Compact Broadband Rat-Race Coupler in Multilayer Technology Designed with the Use of Artificial Right- and Left-Handed Transmission Lines

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Abstract—The paper presents a compact broadband rat-race coupler for the first time designed and realized in a multilayer microstrip technology. To achieve both broad operational bandwidth and a compact size the 270° transmission line of a conventional rat-race, coupler has been replaced by a –90° left-handed transmission line realized with the use of a quasi-lumped element technique. Moreover, to achieve better compactness of the resulting coupler, all 90° right-handed transmission lines have been realized with the use of the same technique. It has been also proved that simple LC approximation of a left-handed transmission line can be successfully used for the design. Moreover, it has been shown that when appropriately chosen, the multilayer dielectric structure allows for realization of structures designed with the use of this simple approximation, for both right-handed and left-handed transmission lines, without loosing too much of a performance.

Keywords—broadband rat-race couplers, left-handed transmission lines, quasi-lumped elements.

1. Introduction

Rat-race couplers are well-known components often used in microwave circuits. They allow for in-phase and out-of-phase power division with the fourth port being isolated, and in a classic approach they are composed of three 90° and one 270° transmission lines. The two major drawbacks of conventional rat-race couplers are their relatively large size and narrow bandwidth. The problem of size reduction is usually approached with the use of lumped-element technique [1], [2], whereas, different techniques have been developed over the years to broader the operational bandwidth [3]–[7]. One of the possible approaches that allows for achieving broadband operation of rat-race couplers involves the application of an ideal 180 transformer, which is difficult to realize [3]. Another technique allowing for significant bandwidth increase is based on the substitution of a 270° transmission line by a –90° left-handed transmission line [8]–[11]. Such an approach also allows for significant size reduction. In [8], the first trials of such devices are shown, in which left-handed transmission lines have been realized with the use of SMD components. Another example of such a rat-race coupler is shown in [9], where right-

handed and left-handed lines have been implemented with the use of complementary split rings resonators. In [10], a compact broadband rat-race coupler has been considered, in which, to achieve smaller size, both right- and left-handed transmission lines have been realized as artificial lines, with the use of metal-air-metal capacitors and short-open circuited stubs. It was shown in [10] that such an approach is suitable for high frequency and low frequency applications, however, only full wave simulations are presented.

In this paper, we present for the first time the design and realization of a compact broadband rat-race coupler in a microstrip multilayer technology. The presented coupler has been designed with the use of both right- and left-handed artificial transmission lines. Right-handed transmission lines have been modeled with the use of a cascade connection of several RH cells and the appropriate number of cells has been selected, so that the effect of substituting the 90° transmission lines by the artificial lines on the overall coupler's performance can be neglected. Similarly, the –90° left-handed transmission line has been modeled with the use of LH cells, and the optimum number of cells has been chosen to ensure from one hand, the good performance of the coupler, and on the other hand, the feasibility of further circuit implementation in a microstrip multilayer technology. Both theoretical and experimental results are presented in this paper.

2. Theoretical Analysis

The concept of a compact broadband rat-race coupler is explained in Fig. 1. The coupler utilizes a well-known idea of substituting 270° right-handed transmission line by a –90° left-handed transmission line. Both right- and left-handed lines have been divided in n equal unit cells. The right-handed unit cell consists of a series inductor L_{RH} and a shunt capacitor C_{RH}, whereas, the left-handed unit cell consists of shunt inductor L_{LH}, and a series capacitor C_{LH}. The values of the lumped elements shown in Fig. 1 would, therefore, depend on the characteristic impedance of the transmission line Z, its electrical length Θ, operating frequency f and the number of applied unit cells n for both
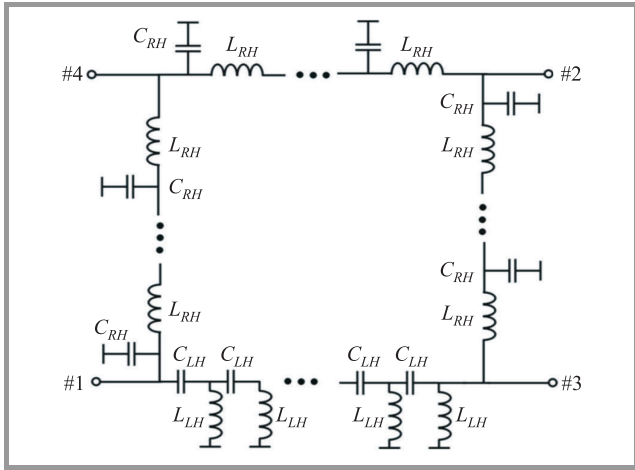
Fig. 1. A schematic diagram of a compact broadband rat-race coupler utilizing artificial right and left-handed transmission lines.

right- and left-handed artificial lines. From the transmission line theory of both right- and left-handed transmission lines we can derive simple formulas for all values of lumped elements shown in Fig. 1, which are

$$L_{RH} = \frac{\Theta Z}{2\pi f n}, \tag{1}$$

$$C_{RH} = \frac{\Theta}{2\pi f n Z}, \tag{2}$$

$$L_{LH} = \frac{Z n}{2\pi f |\Theta|}, \tag{3}$$

$$C_{LH} = \frac{n}{2\pi f Z |\Theta|}, \tag{4}$$

where: Θ – electrical length of the transmission line section in radians, Z – characteristic impedance of the transmission line section, f – frequency at which the electrical length is specified, and n – number of the applied unit cells for transmission-line section approximation.

It should be noted that for the case of a left-handed transmission line, the electrical length is negative (equals $\Theta = -\pi/4$ in case of a rat-race coupler), whereas the elements of its equivalent circuit are positive. It is also known that the higher number of unit cells n is taken, the better approximation of the ideal transmission line section by its artificial equivalent for both right- and left-handed transmission lines. However, to achieve smaller size of the resulting coupler low value of n is preferable. On the other hand, by analyzing formulas (1)–(4) one can see that in case of a right-handed artificial transmission line the higher n, the lower values of the resulting inductors L_{RH} and capacitors C_{RH}. Whereas, in case of a left-handed transmission line this dependence is opposite. Therefore, in the case of a left-handed artificial line, the number of unit cells n is a trade-off between the quality of the transmission line approximation and the feasibility

of further physical realization. The dependence of the rat-race parameters versus number of cells n (for both right-handed and left-handed lines) have been investigated and it turned out that for $n = 8$ ($\Theta = 11.25°$ of each unit cell) the achieved parameters are almost identical as the parameters of the coupler modeled by the ideal transmission lines. To simplify further realization of the left-handed unit cells, the number of cells have been reduced to $n = 6$, which gave lower values of capacitors C_{LH} and inductors L_{LH}. Figure 2 presents calculated fre-
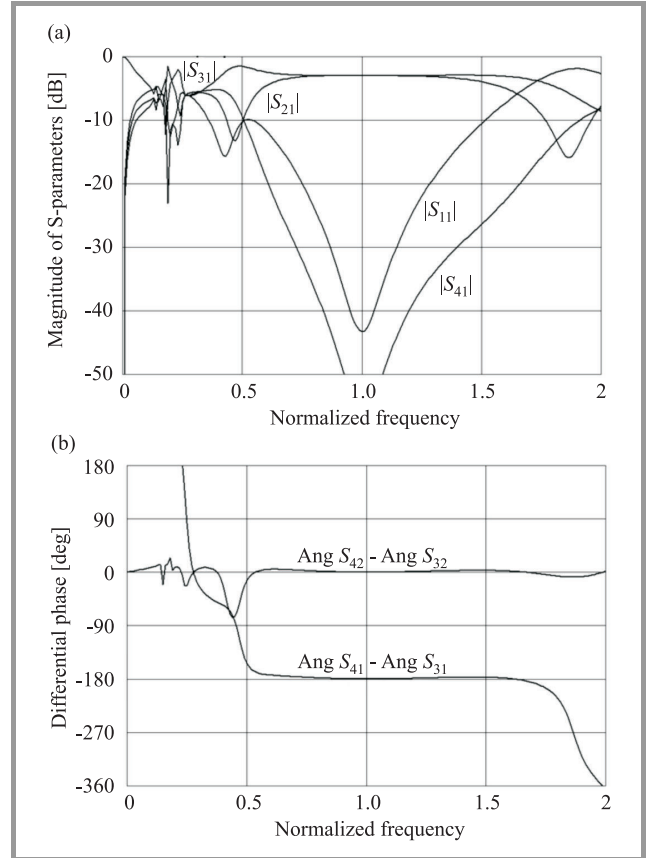

Fig. 2. Calculated amplitude (a) and differential phase (b) characteristics of a compact rat-race coupler in which 90° right-handed transmission lines have been divided into 8 cells and the –90° left-handed transmission line has been divided into 6 section. Results of circuit simulations.

quency characteristics of the coupler, in which 90° right-handed transmission line sections have been modeled by 8 LC unit cells, whereas, the –90° left-handed transmission line section has been modeled by 6 CL unit cells. It seems that good performance have been obtained. The coupler's bandwidth equals 55% for RL > 20 dB and 106% for I > 20 dB, and the coupler features broadband differential phase.

3. Experimental Results

The presented approach for compact broadband rat-race realization has been experimentally verified. For the purpose

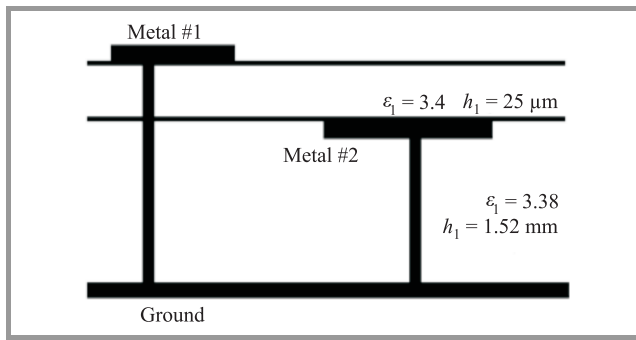of simultaneous realization of large series capacitors and shunt inductors a multilayer structure presented in Fig. 3 has been chosen.

Fig. 3. Cross-sectional view of the dielectric structure used for the design of a compact broadband rat-race coupler.

has been chosen. In such a structure, in which a thin dielectric layer is placed on a thick dielectric layer, it is possible to realize large series capacitors and large inductors having reduced spurious shunt capacitance. The coupler has been designed for the center frequency of 0.5 GHz, for which the following values of lumped elements have been found $L_{RH} = 4.42$ nH and $C_{RH} = 0.884$ pF (for $Z = 70.7$ Ω, $n = 8$, $\Theta = \pi/4$) for the right-handed transmission line and $L_{LH} = 86$ nH and $C_{LH} = 17.2$ pF (for $Z = 70.7$ Ω, $n = 6$, $\Theta = -\pi/4$) for the left-handed
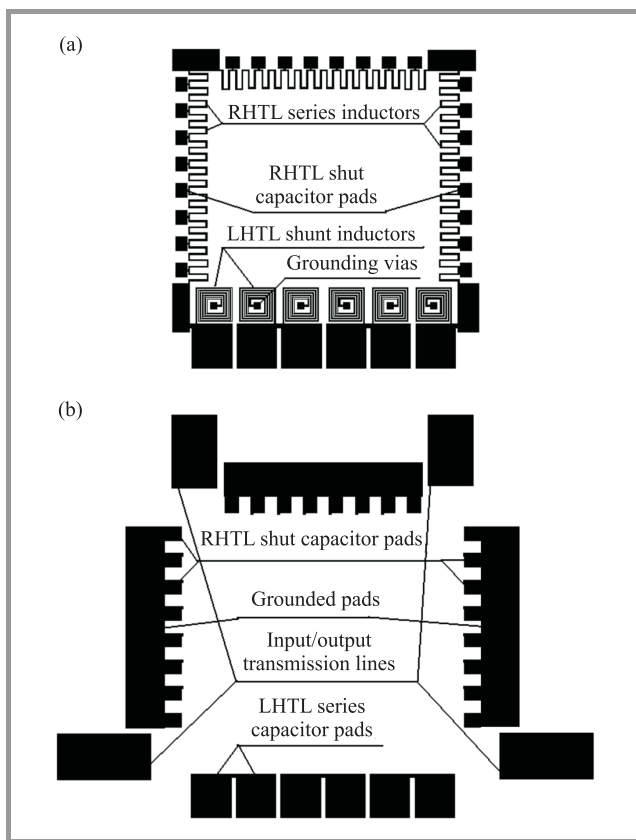

Fig. 4. Layout of the developed compact broadband rat-race coupler (not to scale): (a) upper layer; (b) lower layer.

transmission line. The detailed layout of the developed rat-race coupler is shown in Fig. 4. To ensure symmetry of the right-handed transmission lines, the series inductors LRH have been divided into two equal inductors, between which shunt capacitors CRH are inserted. To minimize metallization pads required for CRH realization, the bottom pads of the capacitors have been grounded. The CLH capacitors have been realized on two sides of the thin laminate, whereas, LLH inductors have been realized as planar square spiral inductors grounded in the center, as it is presented in Fig. 4.

The designed coupler has been analyzed electromagnetically and the obtained results are plotted in Fig. 5. As it is shown, the designed coupler features slightly narrower bandwidth in terms of return losses ($BW = 44\%$). However, the isolation, transmission and coupling, and also differ-
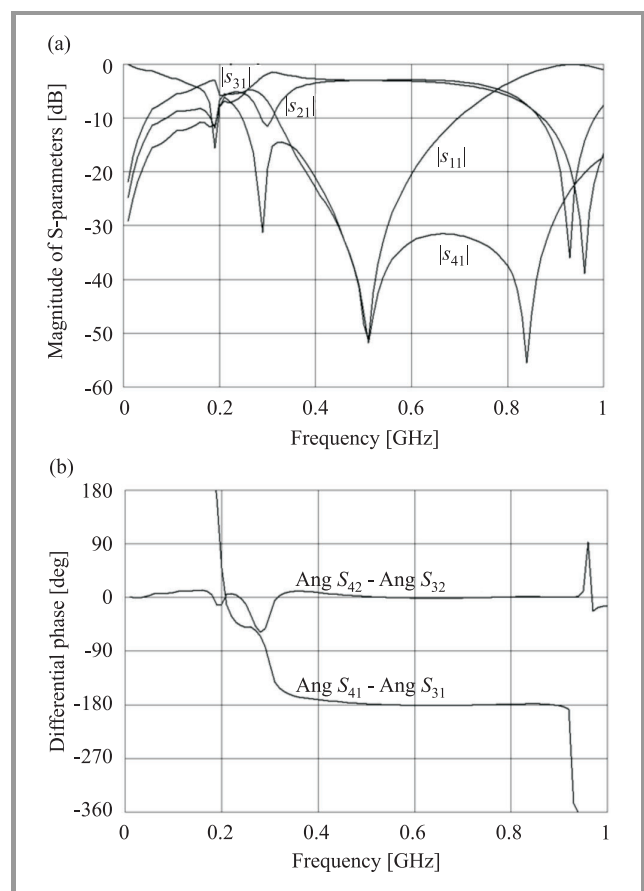

Fig. 5. Calculated amplitude (a) and differential phase (b) characteristics of the developed compact rat-race coupler shown in Fig. 4. Results of electromagnetic calculations.

ential phase characteristics are better within broader bandwidth than the bandwidth of the coupler modeled by simple LC and CL unit cells. This is due to the well-known effect of spurious shunt capacitances, and series inductances of the left-handed transmission line that affects its phase characteristic, resulting in composite right/left-handed transmission lines (CRLH TL). It is important to underline

that CRLH TLs can be used for maximizing bandwidth, in terms of differential phase response, as it was shown in [8]. However, the obtained results prove that the presented simplified approach is also suitable for broadband compact rat-race realization, especially in a multilayer microstrip technique. The achieved size of the developed rat-race coupler in comparison with the classic one is shown
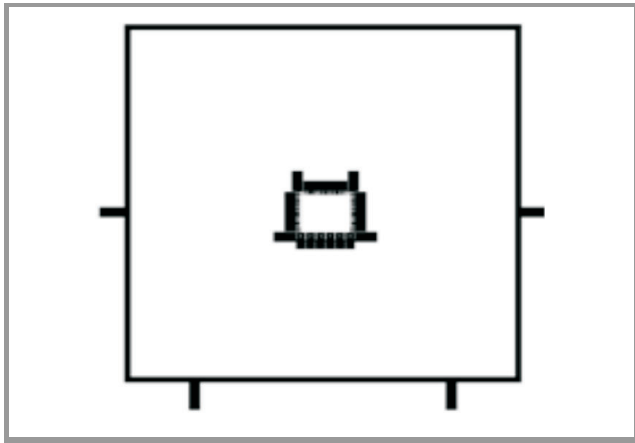

Fig. 6. Size comparison between a classic and the developed rat-race couplers.

Fig. 7. Measured frequency characteristics of the manufactured compact rat-race coupler: (a) amplitude characteristics; (b) differential phase characteristics.

in Fig. 6. In this case a significant size reduction has been achieved.

The designed coupler has been manufactured and the measured results are shown in Fig. 7. A good agreement has been achieved between the calculated and measured characteristics in terms of both amplitude and differential phase. The measured return losses and isolation are better than 20 dB in slightly broader bandwidth than the calculated one. The achieved differential phase ripple does not exceed 10 and the overall insertion loss equals 0.4 dB.
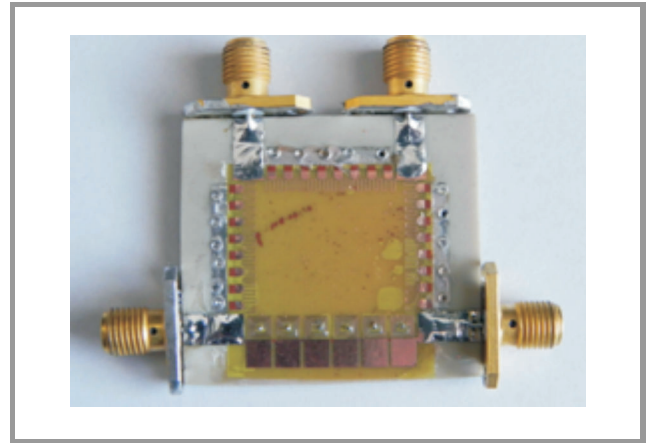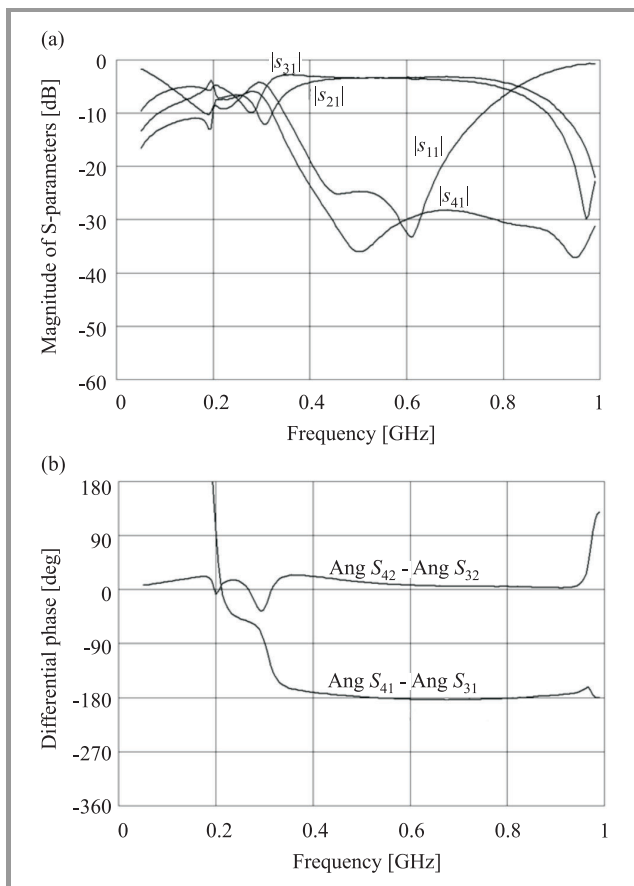

Fig. 8. Photograph of the manufactured compact broadband rat-race coupler.

Figure 8 presents the photograph of the compact broadband rat-race coupler developed in a multilayer microstrip technology.

4. Conclusions

The design of a compact broadband rat-race coupler in a multilayer microstrip technique, and utilizing artificial right- and left-handed transmission lines has been presented for the first time. A simple approach has been proposed, in which both right- and left-handed transmission lines are represented, respectively, by LC and CL lumped-element networks. Simple formulas for the lumped elements constituting both right- and left-handed transmission lines have been given for the arbitrary number of unit cells of each line. Moreover, it has been shown that such a simplified approach gives a good performance of the resulting coupler, and also that such couplers are easily realized in a microstrip multilayer structure. This is due to the fact that a microstrip structure, in which a thin dielectric layer is placed over a thick one, is suitable for large series capacitors and shunt inductors realization. Although, the formulas for lumped-elements of an artificial CRLH transmission line that gives the maximum bandwidth of the coupler are known [8], the obtained results prove that the presented simplified approach can be also used for the design of compact broadband rat-race couplers in a microstrip multilayer technique.

Acknowledgment

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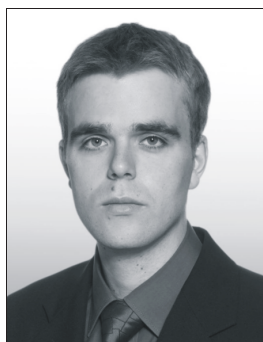
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