A Broadband 3 dB Tandem Coupler Utilizing Right/Left Handed Transmission Line Sections

Kamil Staszek, Jakub Sorocki, Piotr Kaminski, Krzysztof Wincza, and Slawomir Gruszczynski

***Abstract*—A new type of broadband 3 dB tandem coupler has been proposed featuring frequency characteristics of the resulting coupling similar to those of a classic 3 dB two-section asymmetric coupled-line directional coupler. The coupler is composed of two loosely coupled-line sections having electrical lengths close to quarter-wavelength connected by right-handed and left-handed transmission line sections. Theoretical analysis and design equations have been presented with an exemplary realization. Measurements of the manufactured tandem coupler operating at $f_0 = 1$ GHz having wide operational bandwidth have been shown to validate the presented analysis.**

***Index Terms*—Left-handed transmission lines, metamaterials, tandem connection, 3 dB coupled-line directional couplers.**

I. Introduction

TANDEM couplers [1] are very attractive passive microwave components, allowing for realization of 3 dB coupled-line directional couplers in dielectric structures when tight coupling is not available. A lot of research effort has been put over past years into development of methods allowing for broadband operation of tandem couplers having n coupled-line sections. In [2], the authors have shown the design approach allowing for realization of such couplers, whereas, in [3] a modified tandem structure having wide passband, with an additional short-circuited asymmetrically fed coupled-line coupler and quarter-wavelength connecting lines, has been shown. On the other hand, 3 dB directional couplers having broad operational bandwidth can be realized as tandem connection of two multi-section asymmetric 8.34 dB couplers [4]. However, such couplers require much higher coupling level available in dielectric structure, which in some cases is not achievable or complicated structure is required [5]. Recently shown, the unique properties of left-handed transmission lines, described, e.g., in [6], triggered their application in the design of coupled-line directional couplers. In [7] a design procedure of tightly-coupled directional couplers has been presented with the use of composite right-/left-handed coupled-line sections. However, it suffers from high coupling imbalance with respect to classic solutions, moreover the obtained bandwidth does not exceed $f_u/f_l = 1.65$.

In this letter, we propose a novel broadband 3 dB tandem coupler realized as two nearly quarter-wavelength coupled-line sections, connected by right-handed (RH) and left-handed (LH) transmission line sections. The introduction of LH transmission line with its unique phase properties allows for shaping coupling characteristic, hence such a coupler can feature properties similar to those of a classic 3 dB two-section coupled-lined directional coupler. The proposed coupler has been analyzed, and the approximate design equations allowing for calculating the electrical lengths of RH and LH sections have been given. Moreover, the dependence between the required electrical lengths of the coupled-line sections and RH/LH sections, versus the available coupling coefficient of the utilized coupled-line section, has been numerically calculated. The presented concept and its analysis has been experimentally verified by the design and measurements of an exemplary 3 dB directional coupler manufactured in a multilayer microstrip structure.

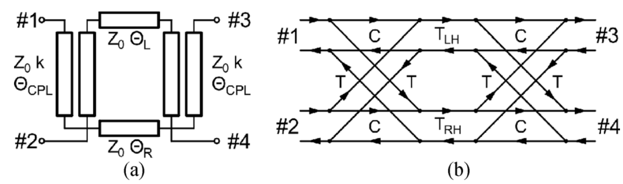

Fig. 1. Schematic (a) and flow graph (b) of the proposed directional coupler consisting of two tandem-connected coupled-line sections between which uncoupled left-handed and right-handed transmission line sections are placed.

II. Theoretical Analysis

A schematic diagram of the proposed directional coupler realized as a tandem connection of two coupled-line sections connected by the left-handed (LH) and right-handed (RH) transmission line sections is shown in Fig. 1(a). The presented network is described by: Z_0 – characteristic impedance, Θ_{L0} and Θ_{R0} – electrical lengths of the uncoupled LH and RH transmission line sections, Θ_{CPL0} – electrical length of the coupled-line sections defined at the center frequency and k – the coupling coefficient of the coupled-line sections. In such a structure, due to the phase properties of the applied LH transmission line section, one can obtain the frequency characteristics similar to the characteristics of a classic two-section coupled-line directional coupler.

Utilizing the flow graph of the proposed directional coupler shown in Fig. 1(b), one can obtain the coupling characteristic

$$S_{41} = CT\left(T_{LH} + T_{RH}\right) \tag{1}$$

where

$$C = \frac{jk\sin\left(\Theta_{CPL0}f\right)}{\sqrt{1-k^2}\cos\left(\Theta_{CPL0}f\right) + j\sin\left(\Theta_{CPL0}f\right)} \tag{2}$$

$$T = \frac{\sqrt{1-k^2}}{\sqrt{1-k^2}\cos\left(\Theta_{CPL0}f\right) + j\sin\left(\Theta_{CPL0}f\right)} \tag{3}$$

$$T_{LH} = \exp\left(j\Theta_{L0}f^{-1}\right) \tag{4}$$

$$T_{RH} = \exp\left(-j\Theta_{R0}f\right) \tag{5}$$

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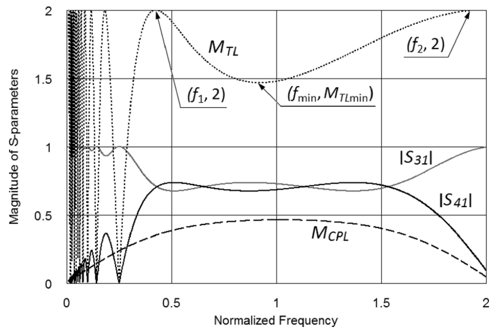

Fig. 2. Exemplary frequency characteristics of the proposed directional coupler and the M_{CPL} and M_{TL} factors.

and f – normalized frequency. Therefore, the magnitude of the coupling characteristic $|S_{41}|$ can be expressed as follows:

$$|S_{41}| = M_{CPL} \cdot M_{TL} \tag{6}$$

where M_{CPL} and M_{TL} are real factors, given by

$$M_{CPL} = \frac{k\sqrt{1-k^2}\sin\left(\Theta_{CPL0}f\right)}{1-\left[k\cos\left(\Theta_{CPL0}f\right)\right]^2} \tag{7}$$

$$M_{TL} = \sqrt{2\cos\left(\Theta_{L0}f^{-1}+\Theta_{R0}f\right)+2}. \tag{8}$$

It can be seen from (6), that the resulting coupling characteristic is a product of two factors: first one, M_{CPL}, is related to the classic tandem connection of two coupled-line sections, and the second one, M_{TL}, is related to the applied LH and RH transmission lines. Therefore, the physical network performance can be explained as a result of interference of two signals having different phases. Fig. 2 shows the magnitude of exemplary frequency characteristics, together with factors M_{CPL} and M_{TL}. As it is seen, the multiplication of such two curves having opposite types of concavity allows one to obtain a nearly flat amplitude response in a broad frequency range. In the presented example, the bandwidth ratio where the coupling and transmission characteristics are equi-ripple is equal $f_u/f_l = 4.3$. In case of a classic tandem, realized as a connection of coupled-line sections, only RH transmission lines are utilized, therefore, $M_{TLclassic} = const = 2$. This fact allows to decrease the coupling coefficient requirements, however, it does not affect the bandwidth of the coupler. In the proposed structure, the factor M_{TL} is frequency-dependent, therefore, it allows for shaping the coupling characteristic in order to obtain the characteristic of a classic two-section coupled-lined directional coupler.

The analysis of (8) allows us to find the approximated parameters of the LHTL and RHTL, which are necessary to design the proposed coupler with the use of the following expressions:

$$f_1 = \frac{\left(\pi - \sqrt{\pi^2 - \Theta_{L0}\Theta_{R0}}\right)}{\Theta_{R0}} \tag{9}$$

$$f_2 = \frac{\left(\pi + \sqrt{\pi^2 - \Theta_{L0}\Theta_{R0}}\right)}{\Theta_{R0}} \tag{10}$$

$$f_{\min} = \sqrt{\frac{\Theta_{L0}}{\Theta_{R0}}} \tag{11}$$

$$M_{TL\min} = 2\left|\cos\sqrt{\Theta_{L0}\Theta_{R0}}\right| \tag{12}$$

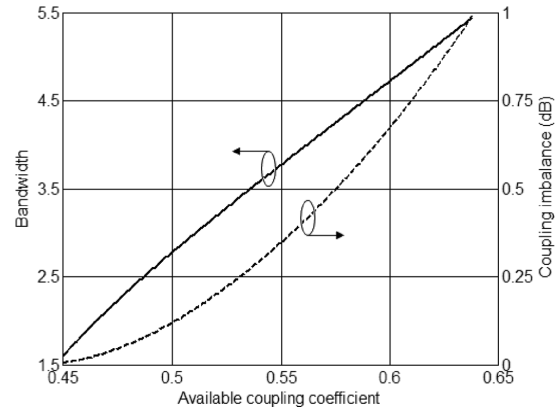

Fig. 3. Bandwidth BW expressed as the ratio of upper and lower frequencies, and coupling imbalance δ_C of the proposed 3 dB directional coupler vs. available coupling coefficient k.

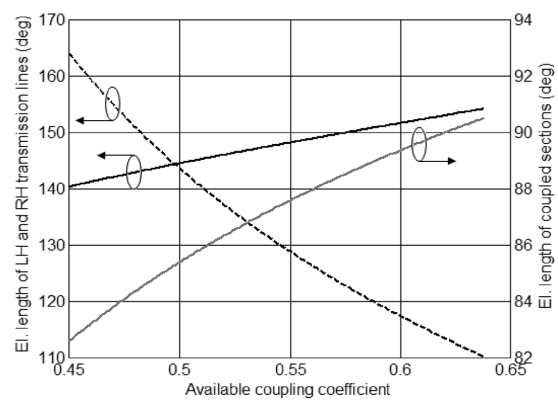

Fig. 4. Electrical lengths of the LH transmission line section Θ_{L0} (dotted line), RH transmission line section Θ_{R0} (solid black line) and coupled-line sections Θ_{CPL0} (solid gray line) vs. available coupling coefficient k.

where f_1 and f_2 are the highest values of frequency at which $M_{TL} = M_{TL\max} = 2$, as seen in Fig. 2, $f_{\min}$ is the frequency at which M_{TL} has local minimum having value $M_{TL\min}$. Assuming $f_2 \approx 2$, $f_{\min} \approx 1$, $M_{TL\min} \approx (\sqrt{2}k\sqrt{(1-k^2)})^{-1}$, and $\Theta_{CPL} \approx \pi/2$ one can obtain approximate parameters of the proposed 3 dB directional coupler. Nevertheless, due to the non-symmetrical frequency characteristic of M_{TL} (with respect to the center frequency), the analysis of (6) enforces utilization of numerical methods in order to find the parameters k, Θ_{CPL0}, Θ_{L0}, Θ_{R0} of the resulting coupler. In our investigation the bisection method has been utilized. Figs. 3 and 4 present the parameters of the proposed coupler vs. the available coupling coefficient k. Such parameters ensure equi-ripple frequency characteristics with three local extremes, similar to the classic two-section coupled-line directional couplers (see Fig. 2). It has to be mentioned, that due to the application of LH and RH transmission lines the phase difference is no longer equal to 90°. The presented analysis applies to the 3 dB tandem couplers, however the concept can also be used for weaker coupling realizations.

III. Experimental Results

To verify the presented approach to the design of broadband 3 dB tandem couplers, an exemplary coupler operating at a center frequency of $f_0 = 1$ GHz has been designed, manufactured and measured. Coupled-line sections having modal impedances equal to $Z_{0e} = 95.6\ \Omega$ and $Z_{0o} = 26.15\ \Omega$ ($k_{CPL} = 0.57$) have been realized in the dielectric structure presented in Fig. 5.

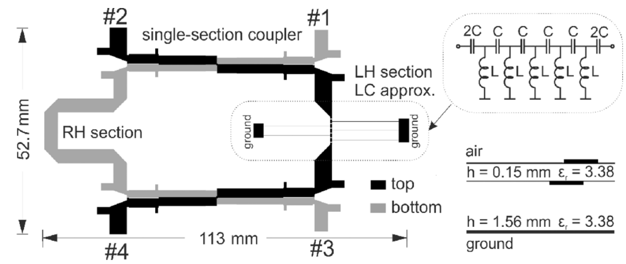

Fig. 5. Dielectric structure used for the design of the developed broadband 3 dB tandem coupler and layout of the designed model.

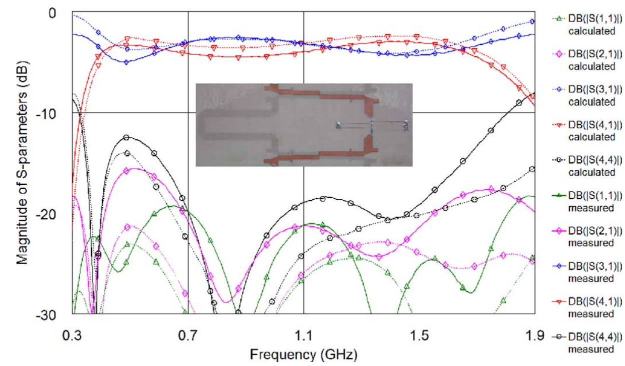

Fig. 6. Calculated (dotted lines) and measured (solid lines) amplitude characteristics of the designed broadband 3 dB tandem coupler. A picture of the manufactured circuit is shown as an inset.

TABLE I
COMPARISON OF PARAMETERS OF THE DEVELOPED BROADBAND 3-dB TANDEM COUPLER WITH OTHER DESIGNS

	Cho [2]	Tang [3]	This paper
No. of coupled-sections	2	3	2
Structure type	Bonded single-layer microstrip	Bonded single-layer microstrip	Multi-layer microstrip
Size (mm)	~ 12 x 10	~ 46 x 41	113 x 52.7
$\varepsilon_{r\,eff}$ (for 50 Ω trans. line)	4.83	3.45	2.89
Bandwidth (GHz)	3.6 - 5.5	0.6 – 1.3	0.4 - 1.7
Bandwidth ratio f_u/f_l	1.5	2.2	4.3
Return Loss. (dB)	15	10	12
Isolation (dB)	15	10	16
Amp. imbalance (dB)	±0.5	±0.7	±1
(W x L) /λ^2_{guided}	0.13	0.065	0.2

The proposed tandem coupler has been theoretically analyzed with the assumption that the conditions for ideal coupled-line section realization are fulfilled, however, for the selected microstrip structure these conditions are not met, i.e., the inductive and capacitive coupling coefficients are not equal, hence a method presented in [8] has been utilized to equalize these coefficients and, therefore, to improve impedance matching and directivity of the resulting coupler.

Following the design procedure presented in Section II, with the use of two coupled-line sections having $k = 0.57$ one can realize a 3 dB tandem coupler having theoretical bandwidth $BW = 4.15$ with coupling imbalance $\delta_C = \pm 0.5$ dB. Such a frequency response can be obtained by taking: $\Theta_{CPL0} = 88.3°$, $\Theta_{L0} = 123.9°$ and $\Theta_{R0} = 149.5°$ ($Z_0 = 50\ \Omega$).

The ideal left-handed transmission line section cannot be physically realized [5], hence we have used 5-subsection LC approximation (T-type). The calculated, according to [9], values of ideal shunt L and series C elements are equal $L_L = 18.4$ nH and $C_L = 7.36$ pF. The required inductors have been realized using high impedance transmission line sections, while capacitors have been realized using 8.2 pF SMD 0402 chip capacitors, which has enforced slight circuit tuning. The designed section is obviously not purely left-handed. However, it is crucial to ensure the dominant LH behavior in the required frequency range.

A picture of the circuit layout is presented in Fig. 5, whereas, the calculated (using *AWR Microwave Office* software) and measured frequency characteristics are presented in Fig. 6. As it can be seen, the developed coupler features bandwidth $BW \approx 4.3$ with coupling imbalance $\delta_C = \pm 1$ dB, isolation is better than 16 dB over the entire operational frequency range and return losses are better than 12 dB. Conductor and dielectric losses, limited manufacturing accuracy and also the utilized chip capacitors have most likely caused the discrepancy between calculated and measured characteristics. The obtained results have been compared in Table I to the previously published designs. As it is seen, the proposed tandem coupler features significantly wider bandwidth, simultaneously ensuring low return losses and good isolation. The size of the manufactured model relative to the guided wavelength is comparable with the one presented in [2] and three times larger as the one proposed in [3]. However, the bandwidth is almost three times wider then the one presented in [2] and almost twice as wide as in [3], whereas the bandwidth of the couplers proposed in [2] and [3] cannot be increased. As it is seen in Fig. 5, the proposed circuit can be further miniaturized by alternative tracing of LH and RH transmission lines, which can be fitted inside the structure.

IV. CONCLUSION

A new broadband 3 dB tandem coupler has been presented together with its theoretical analysis, design methodology and experimental verification. The major advantage of the presented concept of a tandem coupler is that it allows for realization of 3 dB directional couplers having broadband characteristics similar to the classic two-section coupled-line couplers with the use of only two, loosely-coupled, nearly quarter-wavelength coupled-line sections and easy realizable RH and LH transmission line sections.

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