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Multisection Ultra-Broadband Directional Coupler Designed in MMIC Technology

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ABSTRACT An ultra-broadband multisection directional coupler designed in Monolithic Microwave Integrated Circuit (MMIC) technology has been presented. It has been shown for the first time that it is possible to achieve bandwidths exceeding one frequency decade, simultaneously taking under account technological constrains. The proposed directional coupler is composed of three coupled-line sections having different values of electrical lengths and coupling coefficients. The strongest coupled section has been designed as an asymmetric three-strip coupled-line section, whereas the rest of the sections have been implemented as symmetric two-strip coupled-line structures. To improve electrical performance of the coupler, a compensation method has been implemented together with loss analysis which has to be considered in lossy inhomogeneous medium. The proposed 3-dB directional coupler has been designed in PH25 process based on gallium arsenide (GaAs) from United Monolithic Semiconductors (UMS), and fabricated. The measurement confirms applicability of the design method in monolithic technology for such networks operating in bandwidth exceeding one frequency decade.

INDEX TERMS Multisection directional couplers, ultra-broadband couplers, microwave monolithic integrated circuit (MMIC), unequal coupled-lines, compensation method, electrical performance improvement.

I. INTRODUCTION

Directional couplers are commonly utilized components in modern microwave engineering, where are well-implemented in measurement and radiolocation systems [1]–[4], as well as in wireless devices [5], [6]. In general, couplers can be divided into different topologies such as branch-line [7], [8], rat-race [9], [10] and couplers based on coupled-line sections [11], [12]. The first two types are well-applicable solutions in monolithic technologies [13]–[18]. However, classic approaches feature narrow frequency response, thus they are not suitable for broadband applications. Therefore, in literature, improvements related to bandwidth enhancement have been proposed. Basically, to achieve wider bandwidth, hybrid couplers are designed as multisection structures [19], or additional elements such as impedance transformers have to be applied [20], [21]. Monolithic directional couplers consisting of quarter-wave coupled-line sections are devoid of such a disadvantage and features one octave frequency response [22]–[24]. To achieve wider bandwidth, such a coupler can be realized as a multisection structure composed of coupled sections with different coupling coefficients [25]–[28]. However, parameters such as isolation and return losses of such broadband couplers deteriorate with frequency due to inevitable parasitic reactances [29]. Thus, compensation methods utilized in PCB technology has been proposed to improve electrical performance at higher frequencies [29]–[31].

In [32] the Authors proposed a directional coupler consisting of two coupled-line sections connected by an uncoupled section. Moreover, the utilized sections have different electrical lengths what decreases the overall electrical length of the this concept as shown in [33], where implementation in monolithic technology has been presented. On the other hand, in [34], a novel class of broadband directional couplers has been introduced. A new multisection coupled-line topology features significant increase of operational bandwidth by utilizing coupled sections having different electrical lengths and couplings.

In some monolithic coupled-line structures, it is not possible to perform the required strong coupling due to achievable minimum gap between lines. Such situation is commonly

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met in monolithic techniques, where minimum gap between lines is imposed by the technological contains. Therefore, N-coupled-line sections such as Lange topology [34] or three-strip structures [36], [37] have been considered in the literature. Other solutions are based on a tandem configuration [38], [39], in which two coupled-line sections have relatively small coupling coefficient. However, due to the proper connection of these sections, the overall coupling can be much higher. Other methods are related to structures in which buried metallization layer is utilized [40] known as re-entrant structures. Although all the mentioned solutions are mostly realized as distributed elements, the designs implemented with the use of lumped elements are also known [41], [42]. In cases, where lumped elements are considered, the designed directional couplers commonly feature additional losses.

In this paper, a multisection ultra-broadband directional coupler operating from 3.9 GHz up to 40.1 GHz, designed in monolithic technology has been investigated. For the first time, realization of the coupler having bandwidth exceeding one frequency decade in monolithic technology has been shown. The proposed design has been based on [34], and is composed of four coupled-line sections having different electrical lengths, and coupling coefficients. To realize weak coupled sections, symmetric two-strip structures has been utilized, whereas, to achieve strong coupling, a three-strip coupled-line section has been applied. To improve accurateness of the proposed design procedure, loss analysis has been conducted. Moreover, the compensation method proposed in [43] has been utilized to achieve good electrical performance of the coupler, especially at higher operational frequencies. To verify correctness of the proposed design process, the ultra-broadband coupler has been realized in UMS PH25 technology which is based on gallium arsenide. The coupler has been simulated electromagnetically in AXIEM and Analyst solvers which are components of the Cadence AWR Microwave Office and subsequently fabricated. The obtained measurements of the fabricated chip confirms correctness of the proposed design procedure.

II. CONCEPT OF ULTRA-BROADBAND DIRECTIONAL COUPLER

A conceptual view of the proposed directional coupler has been presented in Fig. 1. The considered topology is based on [34] in which the Authors introduced a novel class of multisection directional couplers featuring broad operational bandwidths. For investigation purposes, in this paper a C^{II} topology has been chosen, which is composed of four coupled-line sections with different values of couplings k_1, k_2 and k_3 and electrical lengths Θ_1, Θ_2, Θ_3. Three of them are quarter-wave structures, whereas the forth one has 270° electrical length.

The main goal of this paper is to verify the applicability of directional couplers having bandwidth exceeding one frequency decade in monolithic technology. According to calculations presented in [34], for bandwidth $f_u/f_l = 10.4$ and coupling imbalance equal 1 dB, the coupling coefficients

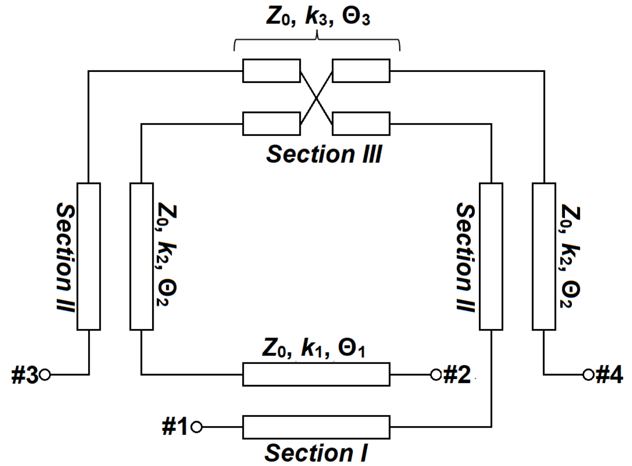


FIGURE 1. Concept of an ultra-broadband directional coupler consisting of four coupled-line sections having different electrical lengths.

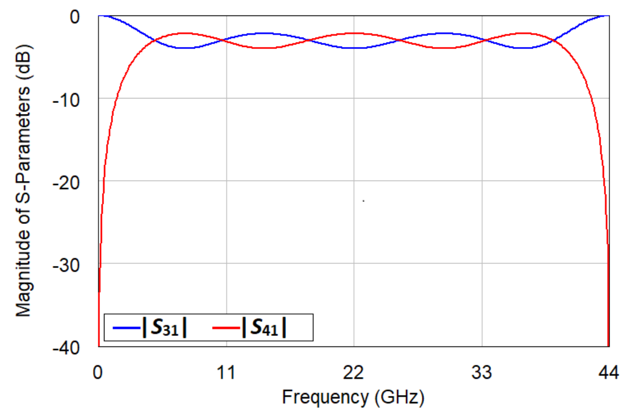


FIGURE 2. Calculated frequency response of an ultra-broadband directional coupler composed of coupled-line sections having unequal electrical lengths.

have to have following values: $k_1 = 0.794$, $k_2 = 0.187$, $k_3 = 0.386$. The calculated response obtained for an ultra-broadband directional coupler consisting of ideal coupled-line sections has been presented in Fig. 2. The operational bandwidth of the considered coupler is in the range from 3.9 GHz to 40.1 GHz.

III. ANALYSIS OF A SINGLE COUPLED-LINE SECTION IN UMS PH25 PROCESS

The PH25 process delivered by United Monolithic Semiconductors (UMS) has been considered during analysis and design. The PH25 allows to design low-loss applications operating up to 60 GHz. A general stratification with essential geometric parameters has been shown in Fig. 3. The technology is based on gallium arsenide (GaAs) which has thickness of 100 μm and dielectric permittivity equal to $\varepsilon_r = 12.8$. Next two layers which can be specified are passivation and nitride layer which have 0.23 μm and 0.21 μm thick respectively. Furthermore, both layers have the same electric permittivity, i.e. $\varepsilon_r = 7.2$.

The PH25 process has three metallization layers. $M1$ and $M2$ layers can be utilized to form complex passive structures such as crosses, air-bridges, multi-strip coupled-lines

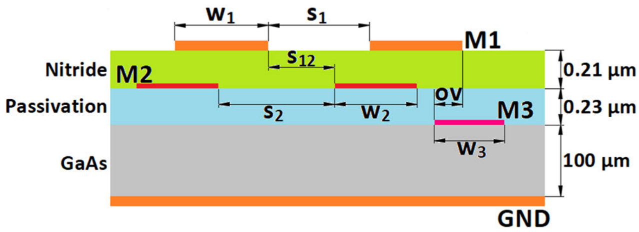


FIGURE 3. Cross-section view of the UMS PH25 process stack-up.

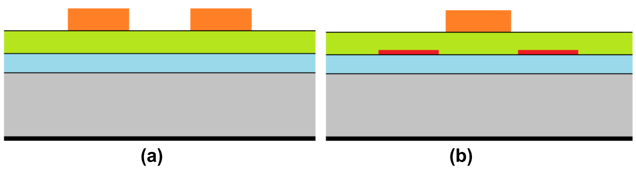


FIGURE 4. Cross-sectional view of symmetric coupled-line section utilizing microstrip lines placed on M1 layers (a), and the asymmetric structure realized as a connection of strips on metallization layer M2 which are coupled with the second coupled-line placed on M1 layer (b).

sections, etc. Due to relatively large sheet resistance (0.8 Ω/□), the $M3$ metallization is commonly utilized to form small areas, which can be adopted as one of the capacitor plates between higher layers.

Losses existing in coupled-lines are a crucial aspect, especially in broadband applications due to the fact, that they increase with frequency. Since, coupling coefficients for the designed multisection coupler are calculated for lossless cases, it is crucial to include these losses during the design process to achieve proper broadband response of the coupler.

To analyze impact of losses on the design process, two coupled-line structures designed in UMS PH25 technology have been taken under consideration. First one is a simple, symmetric two-strip coupled-line section realized at $M1$ layer. The second one is an asymmetric structure which has been designed by utilizing three-strip coupled-lines placed on $M1$ and $M2$ metallization layers. To realize the coupled-line section, strips placed at $M2$ layer have been connected to form one of the coupled-lines. The cross-section views of both coupled-line sections have been shown in Fig. 4.

To verify the impact of total losses on coupling coefficients, both symmetric and asymmetric coupled-line sections have been designed to operate at 22 GHz center frequency. Fig. 5 shows electromagnetically calculated values of total losses for different coupling coefficients. It can be noticed, that the maximum losses are obtained for the highest frequencies what proves the previous conclusions. Moreover, the stronger coupling between lines is assumed, the higher losses are achieved. As it has been mentioned, the three-strip coupled-line section consists of strips placed at two metallization layers. In the considered cases, structure complexity also influences on the losses, and therefore, higher values are obtained for the asymmetric coupled-line structure.

The calculated total losses have been used to compute coupling coefficients for lossless symmetric and asymmetric

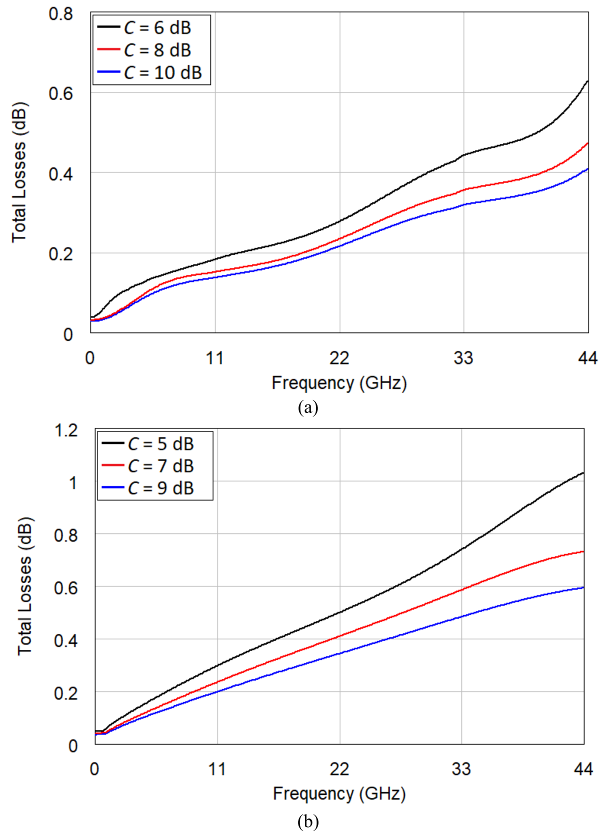


FIGURE 5. Total losses for the considered symmetric (a) and asymmetric (b) coupled-line sections.

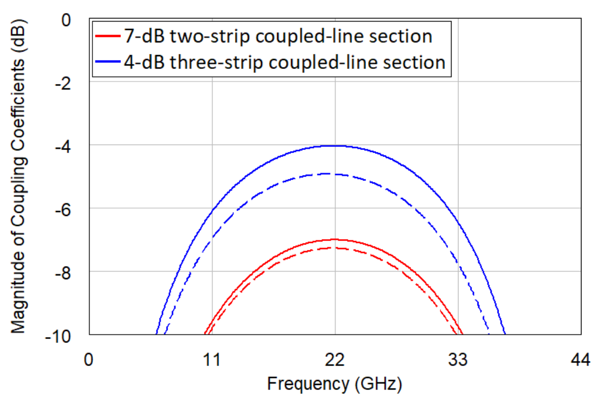


FIGURE 6. Impact of the calculated total losses on 7-dB two-strip coupled-line symmetric (red line) and 4-dB three-strip coupled-line asymmetric (blue lines) sections. Solid lines have been obtained for lossless structures, whereas dashed ones represent coupling coefficients for lossy cases.

sections what has been presented in Fig. 6. Solid lines represent lossless cases, whereas dashed ones are obtained for lossy responses of the coupled sections. It is seen, that differences between both cases can be significant and should be taken into account during the design process.

To achieve broad operational bandwidth, electrical performance of the multisection directional coupler has to be improved by the proper compensation method utilized for each of coupled-line section of the resulting coupler.

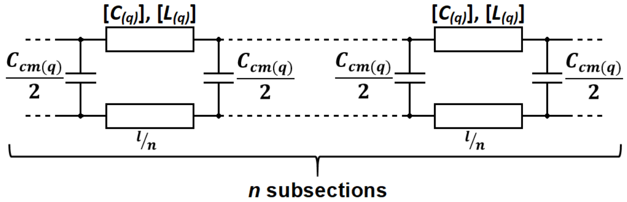


FIGURE 7. Concept of the compensation method utilized in coupled-line sections.

According to the known theory, the equalization of inductive k_L and capacitive k_C couplings coefficients has to be fulfilled for the asymmetric coupled-line sections, whereas in the symmetric one, such relationship has to be met for odd ε_o and even ε_e modal dielectric constants. In [43] the Authors conducted comprehensive studies of the compensation method used in the PH25 process for coupled-line sections in which $k_L > k_C$.

Due to the fact, that k_L is dominant, it is treated as the required coupling coefficient k calculated for a particular coupled-line section of the multisection coupler. To satisfy such an assumption k_C has to be increased by adding additional lumped capacitances. Fig. 7 shows a general concept of the circuit which can be implemented in each of the considered coupled-line section having coupling $k_{(q)}$, where q is a number of coupled-line sections. A single coupled-line section is divided into n-subsections at the ends of which additional compensating capacitances $C_{cm(q)}$ which increase the capacitive coupling coefficient have been added. A particular subsection is defined by capacitive $[C_{(q)}]$ and inductive $[L_{(q)}]$ matrices.

As a result of compensating procedure, the following relation between inductive, capacitive and the required coupling of the considered lossless section is fulfilled:

$$k_{(q)} = k_{L(q)} = k_{C(q)} \tag{1}$$

It has to be underlined that $k_{(q)}$ is obtained for lossless structure, and that terminating impedances of a coupled-line section are also equalized, i.e. $Z_{T1(q)} = Z_{T2(q)} = 50\ \Omega$. For such conditions, the required coupling coefficient can be found as a result of additional compensation capacitance $C_{d(q)}$:

$$k^2_{(q)} = \frac{\left(C_{12(q)} + C_{d(q)}\right)^2}{\left(C_{11(q)} + C_{d(q)}\right)\left(C_{22(q)} + C_{d(q)}\right)}. \tag{2}$$

Substituting (1) into (2), the compensation capacitance can be found by solving quadratic function in the following form:

$$\begin{aligned} &C^2_{d(q)}\left(1 - k^2_{L(q)}\right) \\ &\quad + C_{d(q)}\left[2C_{12(q)} - k^2_{L(q)}\left(C_{11(q)} + C_{22(q)}\right)\right] \\ &\quad - C^2_{12(q)} - k^2_{L(q)}C_{11(q)}C_{22(q)} = 0. \end{aligned} \tag{3}$$

Adding this capacitance to the coupled-line section changes impedances of coupled-lines due to fact, that

$$Z_{T1(q)} = \sqrt{\frac{L_{11(q)}}{C_{11(q)}}} \tag{4}$$

and

$$Z_{T2(q)} = \sqrt{\frac{L_{22(q)}}{C_{22(q)}}} \tag{5}$$

Thus, to preserve impedance values, the equations (4) and (5) have to include C_d. Hence, the modified formulas are as follows:

$$Z_{T1(q)} = \sqrt{\frac{L_{11(q)}}{C_{11(q)} + C_{d(q)}}} \tag{6}$$

$$Z_{T2(q)} = \sqrt{\frac{L_{22(q)}}{C_{22(q)} + C_{d(q)}}} \tag{7}$$

According to the derived equations, when coupled-line impedances and compensating capacitances have fixed values, the coefficients of inductive and capacitive matrices have to be changed. Therefore, geometry of the coupled-line section have to be re-designed. Moreover, it has been shown in [44], that a number of additional capacitances connected to the coupled-line section has direct influence on the level of return losses and isolation. To calculate value of such an additional capacitor the equation

$$C_{cm(q)} = \frac{C_{d(q)}}{n_{(q)}} l_{(q)} \tag{8}$$

has to be used, where l is the physical length of the coupled-line section.

The proposed compensation method has influence on the achievable total losses of the coupled-line sections what has been illustrated in Fig. 8. It is noticed that by utilizing such the compensation method, losses of the coupled-line section are decreased. However, it has to be underlined, that the presented results have been obtained for lossy structure in which ideal compensating capacitances have been utilized. Therefore, the way of realization of compensating elements has to be also taken into account.

IV. DESIGN OF 3-dB ULTRA-BROADBAND MULTISECTION DIRECTIONAL COUPLER

The design of an ultra-broadband multisection directional coupler has been carried out according to the conducted analysis. Firstly, geometries of coupled-line sections having k_1, k_2 and k_3 have been found by using the Linpar software [45]. Initial geometry of two-strip and three-strip coupled-line sections have been computed to obtain inductive [L] and capacitive [C] matrices. It can be noticed, that the three-strip coupled-line structure is defined by matrices having 3 × 3 dimensions. However, one pair of conductors utilized in the structure is electrically connected. Therefore, [L] and [C] of such a section can be reduced to 2 × 2. The obtained results

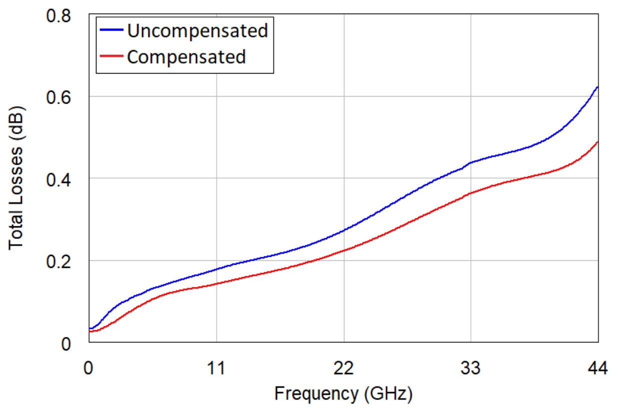


FIGURE 8. Calculated total losses obtained for uncompensated (blue line) and compensated (red one) symmetric coupled-line sections having coupling C = 6 dB.

TABLE 1. Calculated electrical parameters of coupled-line sections utilized in the ultra-broadband multisection directional coupler.

Parameter	Section I	Section II	Section III
Θ [°]	90.0	90.0	180.0
k_L	0.796	0.187	0.386
ε_e	7.539	8.92	8.58
ε_o	4.728	6.92	6.39
C_{11}[pF/m]	191.56	193.70	187.40
C_{22} [pF/m]	185.40	193.70	187.40
C_m [pF/m]	122.58	24.32	56.66
Z_{T1} [Ω]	48.89	49.36	50.52
Z_{T2} [Ω]	48.56	49.36	50.52
n	5	5	6
C_d [pF/m]	110.46	24.27	30.17
C_{cm} [fF]	25.1	4.6	13.6

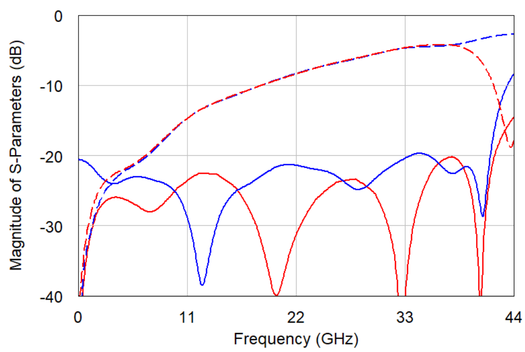


FIGURE 9. Magnitude of reflection coefficient (red lines) and isolation (blue ones) obtained during calculations of the uncompensated (dashed lines) and compensated (solid lines) ultra-broadband multisection directional couplers.

have been used to calculate the electrical parameters such as inductive and capacitive coupling coefficients respectively marked as $k_{L(q)}$ and $k_{C(q)}$. For uncompensated sections the required couplings are these related to inductive coefficients. In the second step, the considered capacitive compensation method has been utilized. Due to the fact, that the proposed methodology change electrical parameters of the coupled-lines, geometries have been iteratively recalculated. Electrical parameters of the compensated coupled-line sections have

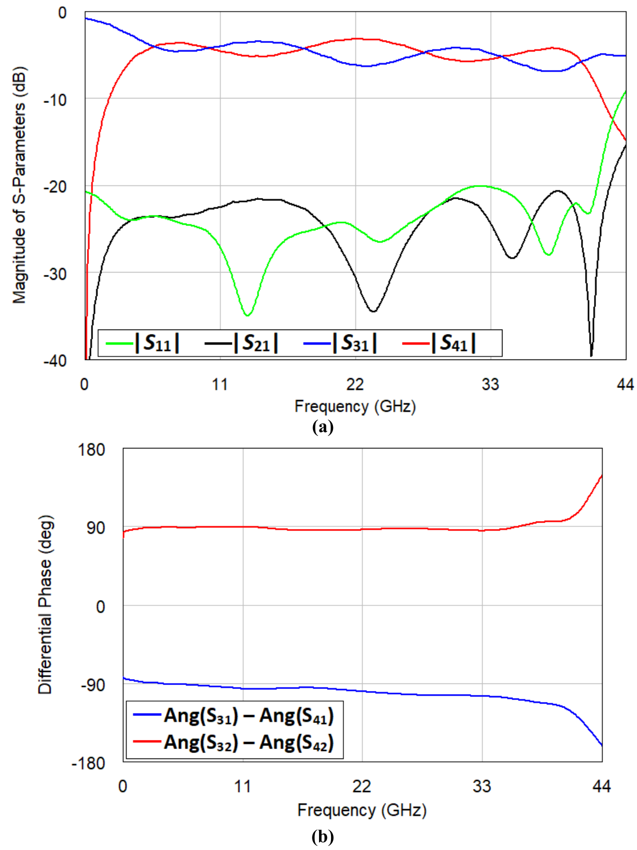


FIGURE 10. Magnitude of scattering parameters (a) and differential phases (b) obtained during electromagnetic simulations of the ultra-broadband directional coupler.

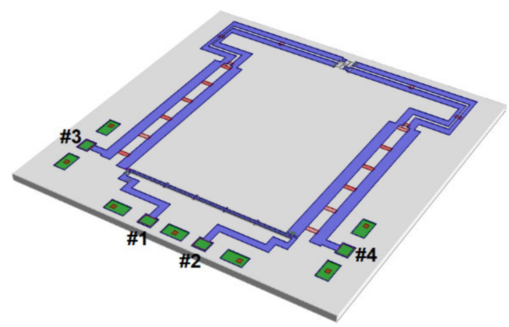


FIGURE 11. A 3D model of the designed ultra-broadband directional coupler used in electromagnetic simulations.

been collected in Table 1. It has to be underlined that due to the insertion losses the values of couplings and transmissions calculated for the ideal circuit cannot be achieved. Therefore, to ensure that each coupled-line section of the entire directional coupler is properly designed, i.e. features the required coupling coefficient, the insertion losses existing in a coupled-line section have been included during the iterative design process. This was achieved by geometry recalculations in which each coupled-line section has been simulated electromagnetically to compute total losses, and subsequently these losses were added to the achieved coupling value to verify whether the designed section features the required coupling.

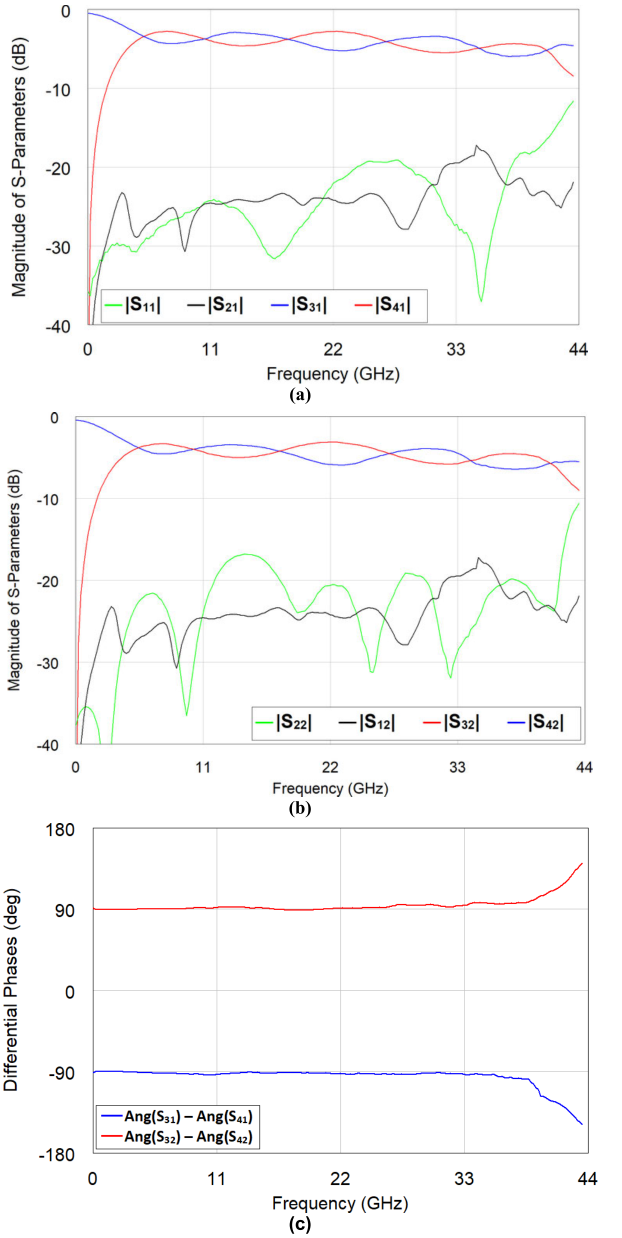


FIGURE 12. **Measured S-Parameters (a)-(b), and differential phases (c) of the designed ultra-broadband multisection directional coupler.**

Section I has been designed as an asymmetric three-strip coupled-line section utilizing M1 and M2 metallization layers. Such a structure has been presented in Fig. 4a. For quarter-wave length coupled-line section having $k_1 = 0.794$, the following geometry have been found: $w_1 = 4$ μm, $w_2 = 18$ μm, $s_{12} = 4$ μm. The coupled-line section has been divided into five subsections. The compensating elements C_{cm} have been realized by air-bridges between center strip on the top M1 layer and small pads on the same layer which are placed above the line formed on M2 layer. Due to the fact, that Section II and III have to have relatively weak couplings, an symmetric two-strip coupled-line structure shown in Fig. 2a has been utilized for both cases. The physical parameters of Section II are as follows: $w_1 = 78$ μm, $s_1 = 74$ μm, whereas, for Section III $w_1 = 56$ μm and $s_1 = 27$ μm. The compensating elements used in symmetric coupled-line sections have been realized on M3 metallization layer as small areas underneath coupled lines. It must to be noticed, that in the 270° section one of the compensating capacitances has been formed by cross structure between M1 and M2 layers. Fig. 9 shows calculated S-Parameters S_{41} and S_{11} (isolation and reflection coefficient) of the uncompensated and compensated ultra-broadband multisection directional couplers. The observed differences are significant, especially at higher frequencies.

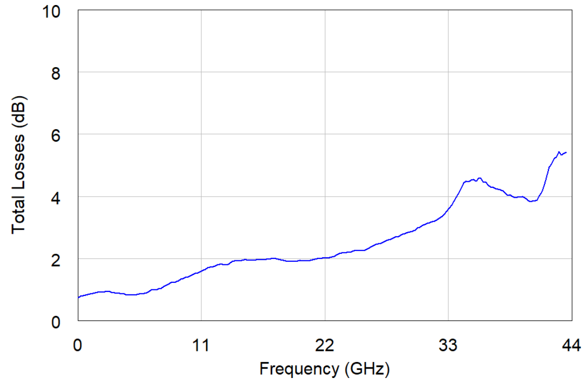


FIGURE 13. **Calculated total losses of the measured ultra-broadband directional coupler.**

The ultra-broadband directional coupler has been simulated electromagnetically by using Cadence AWR Microwave Office, and the results are shown in Fig. 10. It can be seen, that the obtained return losses and isolation are better than 20 dB in the operational bandwidth, and coupling imbalance of the coupler is not greater than 1.15 dB. The differential phase imbalance is not greater than 4.4° at 22 GHz center frequency. The designed coupler operates from 3.9 GHz to 41.2 GHz. A 3D model used during simulations has been presented in Fig. 11.

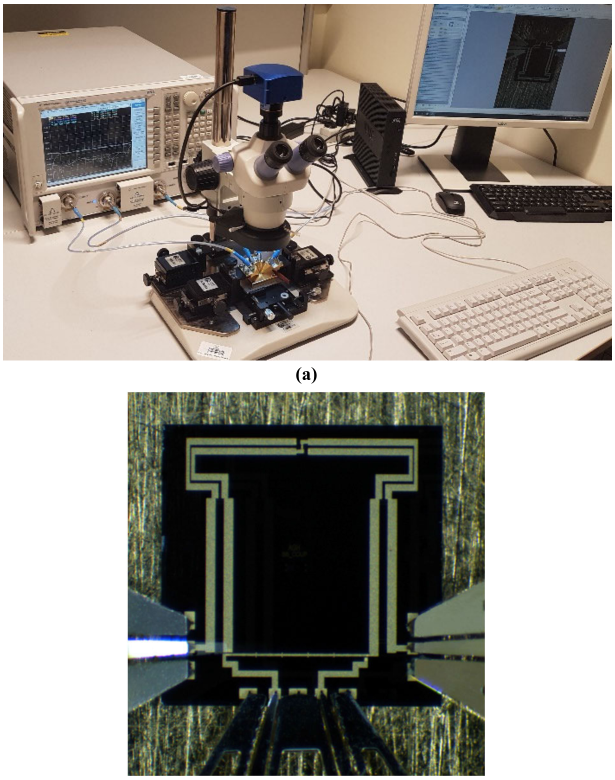
V. EXPERIMENTAL RESULTS

The considered broadband directional coupler has been manufactured in UMS Foundry and measured at AGH by using on-chip measurement setup consisting of single and dual coaxial $|Z|$ probes from Cascade Microtech, LMS-2709 probe station with integrated microscope and Agilent 5224A vector network analyzer (VNA) operating up to 43.5 GHz. The VNA has been calibrated according to Short-Open-Load-Through method utilizing Cascade calibration kit dedicated for IC measurements.

The obtained results have been presented in Fig. 12. As seen, S-Parameters and differential phases are in good agreement with electromagnetic simulations. Fig. 12a shows that the measured return losses which are better than 15 dB, whereas isolation is greater than 17.4 dB in the operational bandwidth. Furthermore, according to Fig. 12b, the maximum differential phase imbalance does not exceed 8.2°. The calculated total losses of the manufactured coupler equal 2.2 dB at the 22 GHz center frequency what is seen

TABLE 2. Performance comparison of the proposed ultra-broadband directional coupler with other solutions designed in monolithic technology.

Reference	Substrate	Coupling (dB)	Return Loss (dB)	Isolation (dB)	Bandwidth (f_U/f_L)	Center frequency f_0 (GHz)
[22]	GaAs	5.0	---	10	3.5	24.0
[23]	Si	3.0	20.0	25.0	2.0	30.0
[24]	Si	14.4	10.0	25.0	4.0	25.0
[24]	Si	4.65	10.0	18.0	1.3	35.0
[26]	GaAs	3.0	15.9	13.5	2.5	6.0
[27]	GaAs	3.0	14.5	13.5	2.3	60
[28]	GaAs	3.0	11.0	11.0	3.0	12.0
This Work	GaAs	3.0	18.4	19.1	10.6	22.0



(a)

(b)

FIGURE 14. Photograph of setup utilized during measurements (a) and the designed ultra-broadband multisection directional coupler fabricated in UMS PH25 GaAs process (b).

in Fig. 13. Photographs presenting the utilized measurement setup and the fabricated ultra-broadband multisection directional coupler is shown in Fig. 14. The overall size of the manufactured die is equal 2.4 mm x 2.4 mm. To compare performance of considered structure with other monolithic applications, the obtained parameters have been presented in Table 2. It is clearly seen that the achieved bandwidth is superior, whereas the other parameters such as directivity and impedance match are comparable with other designs.

VI. CONLUSION

In this paper, a novel monolithic ultra-broadband directional coupler operating in bandwidth exceeding one frequency decade has been presented. It has been shown for the first time, that such a broad bandwidth has been obtain in the coupler designed in monolithic technology. Moreover, the simplified compensation method presented in [43] has been applied to verify its utility in broadband applications. The coupler has been designed in the PH25 process delivered by UMS which is based on gallium arsenide. The influence of total losses on the achievable frequency characteristics together with the compensation method that significantly improves the resulting coupler's performance has been analyzed. It has been shown that the level of coupling has direct impact on the obtained losses what is crucial in coupled-line sections, where strong coupling has to be achieved. It is also proved that the applied compensation method improves electrical performance of the coupler and decreases the overall losses. Such an aspect is relevant, especially in broadband applications, where return losses and isolation degrade with frequency.

The proposed design procedure in which impact of losses is included, has been verified by measurements of the fabricated 3-dB ultra-broadband directional coupler. The measured results show that the manufactured component operates in 3.9 – 41.2 GHz frequency range with coupling imbalance not exceeding 1.2 dB. The obtained electrical performance is satisfying in terms of return losses, isolation and phase imbalance. Therefore, the designed coupler can be utilized in many monolithic applications composed of multiport circuits such as beamforming networks [46], [47], receivers [48], [49] and reflectometers [50], [51]. The last of mentioned devices as well as Butler matrices [52], [2] are applied in microwave measurement techniques as an alternative to expensive vector network analyzers. However, most of broadband designs are realized in PCB technology. On the other hand, integrated monolithic solutions such as those presented in [53], [50] features narrower frequency responses than these which can be achieved for applications consisting of the proposed ultra-broadband directional coupler. Thus the designed coupler can be successfully applied in measurement setups.

ACKNOWLEDGMENT

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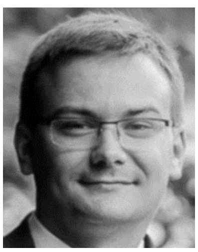

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