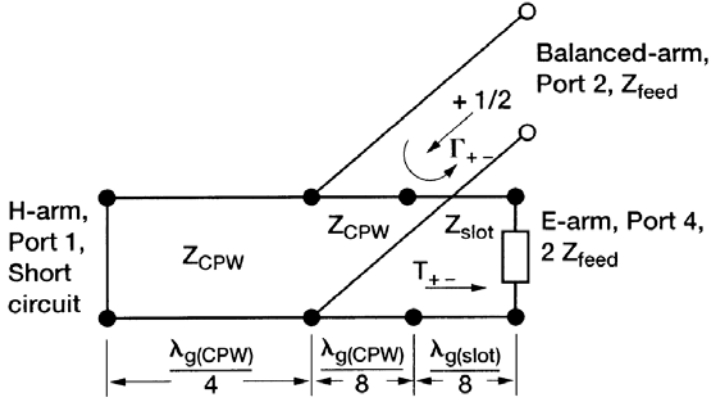

Figure 6. Simplified equivalent circuit

By superimposing the above two cases, the total reflection coefficient at the balanced-arm, port 2 is obtained as follows [4]:

$$S_{22} = \frac{1}{2}\Gamma_{++} + \frac{1}{2}\Gamma_{+-} \tag{6}$$

where Γ_{++} and Γ_{+-} are the voltage reflection coefficients at port 2. To achieve impedance matching at port 2, $|S_{22}|$ must be equal to zero. For this to happen, the following conditions must be satisfied:

$$Z_{slot} = Z_{CPW} \tag{7}$$

and

$$Z_{CPW} = \sqrt{2}Z_{feed} \tag{8}$$

A similar reasoning holds true for port 3 impedance match. The isolation between ports 1 (H-arm) and 4(E-arm) is perfect as long as the 180° reverse-phase CWP-slotline T-junction is ideal.

3 Magic-T proposed

   Double-sided parallel-strip line, as a balanced transmission line, consists of two identical strip lines separated by a dielectric sheet shown in Figure 7, which can be analyzed easily using the image theory [6]. It has an important advantage of easy realization of low characteristic impedance and high characteristic impedance. The inherent out-of-phase feature of the double-sided parallel-strip line between the two strips is frequency independent, which can be applied to the difference balanced circuit's design to improve the circuit's performance such as dynamic range, linearity, anti-jamming, etc [7]-[10].
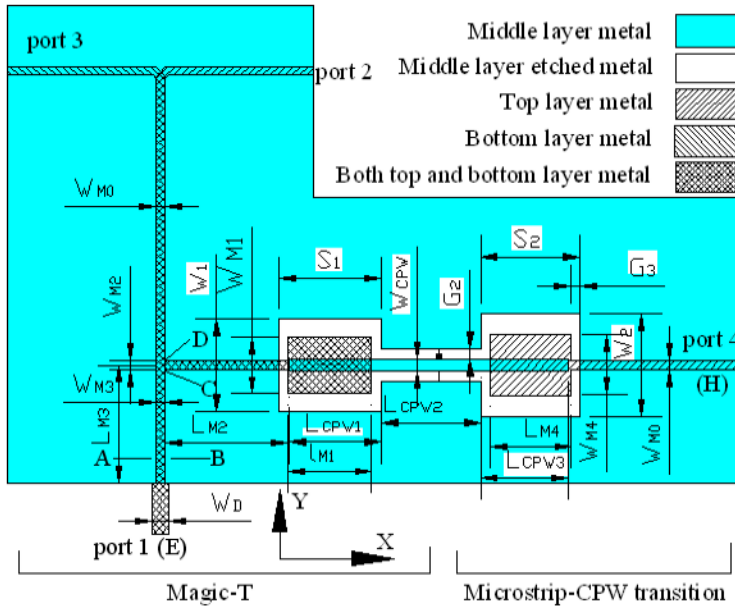

Figure 7. Top view of the proposed Magic-T

   Magic-T is a four-port microwave network. In an ideal case, its sum (H) port and difference (E) port allow incident signals from ports 2 and 3 to be combined or subtracted with a specific relative phase. With these structural properties and electric performance, it has been popularly used as a four-port element in microwave circuits such as correlation receivers, power combiners or dividers, frequency discriminators, balanced mixers, four-port circulators, microwave impedance bridges, reflectometers and monopulse antennas[11]-[12].

   A magic-T requires less dependent on transmission phase delay to perform as in-phase and out-of phase combiners. In order to ensure Magic-T's dividing outputting with lower phase and amplitude imbalance in broader bandwidth, the magic-T must be symmetrical[13]-[14] in physical structure. This letter proposes a configuration of broadband, multilayer circuit magic-T based on double side parallel strip line and microstrip-CPW transitions. We not only obtain symmetry of port H with CPW and microstrip to CPW transition, but also symmetry of port E with DSPSL and DSPSL to double microstrip lines transition. Finally, the characteristics of the proposed configurations of magic-T are experimented and compared with the software simulation results.

4 Configuration and equivalent circuit model

   The proposed Magic-T includes three metal circuit layer, the colorful parts are different metallic layers, with a substrate between the different metallic layers. CPW is etched on the inserted metallic layer in middle of the two substrates. As depicted as Figure 7. Ports 1 is inputting port of power

divider, and two power dividing output ports (port 2, 3) are located symmetrically on the bottom and top metallic layer of this structure.
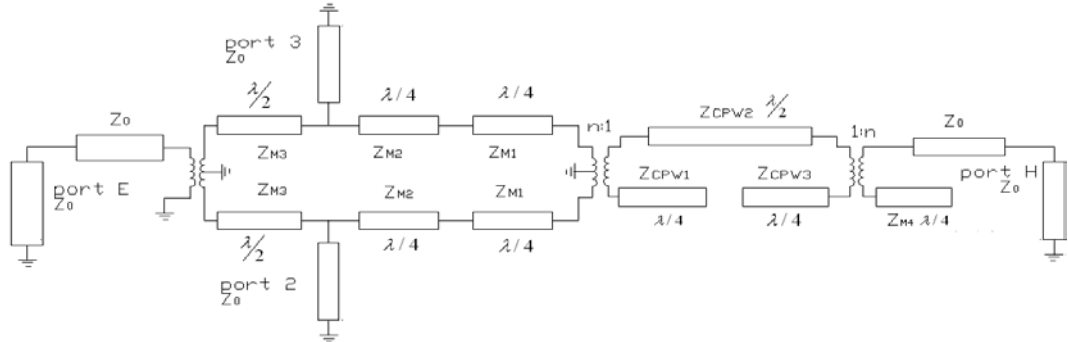

Figure 8. Full equivalent circuit model of the magic-T at the operating central frequency.

The magic-T can be studied by the odd- and even-mode circuit analytical method [15]. By using this analytical method and ignoring parasitic reactance due to step impedance change of line width, the full equivalent circuit model are built, shown in Figure 8, which corresponds to Figure 7. The parameters are provided in Table I and II.

Table 1. Physical parameters in millmeters of the magic-t (dielectric constant ε_r=10.2, turns ratio n=1.98)

Magic-T section	Microstrip-CPW transition
S_1=6.2, S_2=6, W_1=5.5, W_2=6.1, W_D=0.6, W_{M0}=0.52,W_{M1}=3.4, W_{M2}=0.6, W_{M3}=0.6	W_{M0}=0.52, W_{M4}=3.6, L_{M4}=4.9
L_{MI}=5, L_{M2}=7.4, L_{M3}=13.5, L_{CPW1}=5.6, L_{CPW2}=12, G_1=0.5,G_2=0.6, G_3=0.5	S_2=6, W_2=6.1, G_2=0.6, G_3=0.5, L_{CPW3}=5.3, W_{CPW3} =W_{CPW}=0.7,
$W_{CPW1} = W_{CPW2} = W_{CPW3}$ =W_{CPW}=0.7	

Table 2. Circuit parameters at 3.6ghz of the magic-t in ω or electrinical length

Magic-T section	Microstrip-CPW transition
Z_D≈100, Z_{M0}=50, Z_{M1}≈40, Z_{M2}=48, Z_{M3}=48, Z_{CPW1}≈40, Z_{CPW2}≈30,	Z_{M0}=50, Z_{M4}≈50, Z_{CPW3}≈50
θ_{M1}≈90°,θ_{M3}=180°, θ_{M2}≈90°, θ_{CPW1}≈90°, θ_{CPW2}≈180°	θ_{CPW3}≈90°, θ_{M4}≈90°,

In the even mode, port *E* becomes a virtual open circuit and port *H* becomes a virtual open. Using a $\lambda/4$ transformation through the Z_{M1} line and a $\lambda/4$ transformation through the Z_{M2} line, the virtual open becomes an open circuit at point *C* and *D* of tee junction, both port 2 and port 3 of which have characteristic impedance Z_{M0}. The general equation relating Z_{M0}, Z_{M1}, Z_{M2}, and Z_{CPW1} can be expressed as following:

$$Z_{M0} = n^2 \frac{Z_{CPW1}}{2} \left(\frac{Z_{M2}}{Z_{M1}} \right)^2 \tag{9}$$

In the odd mode, port E becomes a virtual open. However port H becomes a virtual ground and its quarter wavelength of Z_{M1} line and quarter wavelength of Z_{M2} line transformed to an open circuit at point C and D of Tee junction. Therefore, there is no constraint on the values Z_{M1} and Z_{M2} in this mode at central frequency f_0. Moreover, ports 2 and 3's impedances are transformed to $2Z_0$ at port E using DSPSL of impedance Z_D. The general solution can be obtained as follows:

$$Z_D = 2Z_{M3} \approx 2Z_0 \tag{10}$$

The general method based on (1) and (2) is used to design and fabricate this magic-T. But the bandwidth of port 2-4 and 3-4 transmission of the magic-T is narrow and dominantly limited by bandwidth of coupling between CPW and microstrip. To increase the return loss and isolation bandwidth of this magic-T, using (3) with $Z_{M1} \approx 40\Omega$ and $Z_{M2} = 48\Omega$, we find that f_1 and f_2 are $0.67 f_0$ and $1.33 f_0$,

$$\frac{f_1}{f_2} = \frac{2}{\pi} \tan^{-1} \left(\sqrt{\frac{Z_{M1}}{Z_{M2}}} \right) = 2 - \frac{f_2}{f_0} \tag{11}$$

5 Circuit fabrication and experimental results

The magic-T was fabricated on a Rogers Duroid 6010 substrate with $\varepsilon_r = 10.2$ and 0.63-mm-thick. The central frequency f_0 is set at 4GHz. And it is measured using a Hewlett-Packard 85104A network analyser. Their all performance is listed in Table 3 and are in rough agreement with the electromagnetic (EM) simulation results.

Table 3. Experimental Results Of The Magic-T

Average insertion loss	1dB bandwidth	Phase imbalance
<0.65 dB	68%	<4°
Amplitude imbalance	Port 2-3 isolation	Port *E-H* isolation
0.6 dB	>16.8 dB	>23.8 dB

6 Conclusion

In this paper, a broadband magic-T adopting double-sided parallel-strip (DSPSL) line and microstrip-coplanar waveguide (CPW) transition has proposed and realized, and this magic-T has characteristic as DSPSL difference inputting of port E, single side microstrip inputting of port H and two sides microstrip outputting of port 2 and 3. The experimental results show that this magic-T provides more than 68% of 1dB operating bandwidth, and its phase and amplitude imbalance is less than 4°and 0.65 dB, respectively. From the experimental data we can induce that amplitude and phase's imbalance of this magic-T is caused by error of circuit's fabrication especially precision of three layers circuit's contraposition. Loss of transition between DSPSL and SMA connector is a little bigger because DSPSL is symmetric structure, But SMA connector is asymmetric. This transition's irregular also caused isolation between port 1 and 4 was deteriorated. This magic-T may be applied for some balanced structures of multilayer microwave integrated circuit as for its circuit characteristic.

Acknowledgements

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