Development of a Low Profile and Wideband Backward-Wave Directional Coupler Using Neural Network

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Abstract **─** In this paper, a low profile and wideband backward-wave directional coupler is introduced. It operates similar to the composite right left handed (CRLH) couplers. Two different mechanisms including connections between the coupled lines to provide shunt inductance for odd mode and defected ground structure (DGS) to add series capacitance for even mode are applied to obtain high performance and wideband coupler. Neural network process is used to obtain the optimized parameters of the proposed coupler. The introduced coupler is then numerically investigated using full wave simulator software. A prototype of the proposed coupler is fabricated and successfully tested. The measured results are in a good agreement with those obtained by simulation. The measured coupling level is 0.49 dB over the frequency range from 6.5 GHz up to 14 GHz, which shows fractional bandwidth of 73.2%.

Index Terms **─** Defected ground structure, directional coupler, neural network.

I. INTRODUCTION

Microstrip coupled-line directional couplers are widely used in microwave and millimeter wave circuits, such as filters, power dividers, transformers and baluns [1-2] due to their attractive performances. These couplers have two kinds of coupling mechanisms [3], depending on the type of the employed transmission lines, constituting the structure of the coupled lines and distance between the lines.

The first type of the coupling is based on the difference between the even- and odd-mode characteristic impedances leading to backward couplers. The difference between these impedances can be increased by reducing the interspacing between the lines. However, this is difficult due to fabrication constrains. Therefore, backward couplers suffer from the low level of coupling.

The second type of the coupling mechanism is based on the difference between phase velocities of even- and odd-modes providing forward couplers. In these types of couplers, the coupling level could be as high as 0 dB, but there are two important drawbacks in implementing them using microstrip lines. The first one is the small difference between even- and odd-mode propagation constants, which require very long coupling length. The other one is non-identical characteristic impedances of even- and odd-modes, which reduce the coupling level of the structure and the directivity performance of the coupler is decreased. A widely used planar coupler providing both broad bandwidth and tight coupling is a Lange coupler [4]. However, it suffers from requiring bonding wires which introduce parasitic effects at high frequencies.

In recent years, the composite right left-handed (CRLH) couplers represent unique alternatives to the Lange couplers [5]. They offer tight coupling over a broad bandwidth using planar structure without requiring bonding wires. In these couplers, the even- and odd-mode characteristic impedances are purely imaginary over the coupling bandwidth. Therefore, the coupling level is related to the attenuation length of the modes instead of the electrical length of the coupled lines.

In this paper, a low profile and wideband backward-wave directional coupler is designed and optimized using neural network. The proposed coupler operates similar to the CRLH couplers over a wide bandwidth. Two different techniques are applied together, for the first time, to obtain a high performance and wideband coupler. The first one is connections between the coupled lines, which provide shunt inductance for odd-mode. The second one is adding series capacitance for even mode using the defected ground structure (DGS) patterns.

The proposed coupler is numerically investigated using High Frequency Structure Simulator (HFSS). A prototype of the coupler is fabricated and tested using network analyzer and its *S*-parameters are measured. Results show that the proposed coupler provides the advantages of wide bandwidth and high coupling level in addition to low profile, low weight and low fabrication cost.

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II. BACKWARD WAVE COUPLED LINE COUPLER

The structure of the proposed coupler is shown in Fig. 1. The coupled lines width and length are *W* and *l* respectively, which are separated by *s*. The proposed coupler is symmetric at the middle of the structure. The connections between the lines are the same. The DGS patterns are etched at the bottom layer of the substrate and they are separated from each other by *t*. The thickness of the substrate is denoted by *h*.

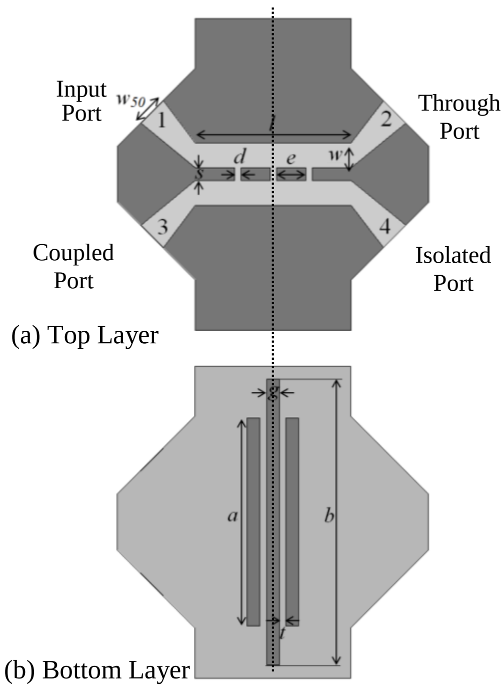


Fig. 1. The structure of the proposed coupler.

Because of the symmetry, the proposed four port coupler can be decomposed to even- and odd-mode two port structures. Even- and odd-mode equivalent circuit models correspond to the structure with perfect magnetic wall and perfect electric wall at the center of the coupler respectively. The equivalent circuit models for even- and odd-modes are shown in Figs. 2 (a) and 2 (b) respectively. For the microstrip coupled line, the propagation of odd-mode has low returned current density on the ground plane. The current of this mode is conducted from one of the coupled lines and returns from the other one. Nevertheless, in case of even-mode, the returned current density on the ground plane is high. This is due to direction of current which is the same for the two coupled lines, and the returned current is conducted by the ground. Hence, the current distribution pattern on the ground plane only affects the even-mode equivalent circuit. Therefore, the DGS patterns in the proposed coupler are modeled by resonating parallel *LC* circuits for only even-mode.

Connections between coupled lines are modeled by inductance and capacitance for odd- and even-modes respectively. However, because of the short length of the connections, the equivalent capacitances for even-mode can be neglected.

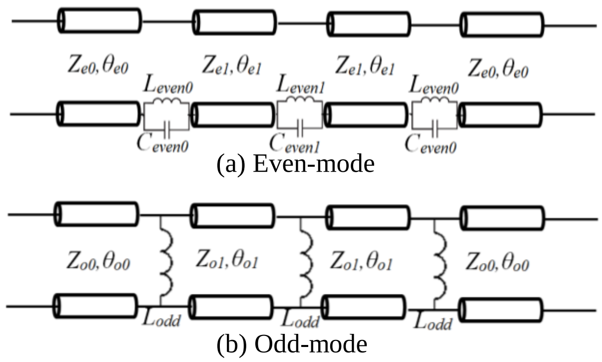


Fig. 2. The equivalent circuit of even- and odd-modes of the proposed coupler.

III. DESIGN PROCEDURE

The proposed coupler is designed based on the back propagation neural network (BPNN), which is normally used to estimate a complicated function of several variables [6] over an enclosed interval. In this work, the applied BPNN, as shown in Fig. 3, contains seven inputs regarding to the physical dimensions of the proposed coupler. In addition, fourteen neurons are used as the hidden layer of the proposed network. The coupling bandwidth, maximum magnitudes of S_{11} and S_{41} in pass band are considered to be the outputs of the BPNN network.

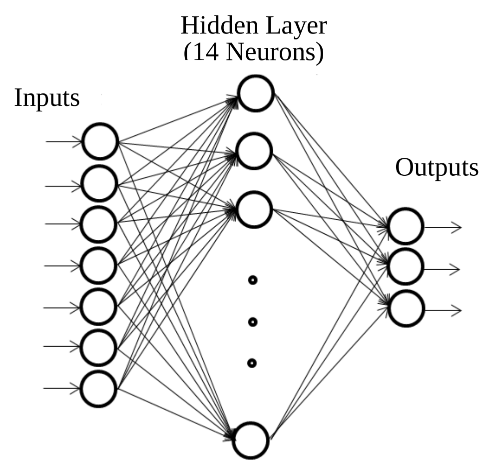


Fig. 3. Back propagation neural network model.

This network has to be trained. Input vectors and the corresponding target vectors are used to train the applied network. The BPNN uses a gradient descent algorithm in which the network weights are moved along the negative portion of the gradient of the performance function. Using Matlab Neural Network Toolbox, trainbr function is chosen to train the applied network. This training function updates the weight and bias values according to Levenberg-Marquardt optimization process. It properly minimizes a combination of squared errors and weights, and then determines the correct combination of the weight and the bias values to obtain a network that can predict the best values of the outputs [7].

For training process of the BPNN, suitable values of input parameters of the neural network are chosen. In this procedure *b* is chosen from 18 mm to 22 mm, *g* is varied from 0.5 mm to 1.5 mm and *a* is selected from 14 mm to 18 mm. Moreover, the other values including *s*, *d*, *e* and *W* are set from 0.5 mm to 1.5 mm, 0.25 mm to 1.25 mm, 1 mm to 2.5 mm and 1.6 mm to 2.4 mm respectively. These are the input parameters of the BPNN network, whereas the coupling bandwidth and maximum magnitudes of S_{11} and S_{41} are the outputs of the network. Also, parameter *T* is defined by Equation (1):

$$T = \frac{BW}{MS_{11}MS_{41}}. \tag{1}$$

In Equation (1), *BW*, MS_{11} and MS_{41} are the coupling bandwidth with 1 dB flatness, maximum magnitudes of S_{11} and S_{41} in pass band respectively. It can be seen from Equation (1) that higher values of *T* lead to better performance for the coupler. Some selected values of the input training parameters including calculated *T* in each case are summarized in Table 1.

Table 1: Selected values of the training data for the designing procedure

g	*a*	*b*	*s*	*e*	*d*	*W*	*T*
0.5	14	18	1	2	1	2	107
0.75	16	18	0.5	1	0.75	1.8	143
1	14	18	0.75	1.5	0.5	2.2	166
1.25	18	20	1.25	1.75	0.25	1.6	82
1.5	18	22	1.5	1.25	1.25	2.4	93
0.75	14	20	1	2.25	0.5	1.6	59
1	16	22	0.75	1	1	2	98

g, *a*, *b*, *s*, *e*, *d* and *W* in mm.

The proposed coupler is numerically investigated using HFSS, which is a software package for solving complicated electromagnetic structure based on finite element method (FEM). The three dimensional structure is defined in HFSS. Using a full wave analysis, it predicts scattering parameters of the structure. *BW*, MS_{11} and MS_{41} in Equation (1) are obtained using HFSS. Testing data are shown in Table 2, which confirms that the BPNN outputs agree well with those obtained by HFSS.

After training the applied neural network, optimum values of the inputs to obtain maximum value of *T* is determined. The obtained optimum parameters of the proposed coupler are summarized in Table 3, which lead to the total length of 0.56λ_g for the proposed coupler.

Table 2: Testing data for the designing procedure

g	*a*	*b*	*s*	*e*	*d*	*W*	*T* BPNN	*T* HFSS
1.2	15	19	0.9	2.4	0.4	1.9	161	155
0.7	17	21	1.3	1.1	0.8	1.7	110	109
1.1	16	20	0.6	1.4	0.7	2.3	89	98
0.8	18	22	1	1.7	0.35	2.1	147	140
1.4	14	18	1.5	1.9	1.1	1.8	96	101
0.7	16	19	0.5	2.4	1	2	29	32
0.8	17	20	1.4	1.5	0.4	2.1	133	128

g, *a*, *b*, *s*, *e*, *d* and *W* in mm.

Table 3: The optimum parameters of the proposed coupler

Parameter	Value (mm)	Parameter	Value (mm)
g	1	*d*	0.5
a	16	*W*	1.9
b	22	*l*	12
s	1	*h*	0.787
e	2.25	*t*	0.5

IV. RESULTS AND DISCUSSIONS

A. Simulated results

The simulated *S*-parameters of the designed coupler versus frequency using the optimized parameters are shown in Fig. 4. It can be seen that the proposed coupler provides 0.58 dB coupling with 1 dB flatness over the frequency range from 6.5 GHz to 14 GHz, which corresponds to 73.2% fractional bandwidth. Maximum simulated return loss and coupler directivity in pass band are 11.62 dB and 13.83 dB respectively. Using the obtained results, *T* is calculated, which is 180.3 using simulation process. This agrees very well with the value of *T* = 188.7, which is obtained by the BPNN network.

To verify the cause of the high coupling strength over the predicted bandwidth, one can calculate even- and odd-mode complex propagation constants and characteristic impedances of these modes, using Equations (2) and (3) respectively [8]:

$$e^{\gamma_i d} = \frac{1 - S_{11,i}{}^2 + S_{21,i}{}^2 + \sqrt{\left(1 + S_{11,i}{}^2 - S_{21,i}{}^2\right)^2 - \left(2S_{11,i}\right)^2}}{2S_{21,i}}, \tag{2}$$

$$\gamma_i = \alpha_i + j\beta_i$$
$$Z_i = Z_0 \sqrt{\frac{\left(S_{21,i}{}^2 - S_{11,i}{}^2 - 1\right) - 2S_{11,i}}{\left(S_{21,i}{}^2 - S_{11,i}{}^2 - 1\right) + 2S_{11,i}}}. \quad (3)$$

In the above equations, i corresponds to even- or odd-mode, and Z_0 represents port impedances which is normally 50 Ω. Moreover, the coupling strength can be calculated using Equation (4) in a backward coupler:

$$C_z = S_{31} = \frac{(Z_e - Z_o)\tanh(\alpha + j\beta)l}{2Z_0 + (Z_e + Z_o)\tanh(\alpha + j\beta)l}. \quad (4)$$

The variation of $\tanh(\alpha + j\beta)l$ versus frequency is plotted in Fig. 5. It can be seen that in pass band, this function is equal to 1, except from 10 GHz to 13 GHz; and so, the coupling in pass band is determined using Equation (5):

$$C_z = S_{31} = \frac{Z_e - Z_o}{2Z_0 + (Z_e + Z_o)}. \quad (5)$$

The simulated imaginary and real parts of even and odd impedances, Z_e and Z_o, are shown in Fig. 6. It can be seen that the real parts of the impedances are negligible in the pass band, except over the frequency range from 10 GHz to 13 GHz. In addition, the imaginary parts in this band have opposite signs, which lead to obtain tight coupling of 0 dB over the mentioned frequency range.

Moreover, over the frequency range of 10 GHz to 13 GHz, $\tanh(\alpha + j\beta)l$ is not equal to 1. However, in this case the imaginary and real parts of Z_e are much greater than the imaginary and real parts of Z_o respectively. Therefore, the coupling coefficient, C_z is equal to 0 dB over the mentioned frequency range.

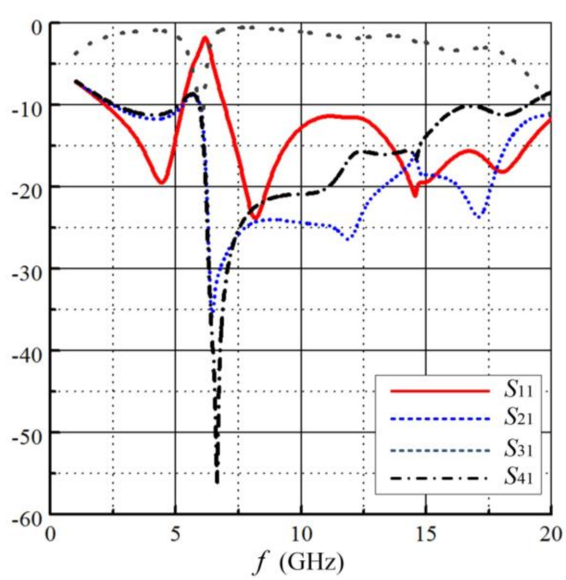


Fig. 4. The simulated S-parameters of the proposed coupler.

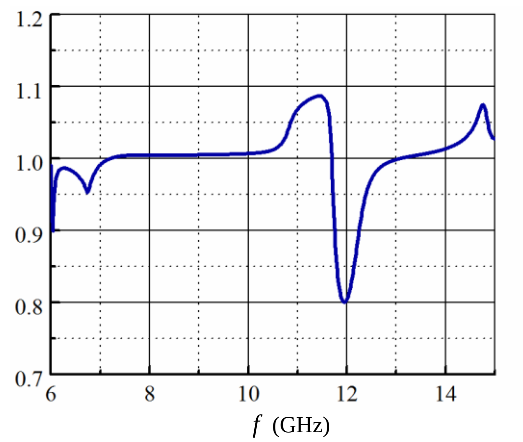


Fig. 5. Variation of $\tanh(\alpha + j\beta)l$ versus frequency.

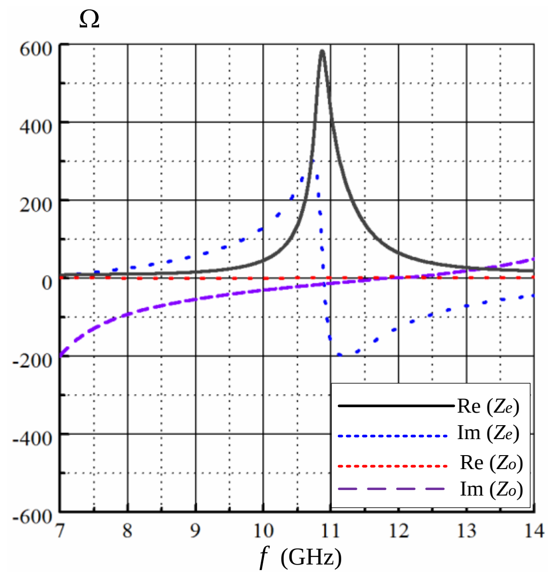
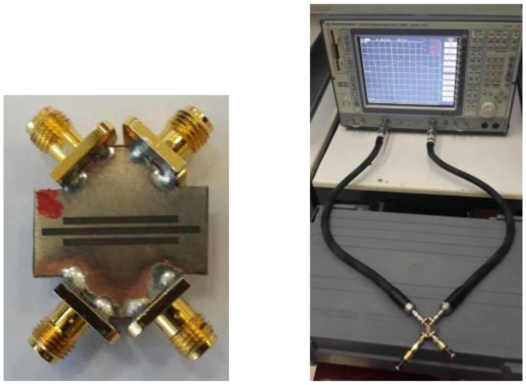


Fig. 6. The simulated imaginary and real parts of even and odd impedances versus frequency.

B. Measured results

To evaluate the designed procedure for the coupler, a prototype of the proposed coupler is fabricated using TLY031 substrate with electrical characteristics of ε_r=2.2, h=0.787 mm and loss tangent of 0.009. A photo of the fabricated coupler and the measurement test bench are shown in Fig. 7.

The measured results for the S-parameters of the designed coupler are shown in Figs. 8 (a) and 8 (b), including the simulation results for comparison. It can be seen that the measured coupling is 0.49 dB with maximum 2 dB variation over the desired bandwidth. In addition, measured return loss is better than 12.45 dB and measured directivity is better than 13.5 dB over the pass band. It can be seen that a very good agreement is obtained between measurement and simulation results.



(a) (b)

Fig. 7. (a)The photo of the fabricated proposed coupler, and (b) the measurement test bench.

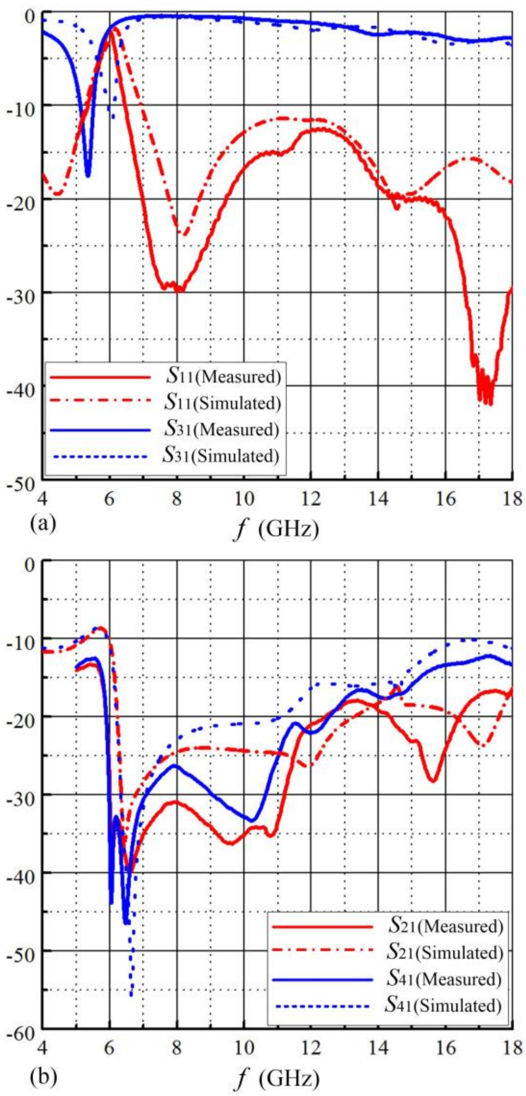


Fig. 8. The measured results of the proposed coupler: (a) S_{11} and S_{31}, and (b) S_{21} and S_{41}.

C. Comparison with the recently published research

The measured results of the proposed coupler are summarized in Table 4, including the measured performance of the recently published research of couplers for comparison. It can be seen that the proposed coupler provides a tight coupling over a very wide bandwidth with a reasonable short length. Although, it suffers from the low directivity compared to that of presented coupler in [14], but the obtained bandwidth is much more.

Table 4: Comparison of the measured results of the proposed coupler with the recently published research

Coupler	FBW (%)	Coupling (dB)	Directivity (dB)	Length (mm)
[9]	84.6	16.6	8	$1.85\lambda_g$
[10]	25.8	0.52	10	$1.50\lambda_g$
[11]	40.0	1.36	10	$7.67\lambda_g$
[12]	72.2	15.1	25	$0.50\lambda_g$
[13]	18.1	0	20	-
[14]	11.1	0	35	$2.26\lambda_g$
[15]	8.7	0.54	20	$0.50\lambda_g$
This paper	73.2	0.49	13.5	$0.56\lambda_g$

V. CONCLUSIONS

A new type of wideband backward-wave directional coupler is presented in this paper. The proposed coupler operates similar to the CRLH couplers. Two techniques, for the first time, including adding shunt inductance in odd mode and series capacitance in even mode are applied together to obtain a high performance and wideband coupler. Neural network based on the BPNN optimization procedure is used for designing process. The proposed coupler is also analyzed using HFSS software. A prototype of the proposed coupler is made and it is successfully tested. The measured results agree well with those obtained by simulation. It is shown that the coupling strength of 0.49 dB with maximum 2 dB flatness, return loss of better than 12.45 dB and directivity of at least 13.5 dB over the pass band are obtained. The proposed coupler provides the advantage of small size and high level of coupling over a very wide bandwidth and it is a good candidate in microwave and millimeter wave circuits.

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