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RESEARCH ARTICLE

Impedance-Transforming Transdirectional Coupled-Line Directional Couplers With Maximum Achievable Transformation Ratio

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ABSTRACT A novel concept of impedance-transforming transdirectional coupled-line directional couplers that feature maximum available impedance transformation ratio is proposed. It is shown that such couplers can be designed as an appropriate connection of two uncoupled two-wire transmission lines, having electrical lengths equal 90° and 270°. The conditions for ideal impedance match and isolation in such couplers are derived and formulas describing the required characteristic impedances of the two two-wire transmission lines are given. It is shown that in such circuits the input and isolated port can be terminated with different impedances than the coupled and through ports. The major advantage of the proposed circuits is their reciprocity which allows for application in multiport amplifiers. The concept has been verified by the design and measurement of a 3-dB transdirectional coupler operating at a center frequency of 1 GHz that allows for achieving impedance transformation ratio $R = 2$ proving the correctness of the presented analysis.

INDEX TERMS Asymmetric coupled-lines, directional couplers, impedance transformers, transdirectional couplers.

I. INTRODUCTION

Coupled-lines have been the subject of intensive studies over the years showing their useful properties [1], [2], [3], [4]. It is known that a section of coupled lines can constitute a directional coupler when appropriate conditions are met [5], [6], [7], [8]. Such circuits can be divided into backward coupled couplers, forward coupled couplers, and transdirectional couplers depending on their directivity properties. Although the commonly used and widely reported are backward-coupled couplers, due to their compact size and broadband characteristics, useful properties feature transdirectional couplers. In such couplers the incident signal is entirely delivered to the coupled line, therefore, they not only realize directive power division with quadrature phase relations but simultaneously can be used as DC blocks, when are used in larger active networks. On the other hand, the design of microwave amplifiers often require impedance transformation since the input impedance of high power transistors can be very low. Therefore, over the years coupled lines that are terminated with different impedances have been also intensively studied [9], [10], [11], [12], [13], [14], [15], [16], [17], [18]. Apart from single-ended couplers also balanced couplers are known [19]. In [16] it is shown that each line in a quarter wavelength coupled-line section can be terminated with different impedance. Such a circuit features the properties of impedance transforming backward-coupled directional couplers, in which input and through port are terminated with one impedance (Z_1), whereas the coupled and isolated port are terminated with another impedance (Z_2). It is also shown that in such couplers the maximum available impedance transformation ratio exits and is equal $R = 1/k^2$,

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where k is the coupling coefficient of the impedance transforming directional coupler. The major disadvantage of such circuits is that their coupled and through ports are terminated with different impedances, and therefore, they cannot be applied in i.e., balanced networks or multiport amplifiers, despite the fact that they are reciprocal. The concept of impedance transforming directional couplers has been further studied and in [17] a class of impedance transforming directional couplers that can be applied in balanced circuits has been proposed. In such couplers each line in coupled-line section operates as a quarter wavelength impedance transformer which allows for having equal terminating impedance at coupled and through port and different than the input impedance. Therefore, such couplers as shown in [17] can be applied in balanced circuits, however, they cannot be used in multiport amplifiers since they require different impedances terminating input and isolated ports.

Another issue of impedance-transforming directional coupled-line directional couplers is the achievable impedance transformation ratio which strictly depends on coupling coefficient. It was shown in [16] that the maximum achievable impedance transformation ratio of the described couplers is limited by the coupling coefficient as $R = 1/k^2$. The same condition has been derived for couplers designated for balanced circuits in [17], which causes that the most useful impedance transformation ratio is equal $R = 2$, since such networks require 3-dB directional couplers. The performed analysis presented in [17] allows to draw a general conclusion that the maximum transformation ratio is the most useful, therefore, such couplers draw further attention. In [18] impedance-transforming directional couplers operating at the maximum achievable transformation ratio have been thoroughly investigated. It was shown that the maximum transformation ratio exists when one of the coupled-lines is completely shielded by the other, which causes that such a coupler can be modeled by an appropriate connection of two two-wire uncoupled lines. Moreover, it was also shown that in such circuits the equalization of inductive and capacitive coupling coefficient, which are naturally different in an asymmetric structure can be easily equalized by varying the electrical lengths of each uncoupled line.

In this paper we extend the analysis of asymmetric impedance-transforming coupled lines and propose impedance-transforming transdirectional couplers. The proposed couplers are modeled and analyzed as a connection of two two-wire uncoupled transmission lines having appropriate characteristic impedances having electrical lengths equal 90° and 270°, respectively. Theoretical analysis of such circuits is presented and the values of the required characteristic impedances are derived. The proposed concept has been verified by the design and measurements of the impedance-transforming transdirectional coupler operating at 1 GHz and having impedance transformation ratio equal $R = 2$. The obtained results are in good agreement with the theoretical ones. Since the proposed couplers feature equal terminating impedances at input and isolated ports and also equal at through and coupled ports, it combines the advantages of the known solutions [16], [17] and allows for realization of not only balanced but also multiport amplifiers. Such a feature was never reported to the best of Authors' knowledge.

II. THEORETICAL ANALYSIS OF TRANSDIRECTIONAL COUPLER WITH MAXIMUM AVAILABLE IMPEDANCE TRANSFORMATION RATIO

As shown in [16] and [17], when a coupled-line section is terminated with different impedances, the condition on maximum impedance transformation ratio exists and equals $R = 1/k^2$, where k is the coupling coefficient of the coupled-line section. Moreover, it was shown [18] that a coupled-line section in which a maximum transformation ratio is achieved can be modelled as an appropriate connection of two uncoupled two-wire transmission lines. This is due to the fact that the maximum transformation ratio is achieved when one coupled line is completely shielded from the ground plane by the other one, and therefore, per-unit-length self-capacitance of the first line equals zero [18]. Additionally it was shown in [18], that capacitive and inductive coupling coefficients in such structures can be equalized by varying electrical length of each uncoupled two-wire transmission lines. On the other hand it is known that transdirectional properties in classic coupled-line sections are achieved when the difference between modal electrical lengths are equal 180°. This led us to a conclusion that an impedance-transforming transdirectional coupler can be designed and modeled with two uncoupled two-wire transmission lines one having 90° and the other 270° electrical lengths, under the assumption that the maximum available impedance transforming ratio is achieved in such a coupler. Fig. 1 presents a schematic diagram utilized for analyzing the properties of such a coupler with the use of a general matrix description. The coupler consists of two two-wire transmission line sections having characteristic impedances Z_{0x} and electrical lengths θ_x, each described by a ABCD matrix A_x. The coupler is terminated with impedances Z_{px}. In Fig. 1 also voltages U_x and currents I_x are marked for impedance $\mathbf{Z}$ matrix derivation.

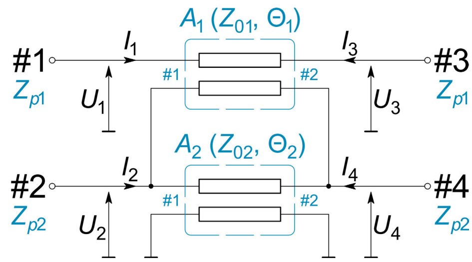

FIGURE 1. Schematic diagram of a two uncoupled two-wire transmission lines constituting impedance transforming directional coupler featuring maximum available impedance transformation ratio.

The ABCD matrix of a single transmission line equals [20]

$$\mathbf{A_i} = \begin{bmatrix} \cos\theta_i & jZ_{0i}\sin\theta_i \\ \frac{j}{Z_{0i}}\sin\theta_i & \cos\theta_i \end{bmatrix} \quad (1)$$

Therefore, matrix $\mathbf{A}_1$ for $\theta = 270°$ at the center frequency becomes

$$\mathbf{A}_1 = \begin{bmatrix} 0 & -jZ_{01} \\ \frac{-j}{Z_{01}} & 0 \end{bmatrix} \quad (2)$$

whereas matrix $\mathbf{A}_2$ for $\theta = 90°$ at the same frequency equals

$$\mathbf{A}_2 = \begin{bmatrix} 0 & jZ_{02} \\ \frac{j}{Z_{02}} & 0 \end{bmatrix} \quad (3)$$

Based on the above matrices the impedance matrix $\mathbf{Z}$ of the entire coupler equals:

$$\mathbf{Z} = \begin{bmatrix} 0 & 0 & j(Z_{01} - Z_{02}) & -jZ_{02} \\ 0 & 0 & -jZ_{02} & -jZ_{02} \\ j(Z_{01} - Z_{02}) & -jZ_{02} & 0 & 0 \\ -jZ_{02} & -jZ_{02} & 0 & 0 \end{bmatrix} \quad (4)$$

To find a condition for a perfect impedance match at the center frequency we need to reduce the matrix $\mathbf{Z}$ by loading its ports #2 and #4 by impedance Zp_2. This leads to the following reduced 2 × 2 matrix:

$$\mathbf{Z}^{red} = \begin{bmatrix} \frac{Z_{p2}Z_{02}^2}{Z_{p2}^2+Z_{02}^2} & j(Z_{02} - Z_{01}) - \frac{jZ_{02}^3}{Z_{p2}^2+Z_{02}^2} \\ \frac{Z_{p2}Z_{02}^2}{Z_{p2}^2+Z_{02}^2} & j(Z_{02} - Z_{01}) - \frac{jZ_{02}^3}{Z_{p2}^2+Z_{02}^2} \end{bmatrix} \quad (5)$$

which can be recalculated to obtain the corresponding $\mathbf{S}^{red}$ matrix. The coefficient $s^{red_{12}}$ of this $\mathbf{S}$ matrix represents isolation of the proposed coupler. It can be derived as follows [21]:

$$s_{12}^{red} = \frac{2z_{12}\sqrt{Z_{p1}Z_{p2}}}{(z_{11} + Z_{p1})(z_{22} + Z_{p2}) - z_{12}z_{21}} \quad (6)$$

It is seen that the transdirectional properties (i.e., ideal isolation between ports #1 and #2 in the reduced matrix) are achieved when z_{12} is equal zero. Therefore, the final condition for ideal isolation at the center frequency equals:

$$Z_{01} = \frac{Z_{p2}^2 Z_{02}}{Z_{p2}^2 + Z_{02}^2} \quad (7)$$

Having found the condition for isolation we can derive the condition for ideal impedance match at the center frequency. The coefficient s_{11}^{red} equals [21]:

$$s_{11}^{red} = \frac{(z_{11}^{red} - Z_{p1})(z_{22}^{red} - Z_{p2}) - z_{12}^{red} z_{21}^{red}}{(z_{11}^{red} + Z_{p1})(z_{22}^{red} + Z_{p2}) - z_{12}^{red} z_{21}^{red}} \quad (8)$$

and the ideal impedance match is achieved when

$$s_{11}^{red} = \left(z_{11}^{red} - Z_{p1}\right)\left(z_{22}^{red} - Z_{p2}\right) - z_{12}^{red} z_{21}^{red} = 0 \quad (9)$$

Taking into account the condition on ideal isolation (6)

$$z_{12}^{red} = 0 \quad (10)$$

and the form of the reduced matrix (5) i.e.,

$$z_{22}^{red} = z_{12}^{red} = 0 \quad (11)$$

following condition with simultaneous ideal isolation (since $z^{red_{12}} = 0$) and impedance match can be formulated:

$$Z_{01} = \frac{Z_{p2}Z_{02}^2}{Z_{p2}^2 + Z_{02}^2} \quad (12)$$

By taking the real and positive solution we get:

$$Z_{01} = Z_{p1}\frac{\sqrt{1-k^2}}{k} \quad (13)$$

$$Z_{02} = Z_{p1}\frac{1}{k\sqrt{1-k^2}} \quad (14)$$

where k is the nominal coupling coefficient of the transdirectional coupler, which defines the impedance transformation ratio as

$$k = \sqrt{\frac{Z_{p1}}{Z_{p2}}} \quad (15)$$

The impedance-transforming directional coupler proposed above features some distinctive advantages over the known solutions [16], [17] which are directly seen by analyzing its schematic diagram presented in Fig. 1. First of all it has to be noticed that the incident signal is completely directed to the other coupled-line (ports #2 and #4), which is actually the classic feature of a transdirectional coupler [22]. However, it needs to be underlined that the isolated port of the coupler (port #3) is terminated with exactly the same impedance as the input port (port #1). This is the major advantage of the proposed solution, since such a coupler will have exactly the same properties for either port #1 or port #3 selected as the input port. This feature cannot be achieved in the known solution described in [16] and [17] and causes that such a coupler can be directly applied not only in balanced networks but also in multiport amplifiers which is its major advantage. Moreover, it has to be noted that, although the above presented analysis assumes that the coupler operates under the condition of maximum transformation ratio, this is the case in practical applications. This is due to the fact that impedance-transforming directional couplers find applications in high-power networks where 3-dB couplers are used. Therefore, the impedance transformation ratio is limited by coupling coefficient of the coupler and equals $R = 2$, and such couplers frequently operate under this condition.

Based on the theoretical analysis and the derived conditions for ideal isolation and impedance match, the design curves that can be used in realization of impedance-transforming transdirectional couplers can be found. Fig. 2 presents the required characteristic impedances of the two two-wire transmission lines (Z_{01} and Z_{02}) that constitute such couplers vs. input impedance Z_{p1} plotted for different nominal couplings. The design curves presented in Fig. 2 allow for easy design of the proposed transdirectional impedance transforming couplers. Fig. 3 presents frequency

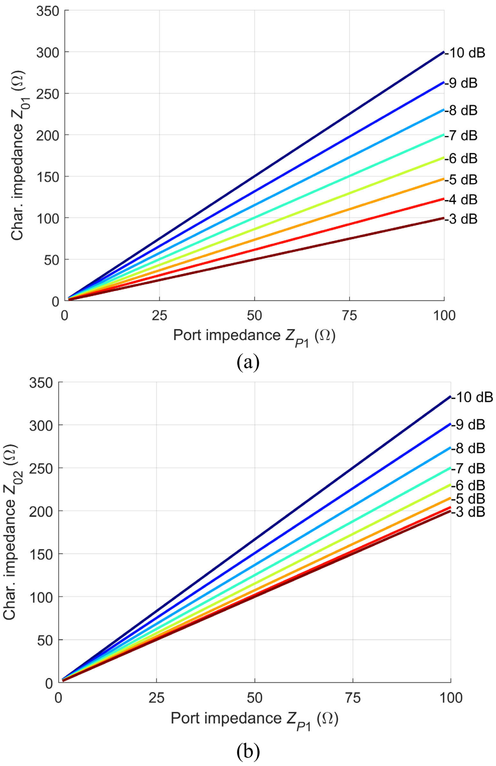

FIGURE 2. Calculated characteristic impedances of (a) first (Z01) and (b) second (Z_{02}) two-wire transmission lines constituting impedance transforming transdirectional coupler vs. the input impedance Zp_1 for different nominal couplings.

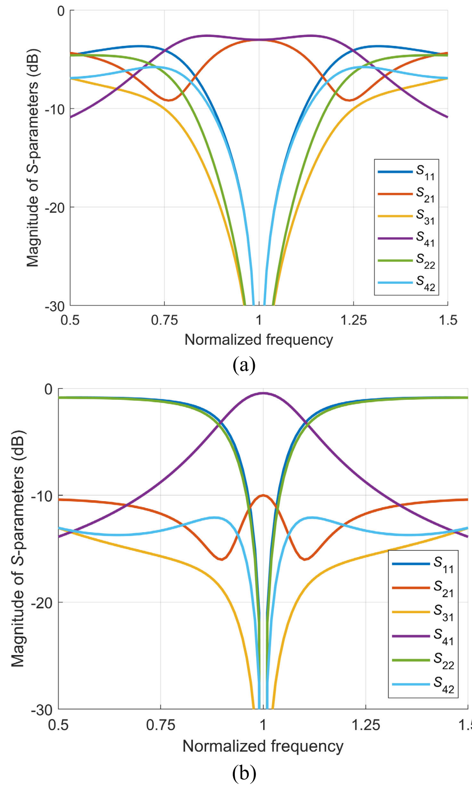

FIGURE 3. Calculated frequency characteristics of (a) 3-dB and (b) 10-dB impedance-transforming transdirectional couplers.

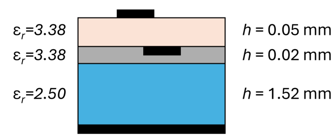

FIGURE 4. Cross-sectional view of the dielectric structure used for the design of a 3-dB impedance-transforming transdirectional coupler.

characteristics obtained for two different couplers i.e., 3-dB coupler having impedance transformation ratio $R = 2$ ($Zp_1 = 25$ Ω, $Zp_2 = 50$ Ω), and 10-dB coupler having impedance transformation ratio $R = 10$ ($Zp_1 = 25$ Ω, $Zp_2 = 250$ Ω). The first coupler is composed of two-wire transmission lines having $Z_{01} = 25$ Ω & $\theta_1 = 270°$ and $Z_{02} = 50$ Ω & $\theta_2 = 90°$, whereas the second one is composed of two-wire transmission lines having $Z_{01} = 75$ Ω & $\theta_1 = 270°$ and $Z_{02} = 83.33$ Ω & $\theta_2 = 90°$. As seen, the larger impedance transformation ratio, and therefore, the lower coupling coefficient the narrower bandwidth is achieved of the entire impedance transforming directional coupler. However, it has to be underlined that the obtained bandwidth is comparable to the solutions presented in [17] and [18] and is sufficient for application in high-power multiport amplifiers.

III. EXPERIMENTAL RESULTS

The proposed concept of impedance-transforming transdirectional couplers has been verified experimentally. Since the most suitable for application in multiport amplifiers are 3-dB couplers, such a value has been chosen as a nominal coupling. The transformation ratio of such a coupler equals $R = 2$, therefore, an impedance transforming coupler which transforms the 25 Ω input impedance into 50 Ω output impedance has been developed. For such a coupler the upper line has the characteristics impedance equal $Z_{01} = 25$ Ω, whereas the lower line $Z_{02} = 50$ Ω. The coupler has been designed for the center frequency $f_0 = 1$ GHz in the dielectric structure shown in Fig. 4 composed of a 1.52 mm thick bottom Arlon 250 laminate and a top 50 μm thin DuPont Kapton laminate bonded together with Arlon 1080 (20 μm thick). For such a structure the width of upper line equals $w_1 = 0.31$ mm, while the lower line width equals $w_2 = 4.3$ mm. The upper line has been appropriately meandered to ensure

TABLE 1. Comparison of the features of the proposed directional coupler with other concepts.

coupler	coupling (dB)	bandwidth (%)	impedance transformation $R = Z_{p1}/Z_{p2}$	transdirectional properties	suitable for balanced circuits	suitable for multichannel amplifiers
[9]	16.6	50	1.66	no	no	no
[23]	3	17.4	2	no	no	no
[17]	3	73	2	no	yes	no
[22]	3	22.8	1 (none)	yes	yes	yes
this work	3	12	2	yes	yes	yes

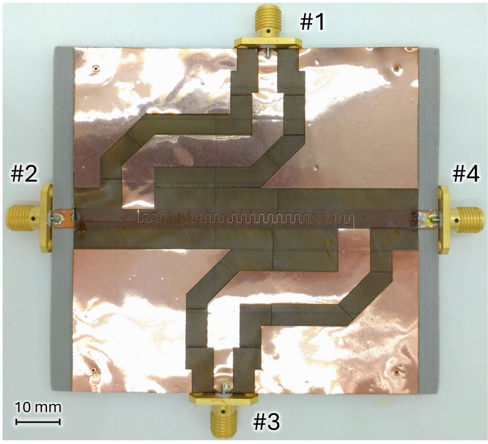

FIGURE 5. Picture of the developed 3-dB impedance-transforming transdirectional coupler.

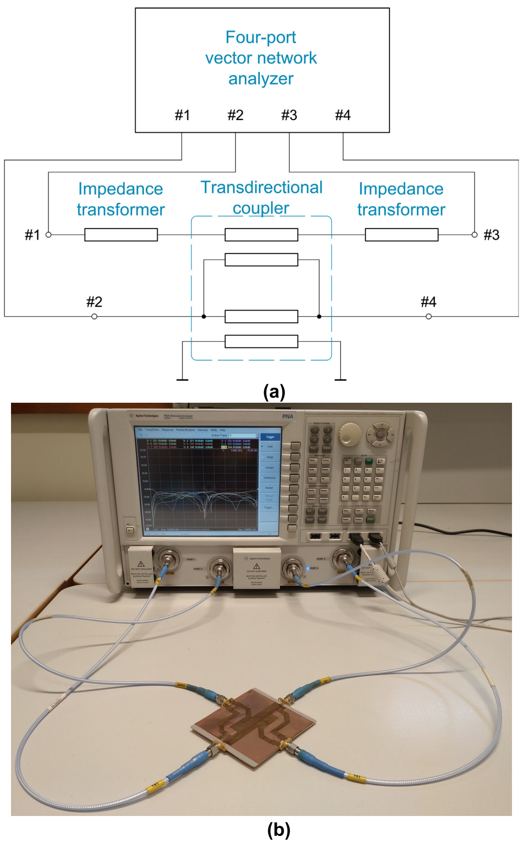

FIGURE 6. Schematic diagram of the measurement setup and the picture of the transdirectional coupler during measurements.

its electrical length equal 270° above the lower line which has length equal to 90°. The coupler has been analyzed and designed with the use of AWR Microwave Office Software. Also the electromagnetic simulations have been performed with Axiem module of AWR Microwave Offfice. The coupler has been fabricated using laser PCB prototyping system by LPKF. Fig. 5 shows a picture of the manufactured coupler in which additional quarterwavelength impedance transformers

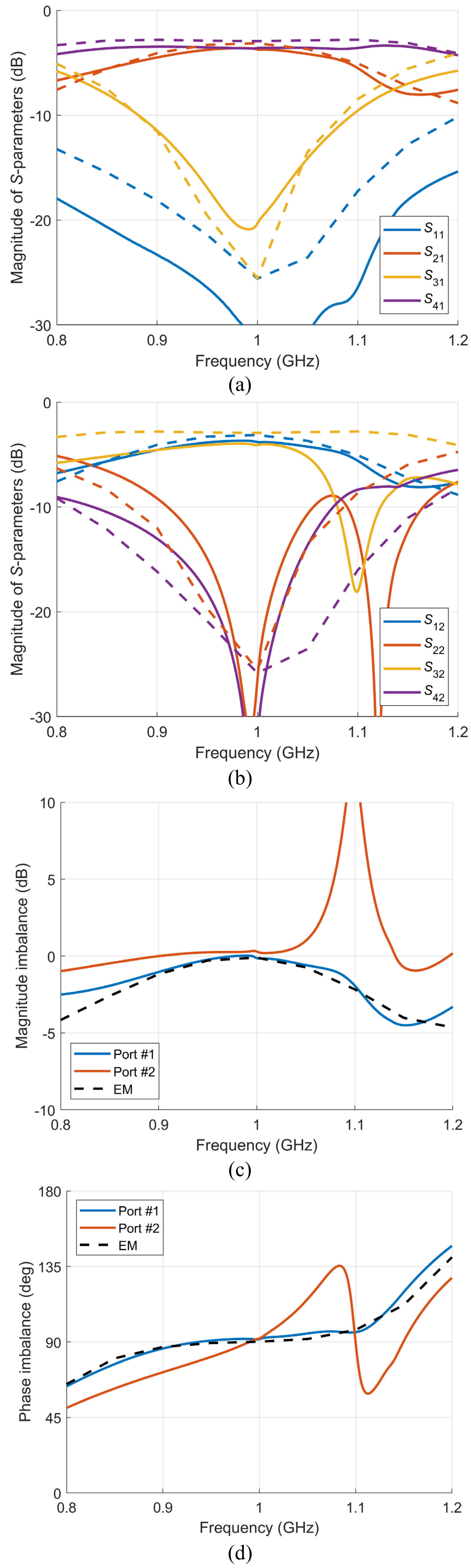

FIGURE 7. Measured (solid lines) frequency characteristics in comparison with the electromagnetically calculated ones (dashed lines) for the developed 3-dB impedance-transforming directional coupler when (a) port #1 and (b) port #2 is fed, (c) amplitude imbalance and (d) differential phase.

transforming 25 Ω impedance to 50 Ω for measurement purpose (width $w_T = 7.5$ mm) are added. The manufactured coupler has been measured with 4-port vector network analyzer PNA N5224A as shown schematically in Fig. 6a, whereas the picture of the measurement setup is shown in Fig 6b. Fig. 7 presents measurements of the manufactured coupler together with the results of electromagnetic analysis obtained when input ports #1 and #3 are fed. The achieved bandwidth of the coupler equals 12% and is narrower than the bandwidth of the classic transdirectional coupler which reaches 34% for 3±1 dB transmission and coupling characteristics. It has to be underlined that the bandwidth reduction results from factors (i) large impedance transformation ratio, and (ii) physical realization where one line is physically 180° longer than the other one. Nevertheless, good electrical properties have been achieved which confirm the correctness of the presented concept and analysis. It is seen that the coupler features quadrature phase characteristics (Fig. 7d) within the bandwidth. The achieved properties of the proposed design have been compared with the solutions presented elsewhere and summarized in Table 1. The developed coupler is the only solution that simultaneously allows for: impedance transformation, application in balanced circuits and application in multichannel amplifiers. Although other known solutions present generally wider bandwidth, they cannot be applied in multichannel amplifiers even though they feature impedance transformation ratio as in the proposed solution.

IV. CONCLUSION

The paper presents a novel concept of an impedance-transforming transdirectional coupled-line directional coupler. It is shown that such a coupler can be modelled with an appropriate connection of two uncoupled two-wire transmission lines having electrical lengths $\theta_1 = 270°$ and $\theta_2 = 90°$ when it operates under the condition of maximum impedance transformation ratio. Theoretical analysis of the proposed coupler has been presented, showing that the coupler features ideal frequency characteristics at the center frequency when its input and isolated ports are terminated with one impedance (Z_{p1}), whereas the transmission and coupled ports are terminated with another impedance (Z_{p2}). Such a feature has not been available in the known solutions and causes that the coupler can be directly applied not only in balanced circuits but also in multiport amplifiers. This is due to the fact that the coupler features the same properties when two different ports are selected as inputs. The presented theoretical analysis has been confirmed by measurements of the manufactured 3-dB coupler which transforms 25 Ω input impedance into 50 Ω output impedance. The drawback of the proposed coupler is its relatively narrow band (12% in the measured coupler). However, it has the unique properties among which the most important one is its possible application in multiport amplifiers where it ensures simultaneously power division and impedance transformation. Future work can be focused on broadening the bandwidth with the use of e.g. multisection technique, similarly as in [12].

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The laser PCB prototyping system by LPKF was used to fabricate the presented transdirectional coupler.

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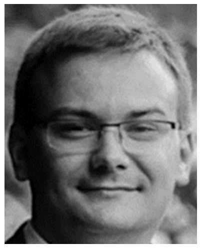

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