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RESEARCH PAPER

A compact single layer branch-line coupler for ultra-wideband (UWB) applications

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This paper presents the design of a compact, planar, single layer, tri-section ultra-wideband (UWB) branch-line (BL) coupler. The prototype offers 10 dB return loss characteristics from 3.1 to 13.7 GHz. Over a major portion of the band, phase imbalance of ±10° is achieved. The method of deploying multi stage impedance feed has been used to achieve improved bandwidth. To enhance the power output through the coupled port throughout the operating band, ring shaped slots have been introduced in the ground plane beneath the series arms. The performance of the fabricated prototype has also been validated experimentally.

Keywords: Passive components and circuits, Modeling, Simulation and characterizations of devices and circuits

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I. INTRODUCTION

For commercial communication applications, the US Federal Communications Commission (FCC) allocated the ultra-wideband (UWB) spectrum, ranging from 3.1 to 10.6 GHz. According to FCC, UWB device is defined as any device, which has a fractional bandwidth greater than 0.25, or occupies 1.5 GHz or more of the spectrum [1]. Directional couplers are an integral part of several components in the UWB microwave commercial communication subsystems that include amplifiers, antenna array network, and balanced mixers [2]. A multilayer UWB directional coupler is realized using slot coupling method in [2, 3] with transmission lines (ports) in different layers. Further in [3], the fabrication complexity is increased, since it requires alignment of printed circuit boards (PCBs) with precision pins and linking with nylon screws. In [4], ultra broad band operation has been realized using multi-section hybrids with varying substrate thickness and additional special dielectric blocks. In [5], UWB is realized using coupled microstrip structures and a lumped capacitor.

The prime focus of the proposed work is to design a coupler that operates over a major portion of the UWB band, using a new simple transmission line technology, without the usage of multi-layered configuration, via holes or lumped components. Certain techniques have been proposed in literature to achieve wideband response in couplers within a single layer. In [6], wide band characteristics is obtained by connecting four open circuited quarter wavelength coupled lines at each feed of the conventional branch-line coupler. However, the transition between microstrip and coupled lines requires the installation of post and screws on the circuit board for mechanical stability.

Multi-section branch-line (BL) couplers are another interesting choice for achieving wideband response. Impedance bandwidth (10 dB return loss) ranging from 1.2 to 3.8 GHz is obtained using four sections of branch-line coupler in [7]. Bandwidth ranging from 1 to 3.8 GHz and 0.9–4.4 GHz is obtained using 6 and 10 sections of BL couplers in [8]. In both these works, the high impedance of the vertical arms is realized using defective ground structures (DGS). In [9], phase inverters and modified ports have been used in a two section coupler to obtain wide bandwidth equivalent to that in four sections. However, phase inverters require two vertical via connecting the signal and ground lines. Wideband dual layer substrate integrated waveguide (SIW) is responsible for providing the wide bandwidth in [10]. In [11], bandwidth ranging from 1.2 to 2.9 GHz is obtained using three sections of BL couplers and open stubs. In [12], bandwidth is enhanced by placing quarter wave transformers at each feed of a conventional single section BL coupler.

In the proposed work, a method of multi-stage impedance feed is employed to enhance the bandwidth of a three section coupler and to achieve wideband performance, covering a major portion of the UWB range and offering an effective bandwidth of over 6 GHz. In addition, a technique to improve coupling throughout the operating band by placing the ring shaped DGS elements in the series arm is implemented. The proposed single layer prototype covers the entire UWB range, with improved percentage bandwidth to number of sections ratio compared with [7, 8, 11].

The design and description of the coupler has been presented in Section II. The results and discussion about the results have been provided in Section III. Section IV concludes the paper.

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II. BL COUPLER DESIGN

The geometry of the proposed UWB BL coupler is shown in Fig. 1. The overall dimension of the coupler is 50 × 16 mm². The prototype is designed on a 0.8 mm thick FR-4 substrate with $\varepsilon_r = 4.3$ and tan $\delta = 0.025$. The ring shaped slot structures are introduced in the ground plane as shown in Fig. 1. 50 Ω coaxial connectors are used to feed the coupler. The lengths l_1 and l_2 (Fig. 1) have been modeled and optimized corresponding to $\lambda_g/4$ at the center frequency of the UWB range. w_1 and w_1' are optimized to obtain enhanced bandwidth.

A study on percentage bandwidth and circuit area variation for different number of coupler sections has been performed. The observations from the study have been presented in Fig. 2.

From Fig. 2, it can be observed that till three sections, both percentage bandwidth and circuit area increases with increase in number of coupler sections. Percentage bandwidth above 90% is achieved for three sections itself. Further, it is observed that there is minimal increment in percentage bandwidth for the four section coupler. Also the circuit area is more for four sections. Hence, the number of coupler sections is chosen to be three.

Further enhancement is provided by the multi-stage impedance feed. An impedance stage is the section of a transmission line with different impedance of that of preceding transmission line section as shown in Fig 3.

A study is performed to observe the effect of number of stages on the bandwidth performance and is depicted in Fig. 3. For a single stage feed a maximum bandwidth of 99% is observed when the impedance stage 1, is 50 Ω. For the two stage design, following the 50 Ω port, two impedance stages are incorporated (stage 1 and stage 2). Following a similar trend, maximum bandwidth of 129% is observed when the impedance of the three stages is fixed as 42, 53 and 64 Ω. The fractional bandwidth required for UWB operation is 109%. Since the two impedance stage itself provides sufficient bandwidth for UWB operation (Fig. 3), it is chosen for the final design.

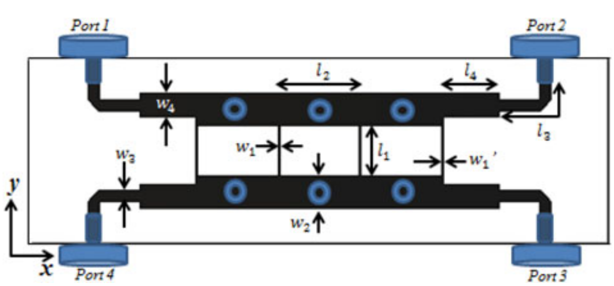

Fig. 1. Geometry of the proposed UWB coupler with slotted ground plane. $w_1 = w_1' = 0.2$ mm, $w_2 = 2.8$ mm, $w_3 = 1$ mm, $w_4 = 2.1$ mm, $l_1 = 4.4$ mm, $l_2 = 7.2$ mm, $l_3 = 8.14$ mm, $l_4 = 4.8$ mm, outer ring radius (R) = 0.8 mm, inner ring radius (r) = 0.6 mm.

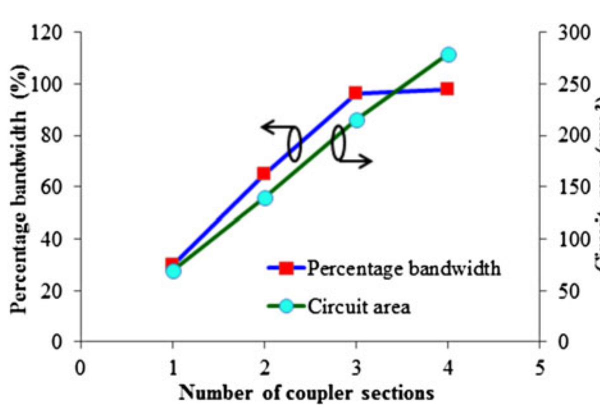

Fig. 2. Percentage bandwidth and circuit area for different number of coupler sections.

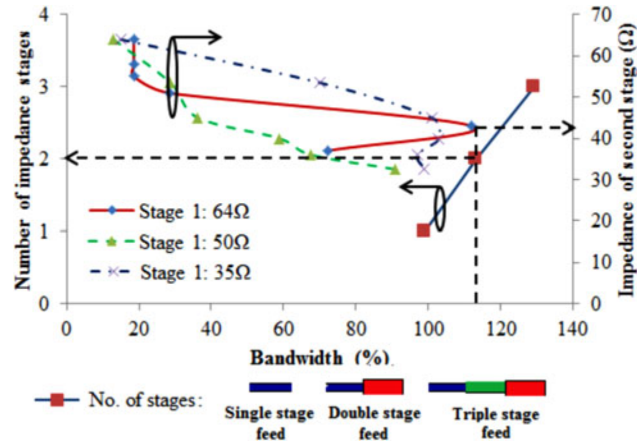

Fig. 3. Bandwidth performance with variations in number of stages and impedance of the second stage while fixing first stage impedance. Legends: stage 1: 64 Ω – solid line with circular marking, stage 1: 50 Ω – dashed line with triangular marking, stage 1: 35 Ω – dash dotted line with crossed marking, no. of stages – solid line with square marking.

For the double stage feed, a study is performed varying the impedance of stage 2, fixing the impedance of stage 1 as 35, 50 and 64 Ω, as shown in Fig. 3. Maximum bandwidth of 113% is observed when the impedance of stage 1 and stage 2 are fixed as 42 and 64 Ω, respectively, as depicted in the legends of Fig. 3.

Another study has been performed to choose the length of the impedance stage as observed in Fig. 4.

The graph (Fig. 4) represents the bandwidth corresponding to variation in length of l_3, keeping l_4 constant as 5 mm, and the bandwidth corresponding to variation in length of l_4, keeping l_3 constant as 5 mm. Bandwidth of 115% is obtained at the point of intersection of both the curves, where the length of both the stages is nearly 5 mm. After final optimization, l_3 and l_4 have been chosen as 5 and 4.8 mm, respectively (corresponds to $\lambda g/6$ at the center frequency).

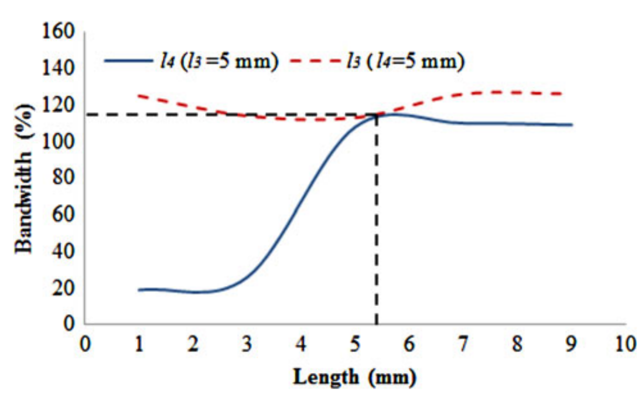

Fig. 4. Bandwidth performance with variations in length of the impedance stages.

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With enhancement in bandwidth, a reduction in power transferred to the coupled port has been observed. The power division to the through port (port 2) and coupled port (port 3) can be related using the power division ratio (k) [13].

$$k^2 = \left|\frac{S_{21}}{S_{31}}\right|^2. \qquad (1)$$

The power division ratio can be related to the impedance of the series arm (Z_1) and impedance of the shunt arm (Z_2) as,

$$k^2 = \left(\frac{Z_2}{Z_1}\right)^2 - 1. \qquad (2)$$

From the above two relations it can be inferred that the power transferred to the coupled port can be increased by increasing the impedance of the series arm. In [7, 8], the impedance of the shunt arm is increased by placing rectangular defects beneath the shunt arm. In the proposed work, the impedance of the series arm is increased by placing ring shaped DGS.

Based on the results obtained by varying the outer ring radius of the ring shaped slots, optimal value of 0.8 mm has been chosen as the outer ring radius, since it provided improved matching and isolation along with a better amplitude stability performance. The inner ring radius reduces the aperture size of the DGS, in turn reducing the radiations caused due to it.

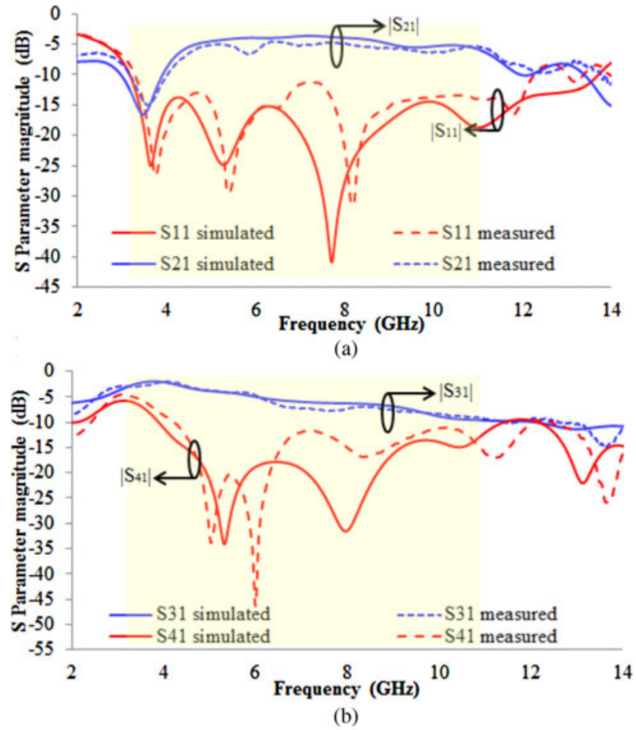

Fig. 6. Simulated and measured *S*-Parameter magnitude characteristics of the UWB BL coupler. (a) Simulated and measured |*S*11| and |*S*21| in dB (b) Simulated and measured |*S*31| and |*S*41| in dB. UWB range is highlighted.

III. RESULTS AND DISCUSSION

The front and rear view of the fabricated prototype is portrayed in Fig. 5. The commercial software package, CST Microwave Studio is the simulation tool used for designing the proposed multi-section BL coupler. The measurements are done using Agilent E8363B Vector Network Analyzer. The simulated and measured *S*-Parameter magnitude characteristics of the proposed UWB coupler are plotted in

Fig. 5. Photograph of the fabricated prototype (a) front view (b) rear view.

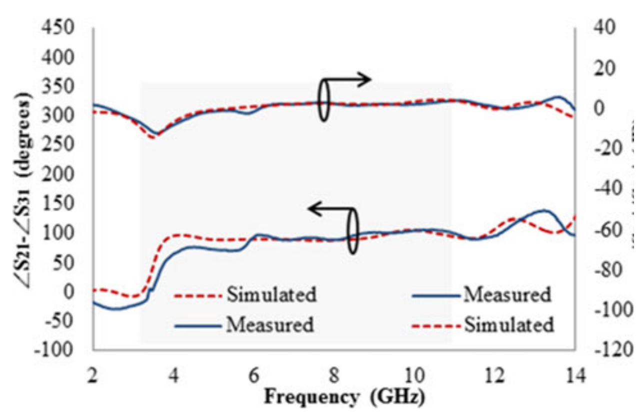

Fig. 7. Simulated and measured amplitude and phase stability plots of the proposed UWB multi-section BL coupler. UWB range is highlighted.

Fig. 6. A close correspondence between the simulated and measured values can be observed from the graph. The simulated and measured amplitude and phase stability plots of

Table 1. Performance comparison of proposed model with several other multi-section (MS) BL couplers reported in literature.

S. no.	Ref. no.	Technique proposed	No. of sections	Measured frequency range (GHz) (10 dB range of |S11|)	Bandwidth to no. of sections ratio (%)
1.	[7]	MS BL coupler with DGS	4	1.15 to 3.85	27
2.	[8]	MS BL coupler with DGS	10	0.88 to 4.03	12.8
			6	1.04 to 3.92	19.3
3.	[11]	MS BL coupler with open circuited stubs	3	1.2 to 2.9	27.3
				1.2 to 2.8	26.6
4.	Proposed	MS BL coupler with multiple impedance stage feed	3	3.3 to 12.2	38

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the proposed UWB BL coupler is depicted in Fig. 7. Flat amplitude and phase is observed over a major portion of the band.

A performance comparison of the proposed model with several other multi-section BL couplers is presented in Table 1. From the table it is evident that the proposed coupler provides improved bandwidth performance with minimal number of sections.

IV. CONCLUSION

The design of a tri-section UWB BL coupler deploying multi-stage impedance feed has been presented. Further, an analysis to observe the bandwidth performance with increase in number of stages of transformation is performed. The proposed coupler with two stage impedance feed offers an enhanced impedance bandwidth of 114.8%, covering the UWB range. It also offers an improved "bandwidth to number of sections ratio" of 38%. The prototype can be fabricated using the normal PCB manufacturing process without the requirement of multi-layer fabrication or via holes.

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