Broadband Compact Single-Layer Magic-T Junction with Separation of DC Signals between All Ports

Wojciech MARYNOWSKI

Dept. of Microwave and Antenna Engineering, Faculty of Electronics, Telecommunications and Informatics, Gdansk University of Technology, Gdansk 80-233, Poland

marynowski.w@gmail.com

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Abstract. *A novel structure for a four-port microstrip magic-T junction is presented. The device is composed of microstrip and slotline circuits etched onto two sides of a dielectric substrate. The device is extremely compact and occupies an area more than three times smaller than similar structures recently reported in the literature. The novelty of the device lies in the use of microstrip/slotline transitions for both input ports: summation (in-phase) port and difference (out-of-phase) port. This ensures electrical separation for DC signals between all four ports, a wide operation band and a very small size for the device. The fabricated prototype operates in a* 95% *fractional bandwidth with return losses better than* 10 *dB and isolation between input ports better than* 35 *dB. The insertion losses for the excitation at the summation port are about* 0.8 *dB and for the excitation at the difference port are about* 1.4 *dB. In the operation band of the device, the maximum amplitude imbalance is equal to* ±0.3 *dB, whereas the maximum phase imbalance is equal to* ±4°.

Keywords

Magic-T junction, microwave hybrid, in-phase/out-of-phase divider, power divider

1. Introduction

Magic-T junctions, also called microwave hybrids, are important components of many RF circuits. The hybrid is generally a four-port device that enables in-phase and out-of-phase signal division between its output ports [1]. The input port that provides the in-phase splitting signals is called the summation port, while the one enabling out-of-phase signal division is called the difference port. The hybrid has found applications in several microwave systems such as frequency doublers [2], mixers [3], power amplifiers and antenna feeding structures.

Several realizations of the hybrid are described in the literature. The most popular is its implementation as a rat-race hybrid, which is very simple and takes a planar form [1]. The rat-race hybrid in the conventional form is realized as a ring, which is composed of four transmission lines: three of these have length $\lambda/4$, and the other has length $3\lambda/4$. Hence, the total circumference of the ring is $3\lambda/2$. As a result, this type of hybrid is very large, which significantly limits its application in compact systems, especially in monolithic microwave integrated circuits (MMICs). Moreover, the hybrid usually operates in a narrow band (fractional bandwidth less than 50%). The operation band is limited mainly by the largest section of the ring ($3\lambda/4$).

In the literature, several studies can be found which are focused on the enhancement of the bandwidth of the rat-race hybrid. One of the concepts described in [4] consists of replacing the $3\lambda/4$ length section with a shorter section composed of a pair of coupled lines, with length, e.g., $\lambda/4$. These lines are short-circuited at opposite ends. Such a section provides a 90° phase shift from the $\lambda/4$ line and a 180° phase shift from the phase-reversing element.

Bandwidth enhancement is also achieved in [5–8], where the different realizations of the phase-reversing structures allow the circumference to be reduced by $\lambda/2$. However, the final structures are very complex and difficult to implement. In [9], [10], different configurations of microstrip/slotline transitions are used for bandwidth enhancement of a planar hybrid. However, the use of a double-sided transition causes the the final structure to be even larger in comparison to a conventional rat-race hybrid. An other technique for bandwidth enhancement is proposed in [11]. The section of length $3\lambda/4$ is replaced by a composite right-/left-handed artificial transmission line composed of quasi-lumped and lumped elements. The use of such elements results in an increase in the fabrication cost and significantly limits the operation band within which the amplitude and phase imbalance is acceptably small.

In the literature, there are several studies which are aimed at reducing the size of the conventional rat-race hybrid. Different techniques are used to achive this, such as a folded line structure [12], periodic stepped-impedance resonator [13], [14], defected ground plane structures [15] and the the multi-layer structures [16–18]. In all the cases, such approaches lead to a reduction in the operational bandwidth and the final structures are difficult to implement.

In this paper, a novel configuration for a magic-T junction is proposed. The device is realized as a single-layer structure. In contrast to the structures presented in [4–15], the device is not a modification of the rat-race hybrid; hence it does not contain transmission lines of length $\lambda/4$. The proposed device employs four microstrip/slotline transitions. In the literature, in-phase [19] as well as out-of-phase [9, 10, 20, 21] power dividers are described, which utilize such transitions. The main novelty of the presented device is the application of microstrip/slotline transitions in one hybrid, for simultaneous in-phase and out-of-phase power division. As a result, all four ports are realized with the use of microstrip/slotline transitions. This allows a wide operational bandwidth to be achived and allows the device to be very small compared to those recently presented in the literature. Moreover, in contrast to the structures presented in [4–18, 20, 21], blocking of the DC signal path between all ports of the device is obtained. This advantage allows the proposed device to be used in complex active microwave systems where parts of the system require DC biasing.

The paper is organized as follows. Section 2 contains a description of the proposed hybrid and its principle of operation. In Sec. 3 the realization of the prototype is described and the numerical results obtained from simulations are compared with the results of measurements. A comparison of parameters and sizes for the proposed hybrid and the devices recently described in literature is also made in this section. The final discussion and the conclusion are presented in Sec. 4.

2. Design

A configuration of the proposed magic-T junction is presented in Fig. 1. All four ports of the device are realized as 50 Ω microstrip lines placed on one side of the dielectric substrate (see Fig. 1(a)). The other side of the substrate is a ground plane with slot lines and resonators etched into the copper (see Fig. 1(b)). The device is composed of two input ports (1) and (2), and two output ports (3) and (4). Port (1) is called the in-phase port (or Σ port) and ensures even output signals at ports (3) and (4). The excitation at port (2) (also called the out-of-phase port or Δ port) results in out-of-phase signals of equal amplitudes appearing at output ports (3) and (4).

The part of the circuit ensuring in-phase signal division is symmetrical along the center of the microstrip line feeding port (1). When port (1) of the structure is excited, the signal passes through the microstrip/slotline transition and is equally divided between slots 3 and 4. Slot 2 has no influence on this excitation because of the magnetic wall which appears at its center. The signals are transmitted to the ends of the slots which are terminated by microstrip/slotline transitions. After passing the transitions, the in-phase signals appear at output ports (3) and (4). For the considered excitation, port (2) is isolated.

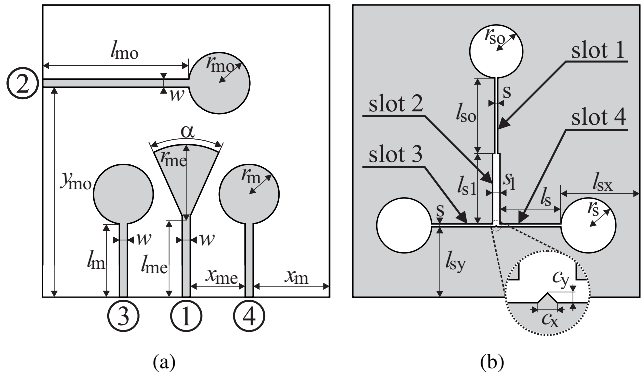


Fig. 1. Configuration of proposed magic-T junction: (a) microstrip (top) circuit; (b) slotline (bottom) circuit.

In order to explain the out-of-phase operation, excitation at port (2) is assumed. After passing the microstrip/slotline transition, the signal appears in slot 1 and then excites the slotline T-junction. This junction is composed of three slotlines of width s. To improve the matching between slot 1 and slots 3 and 4, connected in series, an additional slot 2 of width s_1 is introduced (see Fig. 1(b)). The signal from slot 1, after passing through slot 2, is equally divided between slots 3 and 4. Due to the serial connection of these slots, the excited signals are out-of-phase. There is no coupling to the Σ port because in this excitation the electric wall appears at the center of slot (2). After passing the microstrip/slotline transitions at the ends of the output slots, signals with equal amplitudes and 180° phase difference appear at ports (3) and (4).

3. Numerical and Experimental Results

The proposed structure was designed using the full-wave commercial simulator Ansoft HFSS [22]. The device was realized on a Taconic TLY-5 substrate of thickness $h = 0.254$ mm, relative dielectric permittivity $\varepsilon_r = 2.18$ and loss tangent $\tan\delta = 0.001$. In order to simplify the project it was assumed that all microstip lines have 50 Ω and the three microstip/slotline transitions have the same dimensions. Moreover, based on the principle of operation of microstrip/slotline transitions presented in [23], [24], the initial dimensions of the device were assumed as follow:

- the diameters of the microstrip and slotline circular stubs and radius of microstrip radial stub were about $\lambda/6$,where λ is a wavelength,

- the width of the slotline in the transitions was as narrow as possible (in manufacturing process) to obtain the impedance closest to impedance of microstrip line (required to obtain wide operation bandwidth [23], [24]).

The final dimensions of the structure were obtained in optimization process and are presented in Tab. 1

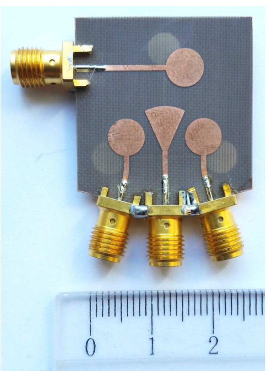
In order to perform the measurements, microstrip feeding lines were terminated with 50 Ω-SMA coaxial connectors. Due to the proximity of the Σ port and output ports, the microstrip feeding lines of ports (3) and (4) were slightly curved. This allowed for the soldering of three SMA connectors onto one edge of the circuit board (see Fig. 2(a)). The structure was very small and occupied a board of only 28 mm x 29 mm in size.

The simulation results were compared to the results obtained in the experimental tests as presented in Figs. 3 and 5. The operational frequency band of the prototype ranged from 1.5 GHz to 4.2 GHz. As can be seen in Fig. 3(a), the highest return losses of 10 dB were at the Δ port. For the remaining ports, the return losses were lower and equal 11 dB, 15 dB and 14 dB for ports Σ, (3) and (4), respectively.

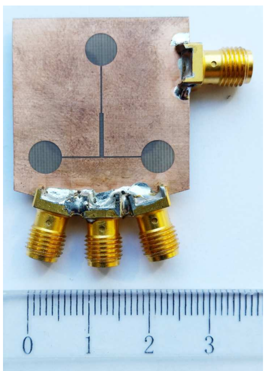
Fig. 3(b) shows the transmission coefficients from input ports (1) and (2) to output ports (3) and (4). These parameters for the ideal magic-T junction are equal to −3 dB. In the case of excitation at port Σ, insertion losses occurring in transmission to ports (3) and (4) were equal to 0.8 dB, (i. e., $S_{31} = -3.8$ dB). For excitation at port Δ, the maximum insertion losses occurring in transmission to ports (3) and (4) were roughly 1.4 dB, (i. e., $S_{32} = -4.4$ dB).

microstrip layer		slot layer	
w	0.78	s	0.29
r_{mo}	2.98	r_{so}	2.59
l_{mo}	14.23	l_{so}	7.38
y_{mo}	20.50	s_1	0.72
r_m	2.91	l_{s1}	6.89
l_m	7.13	r_s	2.68
x_m	7.47	l_s	5.95
r_{me}	7.83	l_{sx}	7.70
l_{me}	7.06	l_{sy}	6.86
x_{me}	5.36	c_x	0.24
α	48.29°	c_y	0.12

Tab. 1. Dimensions of proposed magic-T junction (in millimeters).



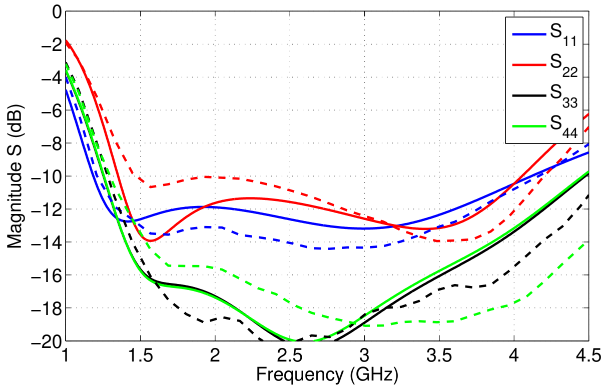
(a)



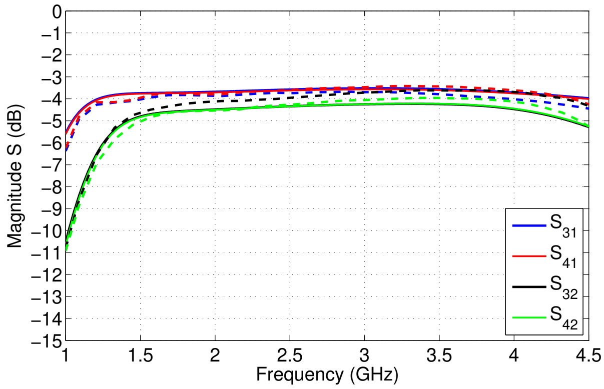
(b)

Fig. 2. Photographs of the fabricated prototype: (a) microstrip (top) circuit; (b) slotline (bottom) circuit.

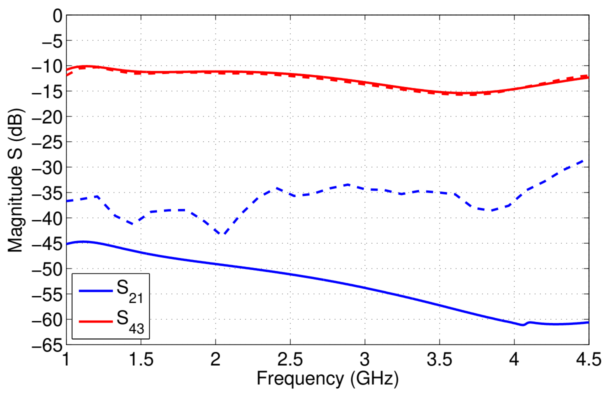
The isolation characteristics between ports (1)–(2) and (3)–(4) are presented in Fig. 3(c). The simulated isolation between input ports (S_{21}/S_{12}) was close to ideal and better than 48 dB. This was as a result of the symmetry of the simulated structure, excluding the microstrip line related to port Δ. Even in the measurement, the isolation between Σ and Δ was still very high: better than 35 dB. The deterioration of the isolation in the prototype is caused by the imperfect manufacturing process. Even small displacements between the circuits on the two sides of the substrate significantly deteriorates this isolation. The simulated and measured isolation between output ports (3) and (4) well agrees and equals about 12 dB.



(a)



(b)



(c)

Fig. 3. Simulated (solid lines) and measured (dashed lines) scattering parameters of the proposed magic-T: (a) return losses; (b) out-of-phase and in-phase transmissions; (c) isolations.

Such level of isolation is the result of mutual coupling between the microstrip circular stubs connected to ports (3) and (4), and the radial microstrip stub connected to port (1). The most simple way to decrease this coupling and simultaneously increase the isolation is to turn upside down the microstrip stubs as presented in Fig. 4(a). The simulated isolation for the modified structure is presented in Fig. 4(b). For this configuration the improvement in level of isolation is achieved in comparison to results from Fig. 3(c). As one can see, the isolation is better than 20 dB near the center operation frequency. However, the drawback of this configuration is the increase in the area occupied by the circuit, which was marked with red color in Fig. 4(a).

The further improvement in isolation between ports (3) and (4) can be obtained by increasing the separation distance between rotated stubs. However this approach will further increase the board size and the circuit will require additional optimization, since the deterioration in performance can be observed with geometry modification. Nevertheless, the author believes that the trade-off can be established between the structure dimensions and acceptable level of isolation, making the proposed structure still attractive in many microwave and antenna applications. Moreover, the proposed magic-T in its current form can be used in applications, where the low isolation between the output ports of such device is not an issue e.g. as in-phase and out-of-phase power divider. The amplitude and phase imbalances are shown in Fig. 5.

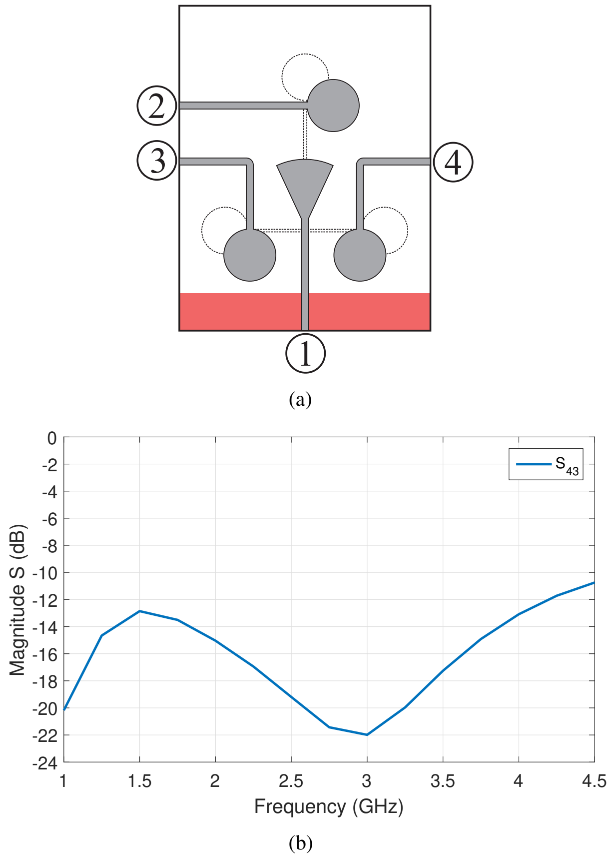


Fig. 4. Improvement of the isolation between ports (3) and (4): (a) modifications in the circuit; (b) simulated results for the modified structure.

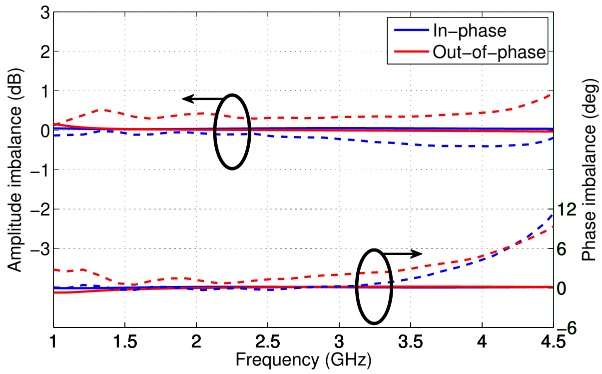


Fig. 5. Simulated (solid lines) and measured (dashed lines) amplitude and phase imbalance of the proposed magic-T junction

Due to the symmetry of the structure, the simulated results are close to ideal. However, the measured values differed from the simulated values. In the operation band, the amplitude imbalance was less than ±0.3 dB, whereas the phase imbalance was less than ±4°. The cause of the deterioration in these characteristics was imprecise positioning of the microstrip and slotline circuits, as in the case of isolation deterioration.

The experimental results were compared to those obtained for similar structures in the recently published literature. The collected results are shown in Tab. 2. In order to compare the dimensions of the structures, two circuit sizes for each device are also presented. The first of these is simply the board size of the device and the second is the minimum size of the structure excluding all feeding lines, evaluated from schemes and photographs of the hybrids [9, 20, 21]. Since the compared devices operated at different frequencies, the fractional bandwidths and minimum sizes of the structures normalized to wavelength $\lambda_g = 2\pi/\beta$ were compared. The propagation coefficient β was determined for a 50 Ω microstrip line, calculated using a fullwave simulator [22] at the center frequency. From Tab. 2 it can be seen that the proposed magic-T junction operated in the widest fractional bandwidth (95%) and was more than three times smaller than the devices [9, 10, 20, 21].

4. Conclusion

The compact configuration of a magic-T junction was presented. The device was realized as single-layer structure with microstrip and slotline circuits etched onto two sides of the dielectric substrate. The novelty of the device lies in the use of the microstrip/slotline transitions for both input ports: summation (in-phase) port and difference (out-of-phase) port. Such a configuration ensures electrical separation for DC signals between all four ports. Moreover, the proposed device operates in a wide frequency band and has a very small size. The measured results of the prototype showed that the fractional bandwidth of the hybrid was 95%, with return losses of better than 10 dB, isolation between ports Σ and Δ better than 35 dB and maximum inser-

Parameter	References				This paper
	[9]	[10]	[20]	[21]	
center frequency [GHz]	2.00	10.1	6.75	6.10	2.85
fractional bandwidth [%]	60	69	81	69	95
excitation at Σ port (transmission S_{31}, S_{41}) [dB]	−4.5	−4.0	−3.5	−4.0	−3.8
excitation at Δ port (transmission S_{32}, S_{42}) [dB]	−5.0	−3.6	−5.0	−4.0	−4.4
amplitude imbalance [dB]	±0.4	±0.3	-	-	±0.3
phase imbalance [deg]	±2.5	±1.0	±0.8	±1.5	±4.0
ports (1)–(2) isolation [dB]	32	32	40	45	35
ports (3)–(4) isolation [dB]	22	15	12	28	12
board size [mm^2]	-	17x21	24x35	15x25	28x29
circuit size without feeding lines [mm^2]	55x81	13x14	8x27	8x18	24x24
wavelength λ_g [mm]	57.25	10.63	26.98	18.75	76.83
circuit size without feeding lines normalized to λ_g^2	1.36	1.61	0.30	0.41	0.10

Tab. 2. Comparison of proposed magic-T junction with similar structures presented in the literature. The operation band was defined for reflection coefficients better than −10 dB.

tion losses better than 1.4 dB. The maximum amplitude and phase imbalances were ±0.3 dB and ±4°, respectively. The final structure was extremely compact and occupied an area more than three times smaller than the areas of similar structures recently reported in the literature.

Acknowledgments

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About the Authors . . .

Wojciech MARYNOWSKI was born in Bydgoszcz, Poland, in 1980. He received the M.Sc.E.E. and Ph.D. degrees from Gdansk University of Technology, Gdansk, Poland, in 2004 and 2011, respectively. He is currently with Department of Microwave and Antenna Engineering, Technical University, Gdansk. His research interests include electromagnetic wave propagation in complex materials, and design of nonreciprocal planar microwave devices, wideband/ultrawideband antennas, and theirs feeding systems.