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Broadband Equal-Split Directional Couplers Composed of Cascade- and Tandem-Connected Coupled-Line Sections Having Unequal Lengths

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ABSTRACT A new concept of broadband equal-split coupled-line directional couplers is proposed. The proposed couplers are based on coupled-line sections, all having the same coupling coefficient, and feature frequency characteristics similar to the ones obtained for classic symmetrical three-section coupled-line couplers. It is shown that appropriate cascade- and tandem-connected coupled-line sections, having all the same coupling coefficients and different electrical lengths allow for achieving equal power split in a broadband frequency range together with the quadrature differential phase response. Therefore, a very flexible design process is possible, in which directional couplers with different bandwidths and coupling imbalances can be realized by changing solely the electrical lengths of the coupled-line sections. Moreover, the proposed networks require significantly lower coupling coefficients and feature slightly shorter overall electrical lengths than their classic counterparts. The theoretical analysis of the proposed circuits is shown in the paper and is followed by the design and measurements of two broadband equal-split quadrature directional couplers operating at the center frequency of 2 GHz.

INDEX TERMS Directional couplers, microwave circuits, passive circuits.

I. INTRODUCTION

Quadrature directional couplers as well-known and often utilized components in contemporary microwave electronics, feature equal-power split between coupled and direct ports and simultaneously they present additional 90° phase shift (delay) of the signal delivered to direct port with respect to the signal delivered to the coupled port. Typically, such components are often realized as a connection of quarter-wavelength transmission-line sections. Such branch-line couplers, despite their simple design suffer from large occupied area and relatively narrow bandwidth [1]–[4]. A competitive method of quadrature directional couplers' realization, which allows for achieving broad frequency response and compact size, utilizes coupled-line sections. It is known that a quarter-wavelength coupled-line section, when appropriately designed, constitutes an ideal directional coupler, in which bandwidths up to one frequency octave can be achieved [5]–[12]. Such couplers can be realized in integrated circuits, where occupied area and insertion losses are critical [13], [14], or can be used to obtain a circuit with tunable center frequency and differential phase [15]. Broader bandwidths are obtained with the use of multisection coupled-line directional couplers realized as a cascade connection of quarter wavelength coupled-line sections with different coupling coefficients or tapered-line couplers in which coupling coefficient changes smoothly from the maximum value to zero [16]–[24]. Although very broad bandwidths can be achieved with such designs the major difficulty in realization of these circuits is that the required maximum coupling coefficient of at least one of the coupled-line sections of the circuit has to be much higher than the nominal coupling of the resulting coupler [16], [17], [23]. Moreover, electrical length of the coupler becomes significant especially for symmetrical couplers, which is always the case when quadrature differential phase is required [16]. Therefore, over the years research effort has been undertaken on reduction of the required maximum coupling coefficient and overall size (total electrical length) in broadband coupled-line directional couplers [25]–[32]. The common approach to the problem of

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strong coupling coefficient realization is the application of a tandem structure, which can be utilized either for realization of the entire coupler [25] or only for the section having the strongest coupling [27]. In yet another techniques the reduction of the required coupling coefficient is achieved due to the application of left-handed transmission lines [28] or by the appropriate rotation of the center coupled-line section [29]. It has to be underlined that in all mentioned solutions the reduction of the required coupling coefficient has been obtained at the expense of the size increase (understood as the total electrical length of all sections constituting the coupler). In particular, the realization of the tandem coupler increases the electrical length of the circuit by the factor of 2. Since the reduction of the required coupling coefficient is generally in contradiction to the reduction of the coupler's electrical length, the developed methods of couplers' length reduction utilize the available coupling in the chosen structure to shorten the resulting coupler [33], [34]. This can be achieved either by connecting coupled and uncoupled sections [33] or by quasi-lumped element approach [34]. Two interesting solutions have been recently proposed in [35] and [36], where tandem connection of unequal length coupled-line sections, being however multiples of a quarter wavelength at the center frequency, have been applied to reduce the required coupling coefficient in multisection couplers. Due to the application of unequal electrical lengths the required coupling is significantly reduced, whereas the overall electrical lengths fall between the ones required for classic multisection couplers and classic multisection tandem couplers. A modification of this method has been recently developed for directional couplers featuring frequency characteristics of single-section coupled-line couplers [37]. In this method tandem-connected coupled-line sections having unequal length and fixed coupling coefficient are used to realize directional couplers with the assumed overall coupling. As a result the electrical length of the coupler varies between 90° and 180° and the margin between the available coupling in the chosen structure and the one required in classic tandem coupler is utilized for electrical length reduction in the designed circuit.

In this paper, we present a new circuit solution to the design of equal-split directional couplers featuring frequency characteristics similar to the ones obtained for classic quadrature three-section directional couplers. In the proposed networks unequal-length coupled-line sections, all having the same coupling coefficients, are appropriately cascade- and tandem-connected to realize a broadband quadrature directional coupler. As shown in the paper, with such a configuration when one of the sections is longer than 90° and the remaining ones are significantly shorter than 90°, it is possible to achieve frequency characteristics corresponding to the ones obtained in classic three-section directional couplers. It is proved that the proposed circuit features simultaneously significantly lower required coupling coefficient and slightly shorter overall electrical length than its classic counterpart, which has never been reported up to date.

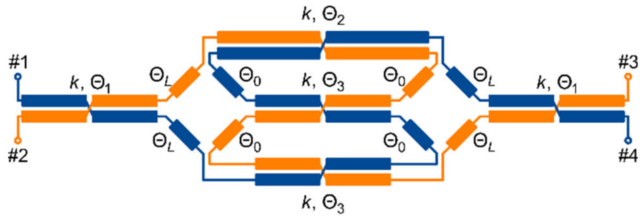


FIGURE 1. Generic schematic of a broadband 3-dB quadrature directional coupler composed of coupled-line sections having unequal electrical lengths.

The paper is organized as follows. In Section II a theoretical analysis of the proposed broadband directional couplers is presented. Section III presents experimental results for the developed two couplers having different coupling-transmission imbalance. In Section IV the comparison of the proposed solution with other known designs is provided. Section IV concludes the paper.

II. THEORETICAL ANALYSIS OF DIRECTIONAL COUPLER COMPOSED OF UNEQUAL LENGTH COUPLED-LINE SECTIONS

A generic schematic of the proposed broadband quadrature directional coupler is presented in Fig. 1. As shown the proposed coupler consists of appropriately connected coupled-line sections all having the same coupling coefficient k, although they differ in terms of their electrical lengths, namely: Θ_1, Θ_2, and Θ_3. The beneficiary properties of the broadband quadrature coupler results from the new conjunction of a cascade- and tandem-connection of such coupled-line sections. As seen the middle part of the circuit is composed of tandem-connected coupled-line sections having electrical lengths Θ_2 and Θ_3, whereas the two outer sections, having electrical lengths Θ_1, are added in a cascade. Additionally, eight short sections of transmission lines are added in between. Their electrical length is denoted as Θ_L and Θ_0. These short connecting lines are inevitable in practical layout of the coupler on one hand. On the other hand, the lines with length of Θ_L add one degree of freedom to the circuit, what makes the design process more flexible, as it will be proved during the theoretical analysis. The electrical length of remaining lines Θ_0 has no impact on the coupler's coupling characteristics, therefore, in the theoretical analysis given below it is assumed to be equal to zero. One might note, that the middle tandem-connected section has been designed as a connection of three coupled-line sections having two different electrical lengths (Θ_2 and Θ_3). This causes that the outer coupled-line sections of the entire coupler (having electrical length Θ_1) can be realized on different metallization layers without the need of interlayer connections what simplifies the design.

We can start the analysis by pointing out that port #2 of the proposed coupler is the coupled port whereas port #4 is the direct port, with respect to port #1. The coupling coefficient S_{21} and the transmission coefficient S_{41} of the broadband

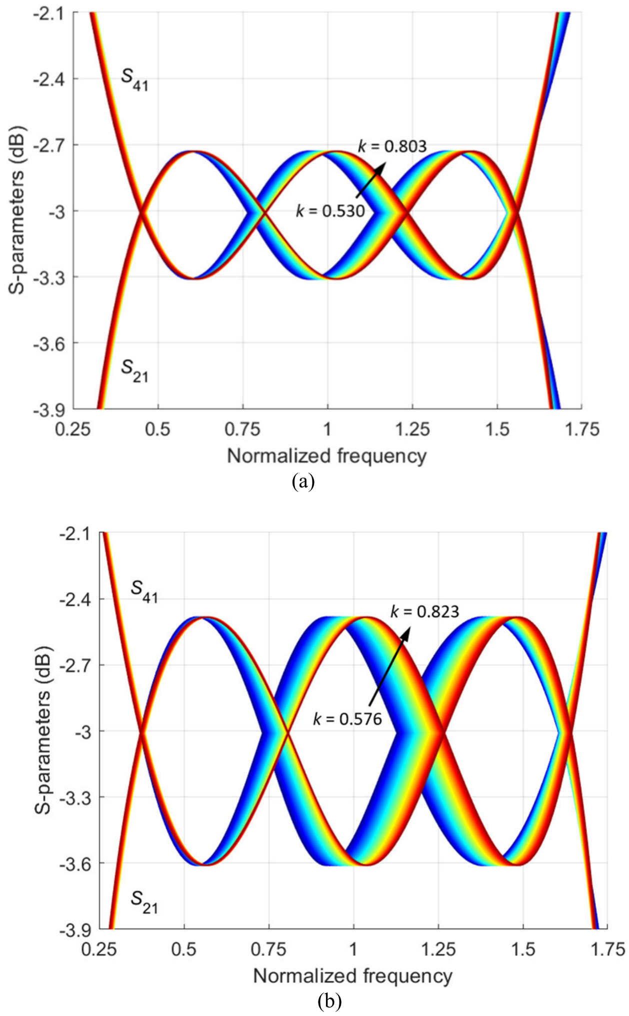


FIGURE 2. Transmission and coupling characteristics of the proposed broadband directional coupler in which nominal coupling C_{nom} = 3 dB (k_{nom} = 0.707) and coupling imbalance δ_C equal (a) ±0.3 dB and (b) ±0.6 dB are assumed, calculated by solving (1) and (2) for different values of the coupling coefficient *k*.

directional coupler shown in Fig. 1 are equal to:

$$S_{21} = C_1 + T_1^2 D^2 \frac{A + C_1 D^2 \left(B^2 - A^2\right)}{\left(1 - AC_1 D^2\right)^2 - B^2 C_1 D^4} \tag{1}$$

$$S_{41} = \frac{BD^2 T_1^2}{\left(1 - AC_1 D^2\right)^2 - B^2 C_1 D^4} \tag{2}$$

where

$$A = C_2 \left(C_3^2 + T_3^2\right) + 2C_3 T_2 T_3 \tag{3}$$

$$B = T_2 \left(C_3^2 + T_3^2\right) + 2C_2 C_3 T_3 \tag{4}$$

$$D = \cos\left(\theta_L\right) - j \sin\left(\theta_L\right) \tag{5}$$

and where C_i and T_i are the coupling and transmission coefficients, respectively, of the i-th coupled-line section ($i = 1, 2$) expressed as [5]:

$$C_i = \frac{jk \sin \Theta_i}{\sqrt{1 - k^2} \cos \Theta_i + j \sin \Theta_i} \tag{6}$$

$$T_i = \frac{\sqrt{1 - k^2}}{\sqrt{1 - k^2} \cos \Theta_i + j \sin \Theta_i} \tag{7}$$

Since, the proposed broadband directional coupler consists of ideal coupled-line sections and sections of transmission lines having the characteristic impedances Z_0, it exhibits ideal impedance match ($S_{11} = S_{22} = S_{33} = S_{44} = 0$) and isolation ($S_{31} = S_{13} = S_{24} = S_{42} = 0$). The total electrical length of the coupler is given by:

$$\Theta_{total} = 2\Theta_1 + \Theta_2 + 2\Theta_3 + 4\Theta_L \tag{8}$$

The parameters of the proposed broadband directional coupler described by the formulas (1) and (2) have been analyzed numerically aiming at achieving equal ripple coupling characteristics, that resemble the ones achieved with the classic three-section directional couplers (in which the coupling characteristic features two maxima and single local minimum having appropriate values). Since the frequency characteristics of the proposed directional coupler are described by five variables (Θ_1, Θ_2, Θ_3, Θ_L and k) and the required frequency characteristic is fixed by 4 parameters (three extrema of nominal coupling – C and the center frequency f_0), there still remains one variable that can be arbitrarily chosen. This in turn makes the design flexible, in particular it is possible to design directional couplers having different coupling ripples with the use of the same nominal coupling k. Therefore, the proposed coupler has been analyzed in such a way that all the required electrical lengths have been found numerically for the assumed nominal coupling value and ripple level, whereas coupling k has remained as a variable. The obtained results are presented in Fig. 2, where transmission and coupling characteristics obtained assuming C_{nom} = 3 dB and two exemplary coupling ripples (δC = ±0.3 dB, and δC = ±0.6 dB) are plotted. As seen the equal-ripple frequency characteristics similar to the ones achievable for classic three-section directional couplers are obtained. Moreover, the required coupling coefficient of the coupled-line sections constituting the coupler can be arbitrarily chosen in a wide range which causes the design process very flexible. It has to be underlined that apart from a very flexible design another important advantage of the coupler is seen in Fig. 2. The nominal coupling equal 3 dB with coupling ripple ±0.3 dB can be achieved with as low coupling coefficient as k = 0.55 (Fig. 2(a)), which is substantially lower requirement than in case of a classic three-section directional coupler for which the required coupling of the strongly-coupled section equals $k = 0.85$.

The proposed coupler has been analyzed theoretically assuming nominal coupling C_{nom} = 3 dB (k_{nom} = 0.707) for large variety of coupling imbalance values and coupling coefficients k of coupled-line sections. The obtained results are shown in Fig. 3, where all the required electrical lengths are plotted against the coupling coefficient k. As seen to achieve the required frequency characteristics one of the coupled-line sections has to be longer than 90°, whereas all the other coupled-line sections and the sections

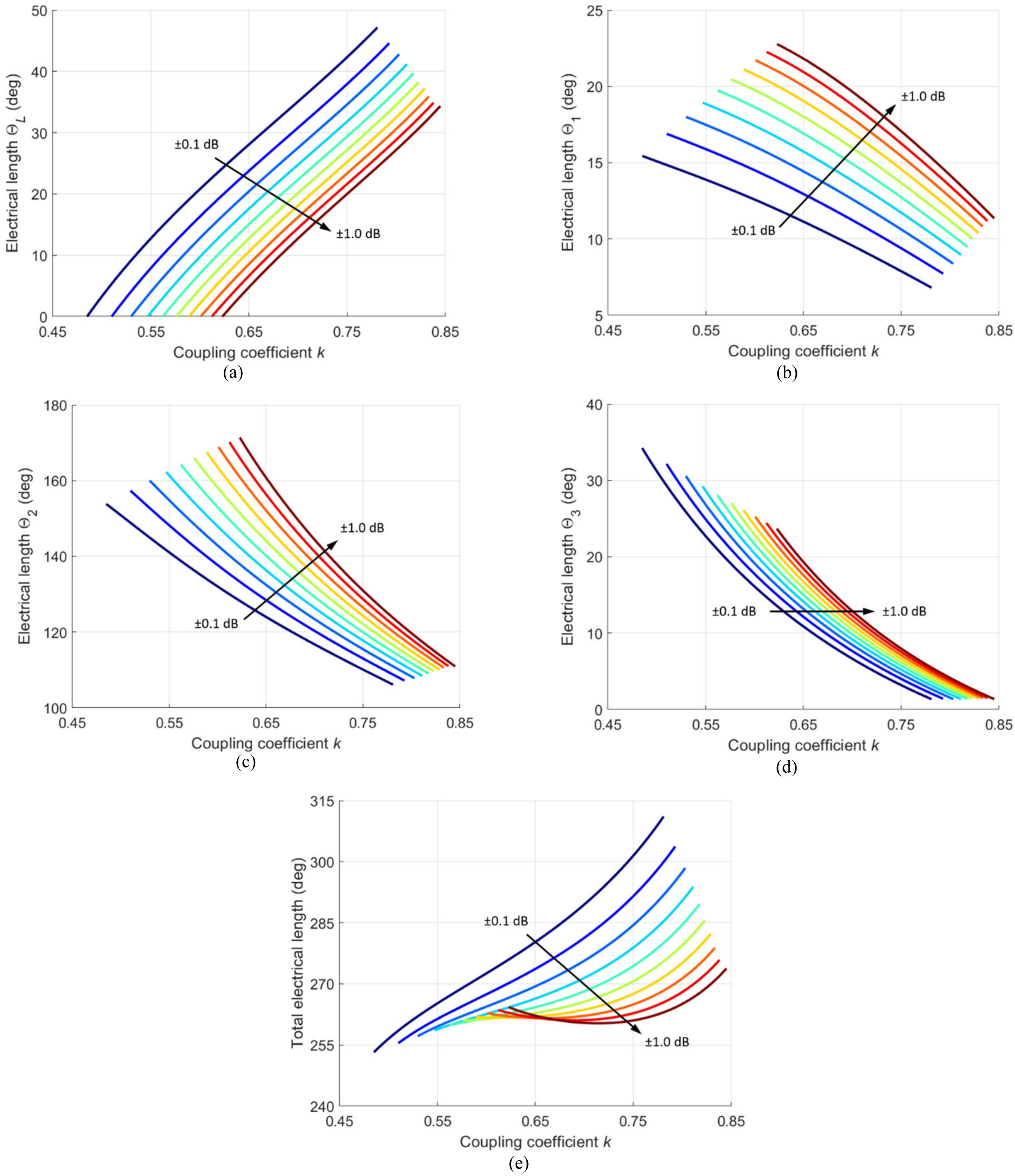


FIGURE 3. **Electrical lengths (a) Θ_L, (b) Θ_1, (c) Θ_2, (d) Θ_3 and (e) the total electrical length of the proposed broadband directional coupler for the assumed nominal coupling $C_{nom} = 3$ dB ($k_{nom} = 0.707$) calculated for ten different coupling imbalance values δ_C from ±0.1 dB to ±1.0 dB.**

of transmission lines are substantially shorter than 90°. It is also seen that the electrical length of transmission-line sections can be set to zero, therefore, as mentioned above they can be removed from the circuit. However, as previously pointed out they might be utilized for connection purposes and also for introducing another degree of freedom into the design. In Fig. 3(e) the total electrical length of the proposed directional coupler calculated based on (8) is shown. As seen the calculated total electrical length Θ_{total} varies, and the larger coupling coefficient of coupled-line sections, the longer overall electrical length of the resulting coupler. Moreover, it can be seen that for short values of Θ_L the total electrical length of the coupler is lesser than 270° which is less than in classic three-section symmetrical couplers. This is another important advantage of the presented circuit.

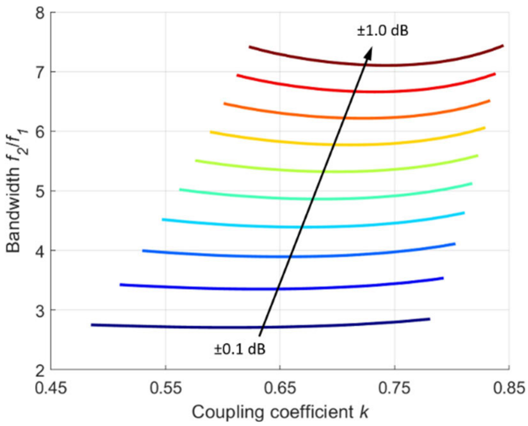


FIGURE 4. Bandwidth f_2/f_1 of the proposed broadband directional coupler for the assumed nominal coupling $C_{nom} = 3$ dB ($k_{nom} = 0.707$) calculated for ten different coupling imbalance values δ_C from ±0.1 dB to ±1.0 dB.

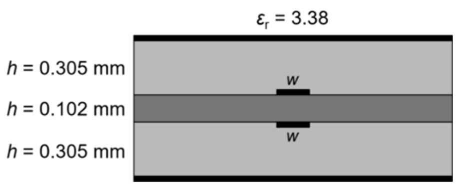


FIGURE 5. Cross-sectional view of the homogenous symmetric dielectric structure with broadside-coupled striplines [38] used for experimental verification of the proposed broadband 3-dB quadrature directional couplers.

It has to be underlined that although the center section of the proposed couplers looks similar to the tandem coupler described in [37], the proposed couplers seem to be similar to the ones described in [37], there are significant differences between these two designs. Firstly, the couplers in [37] feature frequency characteristics close to those of the classic single-section, whereas the ones in the papers exhibit much wider bandwidth, comparable to bandwidth of the classic three-section directional couplers. Secondly, in [37] the coupling coefficient's reduction is obtained by increasing the electrical length (smoothly from 90° corresponding to the classic single-section coupler to 180° corresponding to tandem connection of two single-section coupled-line couplers), whereas in the proposed couplers the electrical length is comparable to the length of the classic three-section coupled-line couplers. Based on the presented analysis we can state that the proposed directional coupler allows for achieving frequency characteristics comparable with the classic three-section symmetrical directional couplers with the use of both lower required coupling coefficient and shorter overall electrical length. Such a feature has not been reported to the best of our knowledge.

Fig. 4 presents the calculated bandwidth of the proposed broadband directional coupler assuming nominal coupling $C_{nom} = 3$ dB ($k_{nom} = 0.707$) obtained for different values of the coupling ripple and coupled-sections' coupling coefficients. As seen broad bandwidth is achieved corresponding to the classic solutions. The achieved bandwidth depends mostly on the assumed coupling ripple, however, slight bandwidth's change is observed for different coupling coefficients k of coupled-line sections.

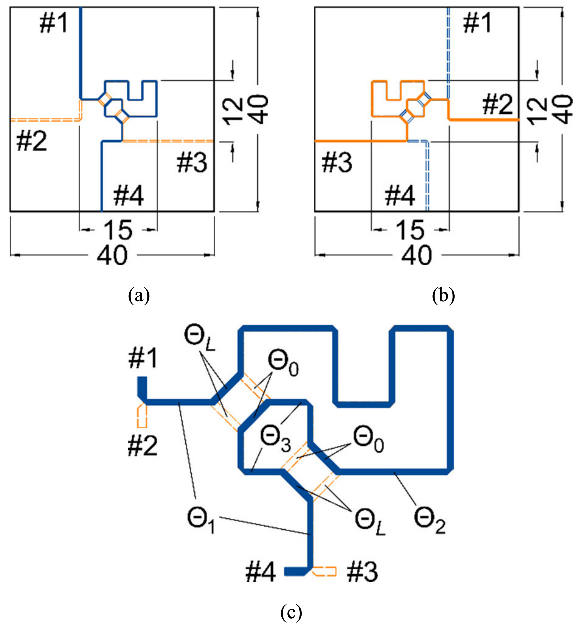


FIGURE 6. Center laminate's view of the developed broadband directional coupler having nominal coupling $C = 3 \pm 0.3$ dB for which $k = 0.6$, $\Theta_1 = 16.02°$, $\Theta_2 = 142.56°$, $\Theta_3 = 18.96°$, $\Theta_L = 13°$: (a) top, (b) bottom, and (c) zoomed top view with indicated particular coupled-line sections and inter-connecting transmission lines. Dashed lines indicate traces on the other side of the laminate. Dimensions given in mm.

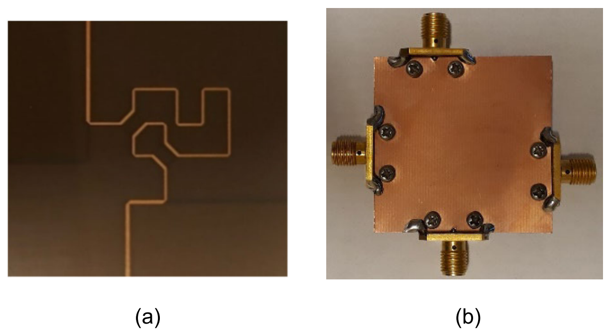


FIGURE 7. Pictures of the developed broadband directional coupler having nominal coupling $C = 3 \pm 0.3$ dB for which $k = 0.6$, $\Theta_1 = 16.02°$, $\Theta_2 = 142.56°$, $\Theta_3 = 18.96°$, $\Theta_L = 13°$. (a) Center laminate layer and (b) picture of the assembled model.

III. EXPERIMENTAL RESULTS

The proposed concept of broadband 3-dB quadrature directional couplers has been verified experimentally by the design of two 3-dB directional couplers having coupling imbalance ±0.3 dB and ±0.6 dB, respectively. Both couplers have been designed in homogenous stripline structure shown in Fig. 5, where all the dielectric layers have the same permittivity equal to 3.38 and dissipation factor of 0.0025. The thickness of the middle layer equals 0.102 mm and is inserted between two layers having thickness equal 0.305 mm. In both designs broadside-coupled striplines [37] have been utilized with zero offset (as shown in Fig. 5) for which coupling

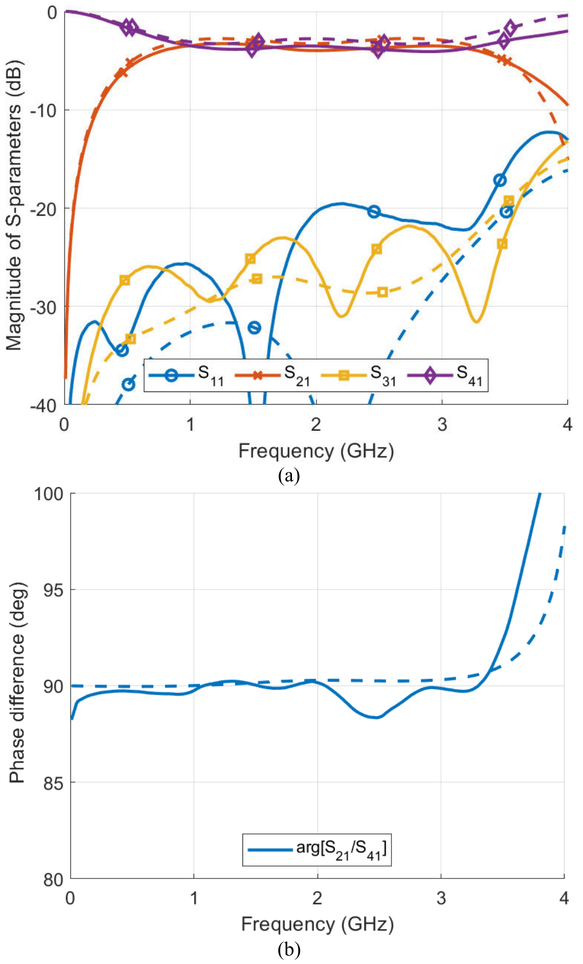


FIGURE 8. Measured frequency characteristics (solid lines) of the developed broadband directional coupler having nominal coupling $C = 3 \pm 0.3$ dB for which $k = 0.6$, $\Theta_1 = 16.02°$, $\Theta_2 = 142.56°$, $\Theta_3 = 18.96°$, $\Theta_L = 13°$, in comparison to the electromagnetically calculated ones (dashed lines). (a) Amplitude characteristics and (b) differential phase characteristics.

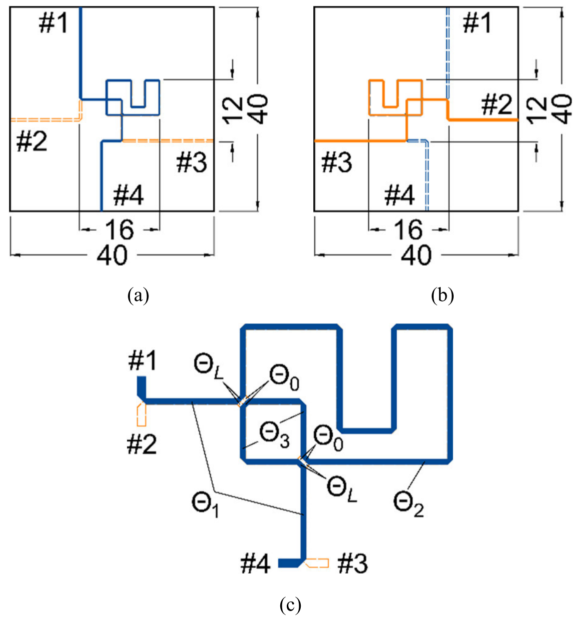
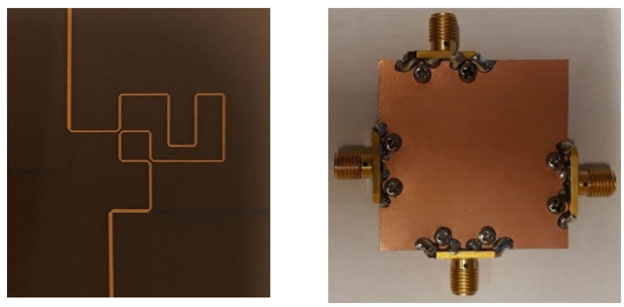


FIGURE 9. Center laminate's view of the developed broadband directional coupler having nominal coupling $C = 3 \pm 0.6$ dB for which $k = 0.6$, $\Theta_1 = 19.75°$, $\Theta_2 = 158.15°$, $\Theta_3 = 22.88°$, $\Theta_L = 4.49°$: (a) top, (b) bottom, and (c) zoomed top view with indicated particular coupled-line sections and inter-connecting transmission lines. Dashed lines indicate traces on the other side of the laminate. Dimensions given in mm.



(a) (b)

FIGURE 10. Pictures of the developed broadband directional coupler having nominal coupling $C = 3 \pm 0.6$ dB for which $k = 0.6$, $\Theta_1 = 19.75°$, $\Theta_2 = 158.15°$, $\Theta_3 = 22.88°$, $\Theta_L = 4.49°$. (a) Center laminate layer and (b) picture of the assembled model.

coefficient equals $k = 0.6$ for strips width being equal $w = 0.27$ mm. In this structure the width of 50-Ohm lines is equal to 0.41 mm. Based on the theoretical analysis presented in Section II the following electrical parameters have been found for the 3-dB coupler having ± 0.3 dB coupling imbalance: $\Theta_1 = 16.02°$, $\Theta_2 = 142.56°$, $\Theta_3 = 18.96°$, $\Theta_L = 13°$, $\Theta_{total} = 264.52°$, and bandwidth $f_2/f_1 = 3.91$. As mentioned in Section II, the electrical length Θ_0 has no impact on the coupler's performance, hence for simplicity it has been chosen to be equal to Θ_L. The coupler has been designed for the center frequency $f_0 = 2$ GHz and manufactured by stacking three laminates. Layout of the designed coupler presented in Fig. 6 has been etched in metallization layers of the middle laminate, whereas the inner side of the outer laminates has been etched completely. Finally, these three laminates have been stacked firmly by mounting screws and soldering SMA connectors. The total occupied area calculated without signal lines equals 15×12 mm, hence a very compact design has been achieved taking into account the operational frequency. Fig. 7 presents pictures of the center laminate layer and assembled model of the manufactured coupler, whereas in Fig. 8 the comparison between the calculated electromagnetically and measured frequency characteristics is shown. As seen a good agreement between the calculated and measured results has been obtained. The coupler features good return losses and isolation and the assumed coupling imbalance. Moreover, the coupler exhibits quadrature differential phase with phase imbalance not greater than $\pm 1°$.

Similarly, the second coupler, with coupling imbalance of ± 0.6 dB has been designed, manufactured and measured. In this case the following electrical parameters have been found: $\Theta_1 = 19.75°$, $\Theta_2 = 158.15°$, $\Theta_3 = 22.88°$, $\Theta_L = 4.49°$ and $\Theta_{total} = 261.38°$, and bandwidth $f_2/f_1 = 5.44$. Fig. 9 shows layout of the designed 3-dB coupler, and it is seen that the occupied area equals 16×12 mm in this case. Fig. 10 presents pictures of the inner laminate layer and the assembled model of the manufactured circuit. The comparison between measured and electromagnetically calculated

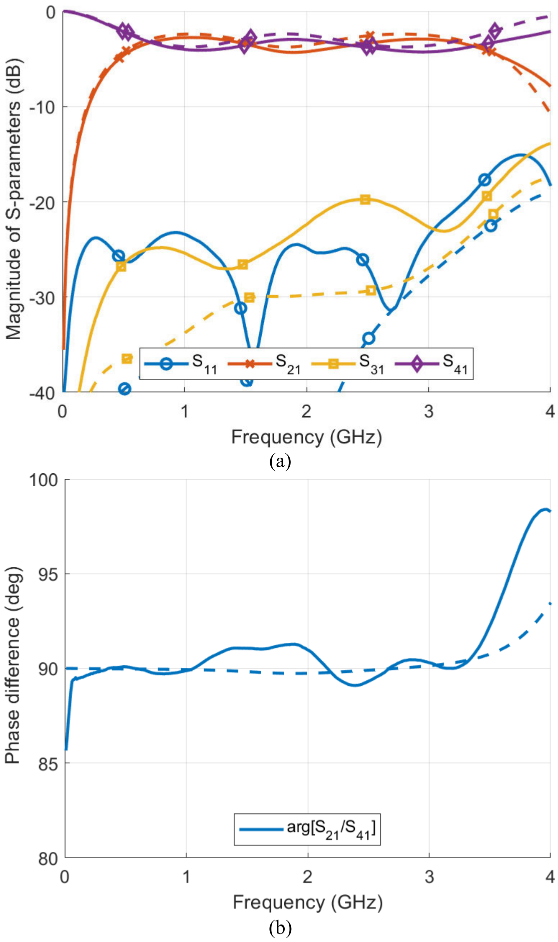


FIGURE 11. Measured frequency characteristics (solid lines) of the developed broadband directional coupler having nominal coupling $C = 3 \pm 0.6$ dB for which $k = 0.6$, $\Theta_1 = 19.75°$, $\Theta_2 = 158.15°$, $\Theta_3 = 22.88°$, $\Theta_L = 4.49°$, in comparison to the electromagnetically calculated ones (dashed lines). (a) Amplitude characteristics and (b) differential phase characteristics.

frequency characteristics is shown in Fig. 11. Also in this case good amplitude characteristics have been achieved and the manufactured coupler features quadrature differential phase. It has to be underlined that in both developed couplers the total electrical length is less than 270°, whereas the required coupling coefficient needed for the design is as low as $k = 0.6$. The obtained broadband frequency responses of equal-split couplers with such low coupling values k and compact size have not been previously reported and make the proposed solution unique and valuable for future engineering applications.

As seen in Fig. 8 and Fig. 11, both fabricated couplers exhibit return loss and isolation being close to 20 dB over the entire frequency range of operation. Such an excellent performance has been achieved thanks to relatively simple topology of the proposed couplers, which are composed of matched elements only. Additionally, selection of zero offset between the coupled lines eliminated the need for crossovers, which are a source of discontinuities impairing the coupler's performance. Deterioration of return loss and isolation at higher frequencies is due to other discontinuities (bends and transition regions between coupled section and transmission lines) present in the couplers' layouts. Nevertheless, significance of this deterioration is marginal, as it occurs beyond the operational bandwidth.

TABLE 1. Impact of the manufacturing intolerances of the performance of the designed coupler with coupling imbalance of ±0.3 dB. Results of electromagnetic calculations.

Coupler state	Coupling and transmission coefficients' imbalance (dB)	Return loss (dB)	Isolation (dB)
nominal	±0.30	24	23
20-μm misalignment in H plane	±0.27	24	23
20-μm misalignment in V plane	±0.31	24	23
20-μm misalignment in H and V planes	±0.27	24	23
20-μm narrower paths	±0.47	24	22
20-μm wider paths	±0.46	24	24

TABLE 2. Impact of the manufacturing intolerances of the performance of the designed coupler with coupling imbalance of ±0.6 dB. Results of electromagnetic calculations.

Coupler state	Coupling and transmission coefficients' imbalance (dB)	Return loss (dB)	Isolation (dB)
nominal	±0.60	23	22
20-μm misalignment in H plane	±0.63	23	22
20-μm misalignment in V plane	±0.64	23	22
20-μm misalignment in H and V planes	±0.58	23	22
20-μm narrower paths	±0.98	22	21
20-μm wider paths	±0.89	24	22

To complete the experimental verification the designed couplers have been tested against manufacturing tolerances. For this purpose, both developed directional couplers have been simulated electromagnetically with artificially introduced deterioration of the final layout. Testing scenarios were as follows: 20-μm misalignment between metallization layers in single plane and in both planes, and decreased and increased paths' widths by 20-μm. Scattering parameters obtained as the worst case across the bandwidth are shown in Table 1 and in Table 2 for the coupler with coupling imbalance equal to ±0.3 dB and ±0.6 dB, respectively. As can be observed the developed couplers exhibit low sensitivity to such manufacturing intolerances, since both return loss and isolation are almost unaffected, whereas the coupling/transmission imbalance varies insignificantly.

IV. COMPARISON OF THE DESIGN WITH OTHER SOLUTION

The achieved parameters of the proposed broadband 3-dB quadrature directional couplers have been compared to the other competitive known solutions. Since the developed couplers feature the properties of three-section symmetrical directional couplers, the achieved properties have been

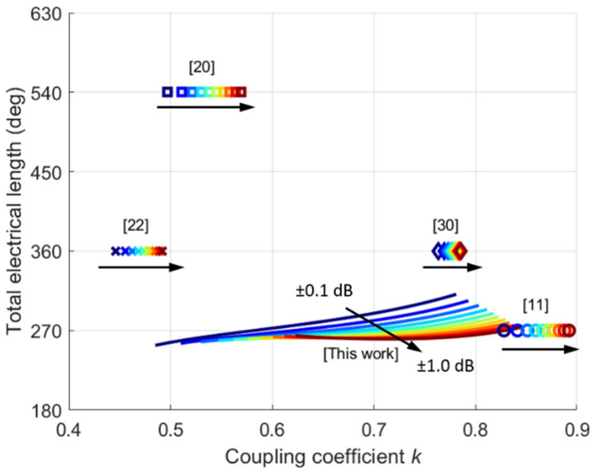


FIGURE 12. The total electrical lengths and coupling coefficients required for the design of broadband 3-dB coupled-line directional couplers for the following circuits: classic symmetrical directional couplers [16], classic symmetrical tandem couplers [25], couplers with tandem-connected center section [27], tandem couplers composed of coupled-line sections having unequal lengths [35] in comparison with the proposed design. Calculated results for different coupling imbalance δ_C from ±0.1 dB to ±1.0 dB.

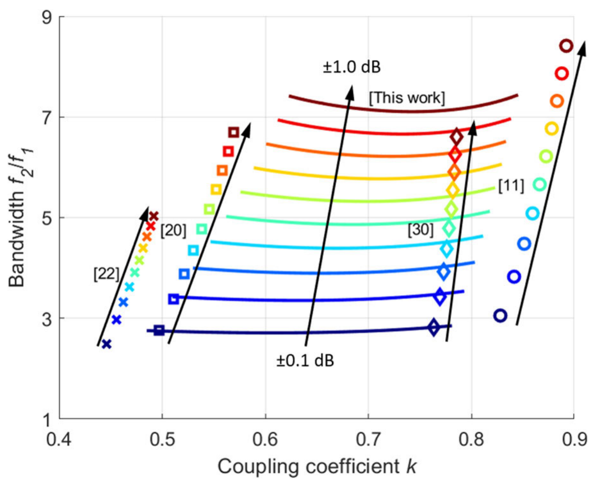


FIGURE 13. Bandwidth f_2/f_1 of broadband 3-dB coupled-line directional couplers achievable for the following circuits: classic symmetrical directional couplers [16], classic symmetrical tandem couplers [25], couplers with tandem-connected center section [27], tandem couplers composed of coupled-line sections having unequal lengths [35] in comparison with the one obtainable in the proposed design. Calculated results for different coupling imbalance δ_C from ±0.1 dB to ±1.0 dB and the required coupling coefficients.

comparted to other published solutions that allow for the design of directional couplers having equal-ripple coupling characteristics over a broad bandwidth i.e.; classic symmetrical directional couplers [16], classic symmetrical tandem couplers [25], couplers with tandem-connected center section [27], and tandem couplers composed of coupled-line sections having unequal lengths [35]. Fig. 12 presents the calculated total electrical lengths and coupling coefficients for all these designs. As seen the proposed solution requires significantly lower coupling coefficients than the classic three-section symmetrical directional couplers [16] together with the comparable electrical lengths. It has to be underlined that the optimum properties of the proposed couplers are achieved when the electrical length of the connecting

TABLE 3. Percentage bandwidth and coupling coefficient of the proposed directional couplers compared against percentage bandwidth and coupling coefficient of other reported solutions.

Couplers' topology	Percentage bandwidth (%)	Coupling coefficient
Classic symmetrical directional couplers [16]	101 – 157	0.828 – 0.892
Classic symmetrical tandem couplers [25]	94 - 148	0.497 – 0.569
Couplers with tandem-connected center section [27]	86 - 134	0.446 – 0.492
Tandem couplers composed of coupled-line sections having unequal lengths [35]	95 - 147	0.763 – 0.785
This work	92 - 153	0.485 – 0.845

transmission lines Θ_L is selected as short as possible. The electrical length of these transmission lines should be selected in such a way to ensure the appropriate connections between the sections, as it was shown in the two experimentally realized couplers. In these cases the proposed couplers are even shorter than the classic ones whereas the required coupling coefficient is significantly reduced. In comparing to other solutions focused on the decreasing of the required coupling coefficient [25], [27], [35], the proposed coupler is significantly shorter, whereas it offers comparably low coupling coefficient when connecting transmission lines are selected as short as possible. It is worth underlining that such low required coupling coefficient allows for a realization of the proposed couplers using single metallization layer with edge-coupled lines. However, in such a solution line-crossovers are required, and a special care must be taken of modal phase velocities equalization, as their difference impairs return loss and isolation. Such an approach makes the proposed couplers particularly suitable for microwave integrated circuits, where reduced number of used metallization layer is crucial, and on the other side air-bridges realizing crossovers are well-developed.

Fig. 13 presents the achievable bandwidth defined as a ratio of the upper and lower frequency f_2/f_1 for the proposed 3-dB couplers in comparison to other known solutions. Furthermore, the maximum and the minimum obtainable percentage bandwidth and the corresponding required coupling coefficients for the same couplers are listed in Table 3. As it is seen the proposed couplers feature slightly wider bandwidth than other solutions focused on coupling coefficient minimization [25], [27], [35], and narrower than the classic three-section couplers [16] which in turn requires significantly stronger coupling coefficient. It has to be underlined that the differences in bandwidths for all these designs are insignificant for low coupling imbalance and become apparent for large values of coupling imbalance. Therefore, taking into account of the above-mentioned properties, it is seen that the proposed solution is superior over all other published designs.

Based on the above presented comparison, we can state that the best properties of the proposed broadband 3-dB directional couplers are achieved when sections of transmission lines are kept as short as possible. On the other hand, as shown in Section II, these lines can be utilized as another degree of freedom, which allows for very flexible design i.e., for the design of 3-dB couplers having different coupling imbalance with the use of the same coupling coefficient k. In this case it has to be underlined that a small change of their electrical lengths offers large variety of the achievable coupling imbalance. For instance, when the coupling coefficient $k = 0.65$, by varying Θ_L between 5° and 28° coupling imbalance's change from ± 0.1 dB up to ± 1 dB can be obtained (see Fig. 3(a) in Section II). Such a change results in the overall electrical lengths' variation of the coupler between 262° and 280° (see Fig. 3(e)), therefore, it is still comparable to the lengths of the classic couplers. This is another important advantage of the proposed design methodology, which has been proved experimentally in Section III.

V. CONCLUSION

In this paper a novel concept of broadband 3-dB quadrature directional couplers is presented. It is shown that frequency characteristics similar to the ones of classic three section symmetrical directional couplers can be achieved when coupled-line sections with fixed coupling coefficient are appropriately tandem- and cascade-connected. Moreover, it is shown that short sections of transmission lines added to the circuit introduce a degree of freedom which makes the design process very flexible. The numerical analysis of such networks has been performed and all the required electrical lengths of coupled-line and transmission-line sections have been found for different assumed available coupling coefficients and coupling imbalances. The proposed concept has been confirmed experimentally by two 3-dB directional couplers featuring different coupling imbalance and developed assuming the same fixed coupling value. The obtained measurement results prove the correctness of the presented analysis. Moreover, the proposed networks have been compared with other known designs that allow for achieving comparable frequency characteristics i.e., broadband equal-ripple coupling characteristics and quadrature phase response. It has been proved that the proposed couplers feature superior performance in comparison to the other described concepts, since they offer low required coupling coefficients without the need of their electrical lengths' increase, and also allow for very flexible design process and for achieving attractive bandwidth similar to their classic counterparts. Such features cause that the proposed couplers can be successfully applied in modern microwave electronics including microwave monolithic integrated circuits.

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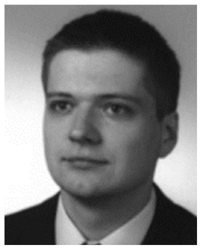

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