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A NOVEL BRANCH LINE COUPLER WITH DEFECTED GROUND STRUCTURE FOR BONE DENSITY MEASUREMENT ANALYSIS

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ABSTRACT

Microwave Integrated Circuits play a vital role in the Medical field for sensing applications. Two hundred million people are affected globally by musculoskeletal diseases, a substantial healthcare burden and one of the most costly diseases. Our proposed design is dedicated to the Bone Density Measurement Analysis (BDAS) RF system. This paper investigates the development of a directional - Branch Line Coupler with Defected Ground Structure (DGS) to differentiate between transmitted and reflected signals in the split ring resonator (SRR) sensor for Bone Density Measurement Analysis using the HFSS V13 design tool. The Coupler operates within the range of 2 GHz - 3 GHz frequency band with a high directivity of 55 dB. The proposed design is compared with a conventional branch-line coupler, and S-Parameters are calculated. The design is optimized in HFSS to meet the required specifications.

Keywords: bone density, branch line coupler, S parameters, microstrip lines.

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1. INTRODUCTION

The rapid development of microwave technology makes microwave devices and components more common compared to 10 years ago. Couplers are one of the critical devices which have applications in the design of microwave devices [1]. A directional coupler is generally a four-port device, often with a good load on the fourth port, but in practice, a load element is always permanently attached [2]. Of many microwave circuits, Branch Line Coupler is suitable for low-cost fabrication. They couple a defined amount of electromagnetic power in a transmission line to a port enabling the signal to be used in another circuit. They are commonly used for high return loss and power combinations in balanced amplifier circuits and mixers.

In the medical field, microwave-integrated circuits play an essential role in sensing applications. The design of a microwave-based sensor for the muscle analyzer system was proposed [3]. A microwave sensor is designed to monitor Intracranial Pressure (ICP) in a non-invasive method [4] and Osseointegration Analysis with proximity coupled Split Ring Resonator (SRR) [5].

This coupler has a tunable high directivity circuit to measure the reflected RF power [6]. A 3-dB coupler using microstrip to coplanar waveguide via hole transitions is proposed [7]. A high-directivity single and dual-band directional coupler operating at 2.35 GHz and 0.8/2.35 GHz are designed based on substrate-integrated coaxial line [8]. A multi-band directional coupler for front-end RF application with a low power loss of less than -21dB [9]. Miniaturized dual-band directional coupler with folded stubs operating at frequencies 0.9 and 2 GHz [10]. A multi resonant directional coupler in the range of 3 to 9 GHz with an open-circuit stub is proposed [11]. Directional couplers separate forward and reverse waves in a transmission system. A microstrip-fed split ring resonator antenna is designed for Osseo integration analysis of skull implants [12]. The designed Coupler has a suitable impedance matching with the Split Ring Resonator (SRR) [13] sensor used in the Bone Density Measurement Analysis System (BDAS) [14] project. The designed Coupler reads the reflected signal from the SRR sensor.

2. CHARACTERISTICS OF BRANCH LINE COUPLER

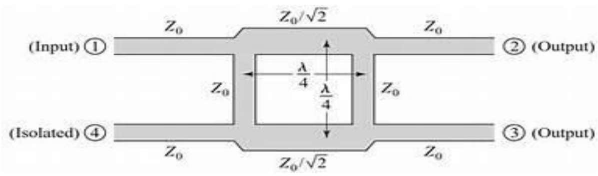

Figure-1. Geometry of typical branch line coupler.

The Basic Branch line coupler comprises four ports, as shown in Figure-1.
The first port is the input port. (Incident)
Port 2 is the output port (Transmitted)
Port 3 is the coupled port (Forward Coupled Port)
Port 4 is the isolated port. (Reverse Coupled Port)

Terms in brackets refer to alternative names for ports that may give little more explanation of coupler port. Typically the main line is the one between Port 1 and Port 2. The other ports are intended to carry a small portion of mainline power. Port 3 and Port 4 may even have small connectors to distinguish them from the mainline ports of Coupler.

Due to the high degree of symmetry, any port can be used as the input port, the other port on the same side will be the isolated port, and the output ports will be on the opposite side of the junction from the input port [15]. A Branch line Coupler is a 3 dB directional coupler with a

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90° phase difference in the output of the through and coupled arms. The bandwidth of branch-line Coupler is limited to 10 - 20 %, which can be applied only for narrow band circuits [16]. It is composed of four-quarter wavelength transmission lines. The Characteristic Impedance of the shunt arm is 50 ohm. The characteristic impedance of the series arm is reduced by $1/\sqrt{2}$, i.e. 35.35 ohms. The characteristic impedance of the mainline and shunt branches of the branch line coupler can be computed using the given equations.

$$Z_{0s} = Z_0 \, |S_{21}| = Z_0 \sqrt{1 - |S_{31}|^2}$$

$$Z_{0p} = \frac{Z_{0s}}{|S_{31}|} = \frac{Z_{0s}}{\sqrt{1 - |S_{21}|^2}}$$

3. DESIGN OF CONVENTIONAL COUPLER

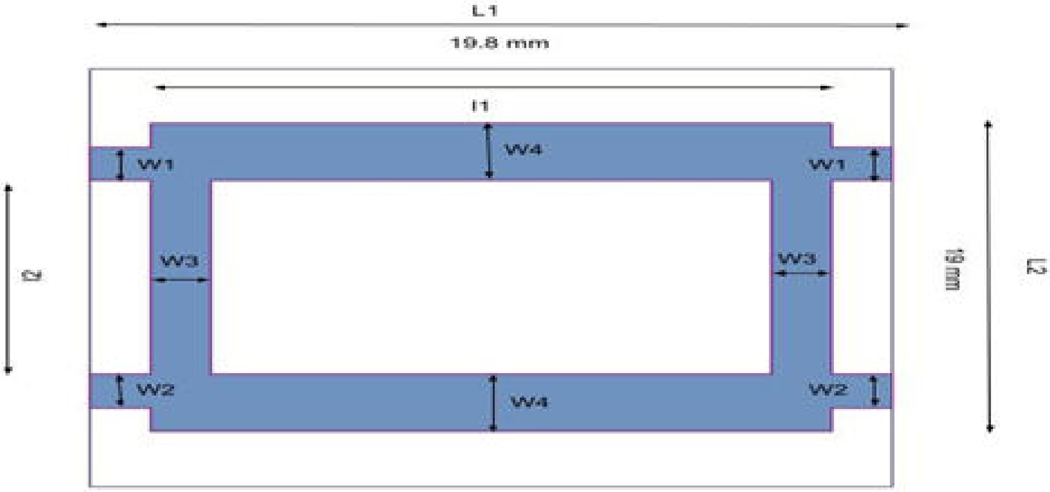

Figure-2. Geometry of conventional Coupler.

The Topology of the conventional Branch line coupler is shown in Figure-2. L1 is a series arm connecting Port 1 and Port 2. The arm connecting Port 3 and Port 4 is also a series arm. L2 is a shunt arm connecting Port 1 and Port 4. The arm connecting Port 2 and Port 3 is also a shunt arm. This branch line coupler design has symmetrical characteristics with L1=L2. The length and width of feeding lines, as well as shunt and series arm, is calculated using above mentioned design equations which are defined based on a theoretical study by R.K.Moniga *et al.* [17].

The design layout is shown in Figure-2, with dimensions shown in Table-1.

$$W = \left(\frac{e^H}{8} - \frac{1}{4e^H}\right)^{-1} . h$$

$$L = \left(\frac{Z_0 \sqrt{2(\varepsilon r - 1)}}{119.9}\right) + \frac{1}{2}\left(\frac{\varepsilon r - 1}{\varepsilon r + 1}\right)\left(\ln\left(\frac{\pi}{2}\right) + \ln\left(\frac{4}{\pi}\right)\right)$$

$$\lambda g = \frac{c}{f\sqrt{\varepsilon eff}}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2}\left(1 - \frac{1}{2H}\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\right)\left(\ln\left(\frac{\pi}{2}\right) + \frac{1}{\varepsilon_r}\ln\left(\frac{4}{\pi}\right)\right)\right)^{-2}$$

Table-1. Dimensions of the conventional coupler.

Symbol	W1 = W2=W3	W4	l1	l2
Value (mm)	1.5	2.1	16.8	13

The Total dimension of the Coupler is 19.8 x 13 mm^2. The length of the primary arm L1 is 19.8 mm. The length of the side arm is 19 mm. The width of the main arm is 2.1 mm. The width of the side arm is 1.5 mm. The substrate used for simulation is FR4 with a thickness of 1 mm, and copper cladding of 35 µm. The size of the Conventional Branch line coupler is enormous at lower frequencies. If dimensions of the branch line coupler are reduced, then bandwidth is also reduced. However, an increase in dimension causes the frequency to decrease, and the low width of the Branch line coupler causes an increase in permittivity. Hence to reduce these issues, FR4 substrate with the dielectric constant of 4.4 is used.

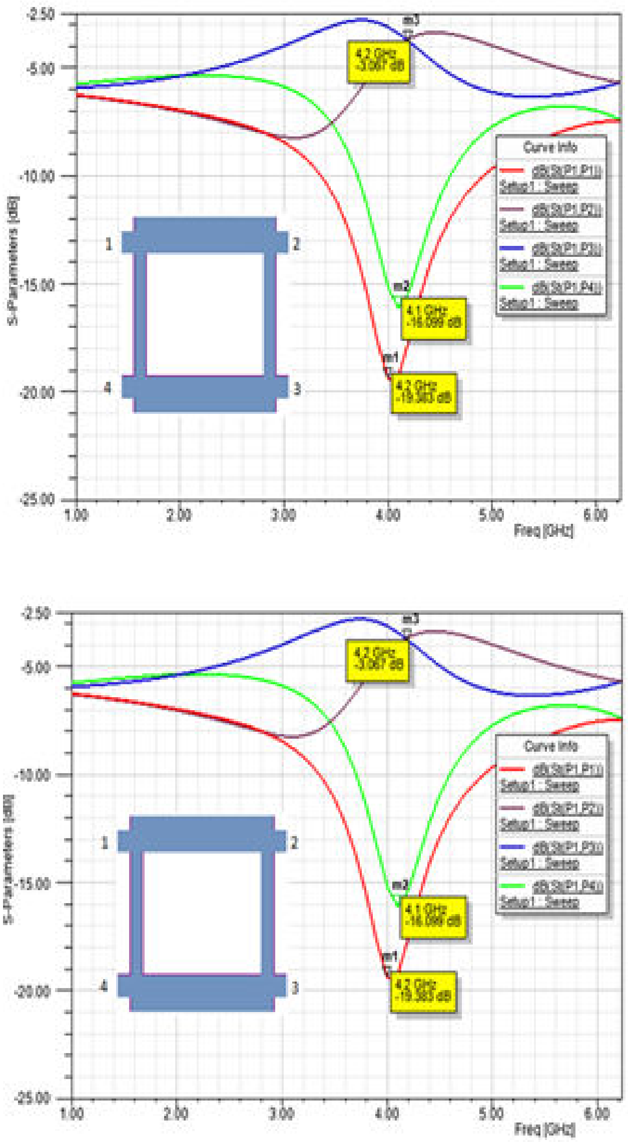

Figure-3. Simulated S-Parameters of conventional coupler.

Figure-3 depicts the simulated results of the conventional Coupler. There are four curves which are indicated in different colours. Each of the results is assessed in terms of

- Return loss (S_{11})
- Insertion loss (S_{21})
- Isolation (S_{41})
- Coupling factor (S_{31})

We can notice that the Reflection coefficient of Return loss S_{11} is -19.38 dB. The directivity coefficients S_{21} and S31 are in the range of best requirement results which are - 3 dB ± 1.5 dB, around -3.06 dB. Isolation S14 is -16.09 dB. Enhancements in these parameters are discussed in the proposed coupler section.

3.1 Phase error analysis

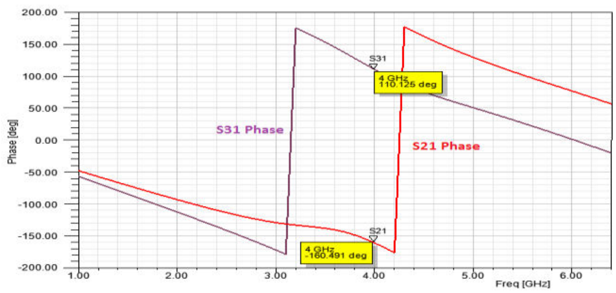

Figure-4. Phase Error Analysis.

The phase Error analysis is an essential measurement for Coupler when it is subjected to oscillations of microwave source. Figure-4 shows the phase error analysis. From Figure-4.4, we can notice sharp changes near the frequency of interest.
Phase difference = 270.62 deg

4. PROPOSED DESIGN

It is seen that there is a physical discontinuity present at each port. It should be considered in evaluating the performance of the circuit. The key of the proposed design is substituting the quarter wavelength branch-line coupler with an equivalent section that exhibits desirable characteristics at the centre frequency.

The proposed design of the Branchline coupler is dedicated to applying in the RF System of the Bone Density Measurement Analysis. Figure-5 depicts the proposed branch-line coupler. The design comprises perfect Serpentine as shown in Figure-5(a) and etched on the ground plane as shown in Figure-5(b). Due to its simple structural design, DGS has been used in various microwave circuits to enhance the parameters, and increase coupling coefficient. Etched slots or defects in the ground plane of the microstrip circuit are referred to as Defected Ground Structure (DGS) [18]. It is incorporated in the Ground plane of the branch line coupler, which limits the current distribution and gives rise to increase capacitance. Inductance is one of the most exciting areas of research.

The occupied area of the proposed Coupler is 0.41 $\lambda g \times$ 0.21 λg (24 mm × 12mm). The length of the main arm is 24mm, and the Sidearm length is 12mm.

The layout of the design's front view is shown in Figure-5 (a), with dimensions shown in Table-2.

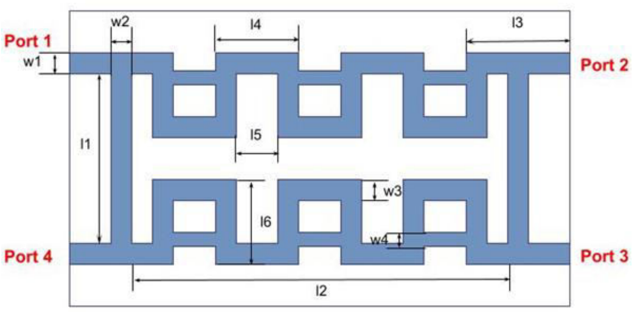

Figure-5. (a) Front view of proposed design.

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Table-2. Dimensions of the proposed coupler.

Symbol	$w_1 = w_2 = w_3$	w_4	l_1	l_2	l_3	$l_4 = l_6$	l_5
Value (mm)	1	0.65	10	18	5	4	2

The Total dimension of the Coupler is 24 × 12mm^2. The length of the primary arm L1 is 10 mm. The length of the side arm is 18 mm. The width of the feeding lines, main arm and side arm is constant (1 mm).

This design comprises of inward serpentine structure in the main arm. The number of folds in this design is 5. The folded length is 4 mm Folds represent the simple strip displacement (two 90-degree bends). Stubs of width 0.65 mm are added in the central arm's odd folds (Fold 1, 3, 5). The stub is the length of the transmission line or waveguide. Several folds and stubs decide the shape factor and value ofS_{11}, S_{21}. Several stubs improve the insertion loss, but the size also increases as many stubs increase. So the number of stubs should be chosen minimum, provided the insertion loss should be minimum and high selectivity.

The layout of the back view of the proposed design is shown below in Figure-5(b), with dimensions shown in Table-3.

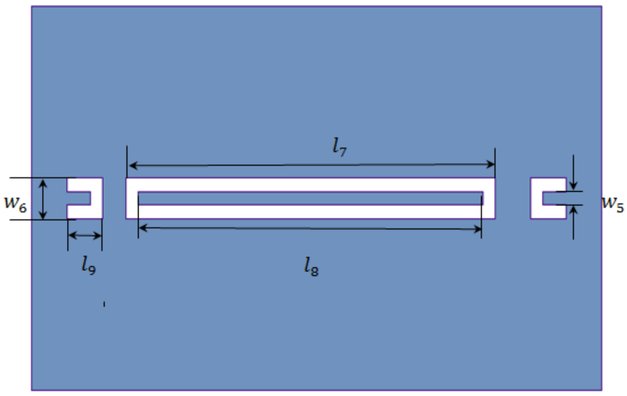

Figure-5. (b) Back view of proposed design.

Table-3. Dimensions of the back view of the proposed coupler.

Symbol	w_5	w_6	l_7	l_8	l_9
Value (mm)	0.5	1.5	15.5	14.5	1.5

Pair of U-shaped DGS is etched along with a rectangular slot on the ground plane. U Shaped DGS can be seen as a transformation of the Conventional Dumbbell DGS.

5. SIMULATED RESULTS OF BRANCH LINE COUPLER WITH AND WITHOUT DGS

The designed Coupler is simulated in HFSS V13. The size of the Conventional Branch line coupler is huge at lower frequencies. If dimensions of the branch-line coupler are reduced, then bandwidth is also reduced. However, an increase in dimension causes the frequency to decrease, and the low width of the Branchline coupler causes an increase in permittivity. Hence, an FR4 substrate with a dielectric constant of 4.4 is used to reduce these issues. The proposed Coupler operates at 2.5 GHz. The simulated S parameters of Branchline Coupler with and without DGS are shown in Figure-6(a) and Figure-6(b), respectively. Each result is assessed in terms of Return loss, Insertion loss, Isolation, and Coupling factor. From Fig (a), the reflection coefficient of return loss S11 is -22.235 dB. The directivity coefficient S21 is -3.523 dB. Coupling factor S31 is -3.523dB. Isolation loss S41 is -41.3 dB

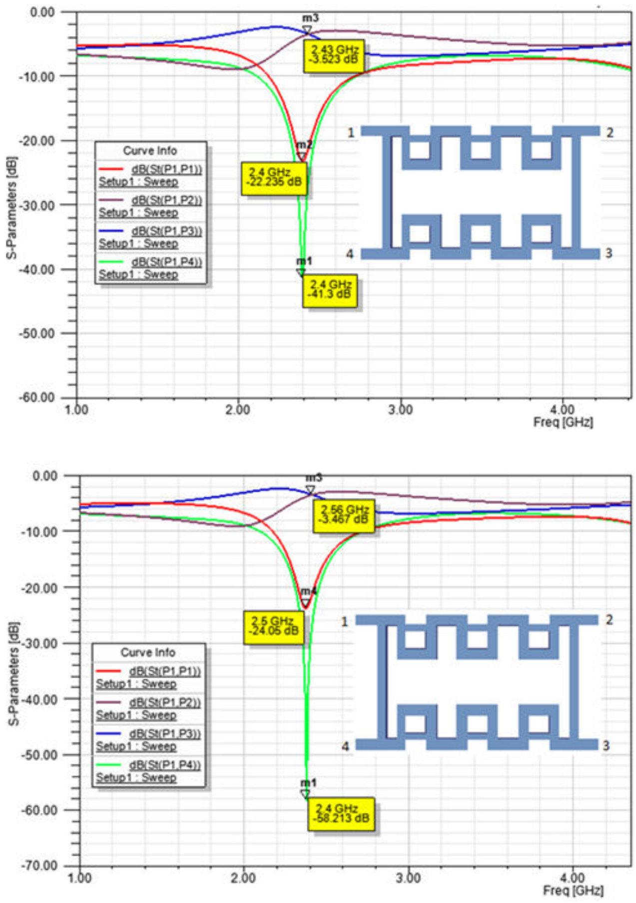

Figure-6. Scattering parameter analysis of proposed branch line coupler with and without DGS.

The simulated S parameters from Figure-6. We can notice that directivity coefficient S_{21} and Coupling factor S_{31} are in the range of best requirement results which are - 3 dB ± 1.5dB.

- Reflection coefficient of Return loss S_{11} is -24.05dB.
- The directivity coefficient S_{21} is -3.467dB.

- Coupling factor $S_{31}$is -3.467dB.

- Isolation loss S_{41} is -58.213dB.

Comparing the results, it can be observed that Insertion loss and Coupling (S21 and S31) are in the range of best requirement results which are - 3 dB ± 1.5 dB. However, Coupler with DGS shows better performance as Isolation reaches -58.213dB and Return loss reaches -24.05dB. Optimizations in the transmission line by modifying the length and width of the series arm and shunt arm are done to obtain the best Isolation value.

Comparing the Conventional Coupler and the Proposed Coupler, we notice an enhancement in all the parameters. A maximum Directivity of 55.035 dB has been measured, an improvement over Conventional Branch Line Coupler. This result is as expected as implementing branch line Coupler with DGS increases the performance of Coupler.

5.1 Directivity

The performance of a coupler is computed using the Directivity factor. The directivity is a calculated parameter from the isolation and coupling factors. The performance of a directional Coupler is usually evaluated by its directivity between port 3 and port 4. Calculated Directivity [D] as 55.035

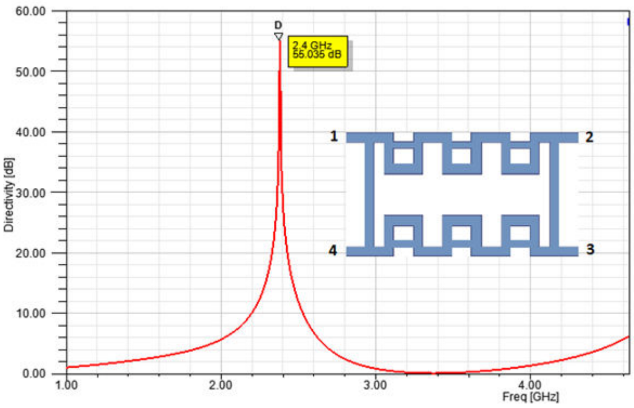

Figure-7. Directivity of proposed branch line coupler.

5.2 Phase Error Analysis

The phase Error analysis is an important measurement for Coupler from Figure-6.5 we can notice sharp changes near the frequency of interest. Phase difference = 274.2 deg

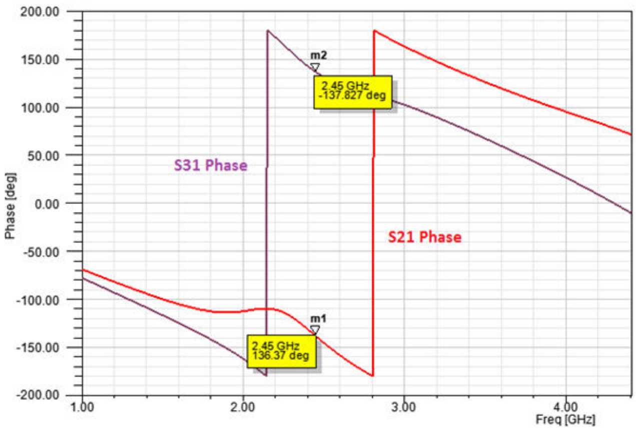

Figure-8. Phase difference of proposed branch line coupler.

Table-4. 13 Bandwidth summary of simulated results.

S-Parameter	Frequency (GHz)		Bandwidth (%)
S11	f_H	3	22.95
	f_L	1.88	
S21	f_H	3.4	19.88
	f_L	2.32	
S31	f_H	2.52	21.154
	f_L	1.64	
S41	f_H	3.22	27.52
	f_L	1.83	

6. APPLICATION OF PROPOSED BRANCH LINE COUPLER

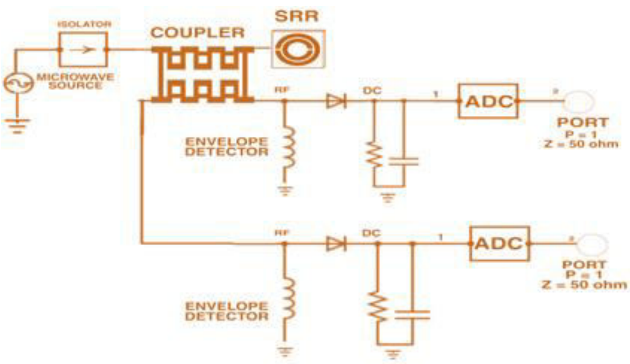

Figure-9. Application of proposed branch line coupler.

In this section, Radio Frequency (RF) system design using a directional coupler, envelope detector, Analog to digital converter, isolator, and signal source.is depicted. Figure-10 shows a detailed schematic of the device block connection. The function of the microwave source is to produce an alternating voltage with a frequency defined by the analysis frequency. The device should be set up for reading the frequency characteristics from the split-ring resonator (SRR). The signal from the microwave source passes through an isolator implemented with low forward insertion loss and reverse isolation, which makes the signal travel in the forward direction only. The function of the directional Coupler places a very important role in this system design to read the reflected signal from the SRR.

7. CONCLUSIONS

A Branch line coupler operating at 2.5 GHz is designed and measured for sensing aapplication The proposed design is a symmetrical configuration of perfect Serpentine and Rectangular slot with U shaped Defected Ground Structure. The design is fabricated on FR4 substrate. The results are optimized as per the requirement this work shows improvement over conventional branch line coupler and provides key parameters to tune Coupler. A maximum Directivity of 55.035 dB has been measured which is an improvement over Conventional Branch Line Coupler. The main goal of this work is to design a coupler that would be useful in measuring system of SRR of BDAS.

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