Pin diode-based variable directional coupler

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PIN DIODE-BASED VARIABLE DIRECTIONAL COUPLER

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ABSTRACT: *Analysis and design of a novel variable directional coupler based on a parallel line directional coupler using the even-odd mode technique are proposed. In this coupler, the variation of coupling is achieved using a PIN diode, connected to the nominally coupled port of a parallel line directional coupler, while the output is derived from the normally isolated port. To verify the theory, a parallel microstrip line coupler is fabricated on a substrate with $\varepsilon_r = 3.66$, $h = 762$ μm, and $\tan\delta = 0.006$ and measured. The measured results show a variation in the transmission coefficient of nearly 20 dB, while at the same time, the change in the direct arm insertion loss is lower than 0.2 dB.* Microwave Opt Technol Lett 54:2643–2646, 2012; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.27151

Key words: *coupled transmission lines; directional couplers; PIN diode; variable directional coupler; varactor*

1. INTRODUCTION

The interest in tunable radio frequency (RF) passive components has increased in recent years, driven by the need of high integration and cost minimization of the overall transmission system.

Tunable directional couplers attracted attention in the 1980s driven by the requirement of adaptive power control monitoring [1]. As an example, base station RF front-ends require constant power monitoring as a means of control of interference to other users and, also, for adequate measurements of the received power. More specifically, optimum detection accuracy depends on the appropriate amount of sampled RF power coupled into the monitoring circuit [2, 3]. Furthermore, tunable directional couplers can be used in the design of baluns with tunable impedance transforming ratios [4].

In the design of tunable couplers for power monitoring purposes, it is essential that the coupling is loose so that the power in the direct port shows little or no variation with the changes in the coupling coefficient. In this way, the amount of coupled power needed for optimum detection can be provided without a significant influence on the power in the direct port. This is different from the requirement imposed on conventional PIN diode-based amplitude modulators [5]. PIN diode amplitude modulators are essentially variable attenuators, and usually require a tight coupling coefficient normally provided in the form of a 3-dB coupler with PIN diodes placed in the circuit of the reflection loads.

In this article, a novel variable directional coupler configuration based on a parallel microstrip line directional coupler with loose coupling is proposed. Here, the nominally coupled port of the coupler is terminated in a variable resistance device (PIN, field effect transistor (FET), and microelectronic mechanical system (MEMS)) while the output is taken from the normally isolated port. By varying the termination resistance of the coupled port, the amount of RF power reflected on the nominally coupled port toward the nominally isolated port is also varied. By ensuring that the coupling coefficient is loose, variations of coupling against the termination resistance of the coupled port are achieved, with minimal changes to the power in the direct port. As an experimental verification, a variable directional coupler based on a parallel microstrip line coupler operating at 2.5 GHz is fabricated on a Rogers [6] material, and a PIN diode is used as a variable resistance device (switch). The results are discussed.

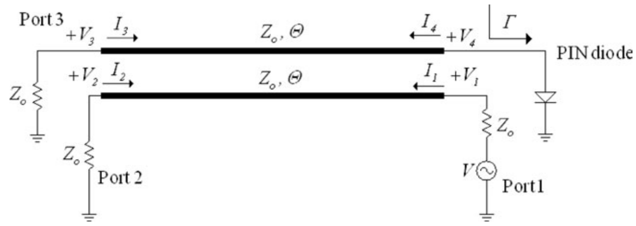

Figure 1 PIN diode-based variable directional coupler

2. THEORY AND ANALYSIS

Figure 1 shows a schematic of the proposed PIN diode-based variable directional coupler. It consists of a parallel microstrip line coupler, with a PIN diode (variable resistance) connected to the normally coupled port. The use of PIN diodes as variable resistances is widely known; its high frequency equivalent circuit is given in Figure 2 [7]. Here, R_I stands for the current controlled variable resistance of the intrinsic layer of the diode, while C_I, L_P, and R_P represent the parasitics of the diode. In particular, C_I is a constant capacitance dependent on the geometry of the diode, and L_P and R_P are the package inductance and resistance, respectively. Usually, in a well-designed PIN diode, the parasitic elements (C_I, L_P, and R_P) are small enough to be neglected and, therefore, a PIN diode can be adequately represented as a current controlled variable resistance, R_I.

Due to the fact that the symmetry of the proposed coupler of Figure 1 is disrupted by the presence of the PIN diode, the even- and odd-mode analysis is performed for the general case using a four-port model. The four-port transmission *ABCD*-matrix of a system of two identical lossless transmission lines in an inhomogeneous dielectric medium can be written as

$$\begin{bmatrix} V_1 \\ V_4 \\ I_1 \\ I_4 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & b_{11} & b_{12} \\ a_{21} & a_{22} & b_{21} & b_{22} \\ c_{11} & c_{12} & d_{11} & d_{12} \\ c_{21} & c_{22} & d_{21} & d_{22} \end{bmatrix} \begin{bmatrix} V_2 \\ V_3 \\ -I_2 \\ -I_3 \end{bmatrix} \quad (1)$$

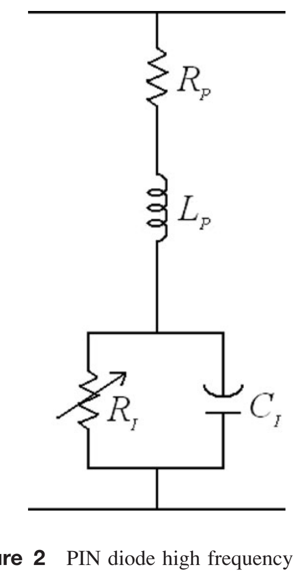

Figure 2 PIN diode high frequency circuit

where

$$a_{11} = a_{22} = d_{11} = d_{22} = \frac{1}{2}(\cos\theta_e + \cos\theta_o)$$
$$a_{12} = a_{21} = d_{12} = d_{21} = \frac{1}{2}(\cos\theta_e - \cos\theta_o)$$
$$b_{11} = b_{22} = \frac{j}{2}(Z_{0e}\sin\theta_e + Z_{0o}\sin\theta_o)$$
$$b_{12} = b_{21} = \frac{j}{2}(Z_{0e}\sin\theta_e - Z_{0o}\sin\theta_o)$$
$$c_{11} = c_{22} = \frac{j}{2}(Y_{0e}\sin\theta_e + Y_{0o}\sin\theta_o)$$
$$c_{12} = c_{21} = \frac{j}{2}(Y_{0e}\sin\theta_e - Y_{0o}\sin\theta_o)$$

where $Y_{0e} = 1/Z_{0e}$ and $Y_{0o} = 1/Z_{0o}$, Z_{0e}, and Z_{0o} are the even- and odd-mode characteristic impedances,θ_e and θ_o are the even- and odd-mode electrical lengths of the transmission lines, respectively [8]. In a homogeneous dielectric medium, the electrical lengths for even and odd modes are equal, that is, $\theta = \theta_e = \theta_o$. In this case, the coupling coefficient C between the coupled transmission lines can be written for $\theta = 90°$ as

$$C = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}} \tag{2}$$

where $C = 0$ for zero coupling and $C = 1$ for completely superposed transmission lines.

Imposing the boundary condition of $I_4 = -I_4$ (the formal change of current direction required by the *ABCD*-parameters) in Eq. (1) results in the following *ABCD*-parameters of the remaining two-port network where Port 1 is an input port and Port 3 is an output port:

$$A = \frac{c_{11}b_{11}R}{c_{12}RZ_0 + b_{12}} + a_{12}B = \frac{b_{11}^2}{c_{12}RZ_0 + b_{12}} + b_{12}$$
$$C = \frac{c_{11}^2RZ_0}{c_{12}RZ_0 + b_{12}} + c_{12}D = \frac{c_{11}b_{11}Z_0}{c_{12}RZ_0 + b_{12}} + a_{12} \tag{3}$$

where $Z_0 = (Z_{0e}Z_{0o})^{1/2}$.

Hence, the voltage transmission coefficient (coupling) S_{31} between the matched source (Port 1) and coupled Port 3 can be written as

$$S_{31} = \frac{2}{A + B/Z_0 + CZ_0 + D} = jC\sqrt{1 - C^2}\frac{Z_0 - R_I}{Z_0 + R_I} \tag{4}$$

which proves that no power appears at Port 3 when $Z_0 = R_I$ and maximum coupled power transmission to Port 3 is provided when $R_I = 0$ or ∞, that is, when the PIN diode is either completely switched ''OFF'' or fully switched ''ON.''

Similarly, the voltage transmission coefficients S_{21} between the matched source (Port 1) and the through port (Port 2) can be written as

$$S_{21} = -j\sqrt{1 - C^2} \tag{5}$$

which is independent of the PIN diode resistance, R_I , at Port 4. The isolation (coupling between Port 3 and Port 2) is now

$$S_{32} = -C\frac{Z_0 - R_I}{Z_0 + R_I} \tag{6}$$

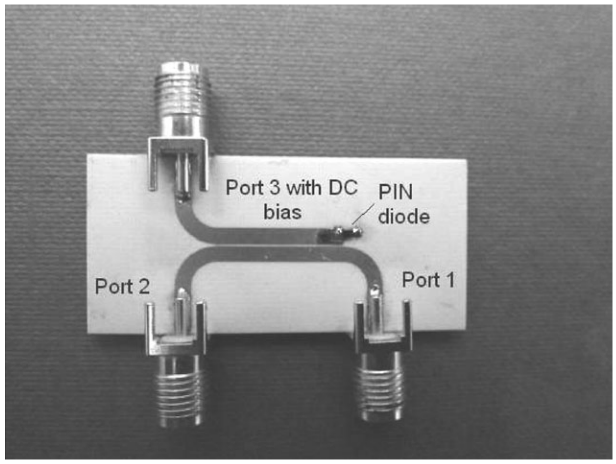

Figure 3 Fabricated microstrip variable directional coupler with PIN diode

which shows that the isolation between Port 3 and Port 2 is optimum, that is, 0 when $Z_0 = R_I$, while, when $R_I = 0$ or ∞, the magnitude of isolation becomes equal to the coupling coefficient, C.

3. RESULTS

On the basis of the equations of the previous section, a coupled microstrip line coupler is designed and fabricated at a centre frequency of 2.5 GHz. In the fabrication, a commercially available dielectric substrate, RO4350B from Rogers [6], was used. This material has the following characteristics, $\varepsilon_r = 3.66$, $h = 762$ μm, tan$\delta = 0.006$, and copper thickness $h_c = 17$ μm. The width of the electrodes is $w = 1770$ μm, corresponding to the characteristic impedance of 50 Ω. The coupling coefficient for the case of a 50-Ω terminated coupled port is set to 13.3 dB, corresponding to a coupling gap of 200 μm.

The fabricated directional coupler is shown in Figure 3. A PIN diode used in the measurements is a diode from Skyworks [9], with a part number, SMP1345-79. According to the manufacturer's datasheet, this diode possesses a low DC resistance of about 2 Ω at a bias current of 10 mA. The RF performance of the diode is measured at the frequency of 2.5 GHz and its reflection coefficient, referenced to 50-Ω, is given in Figure 4. In this figure, the *x*-axis, indicating the bias current from 0 to 10 mA, is plotted on the logarithmic scale to facilitate the viewing. This figure indicates that at lower bias currents (within 2–9 μA) the PIN diode absorbs RF energy with a reflection coefficient lower than −10 dB. Outside this bias current range, the majority

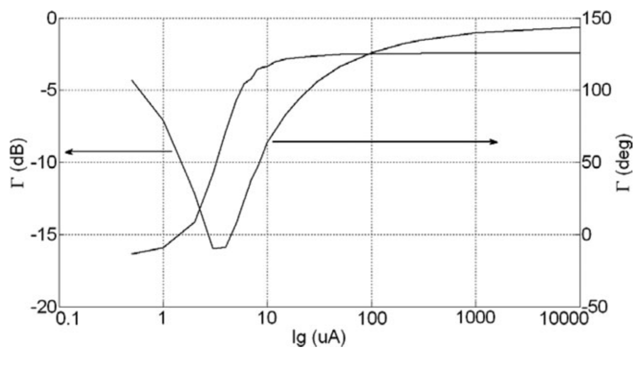

Figure 4 Measured reflection coefficient of diode versus bias current at 2.5 GHz

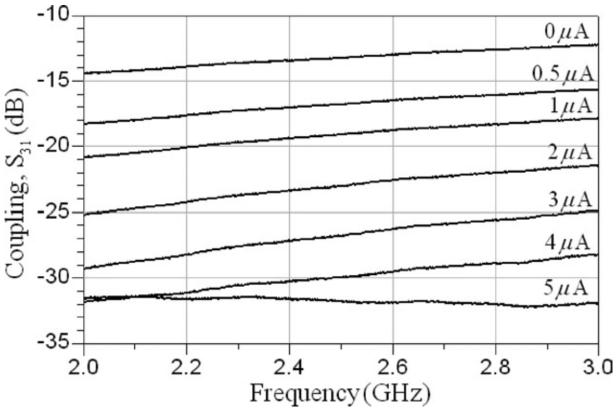

Figure 5 Measured coupling of proposed coupler versus bias current

of the incident RF power is reflected; however, the phase of the reflected signal is dependent on the magnitude of the DC current applied to the diode. For this particular diode, the phase of the reflected signal in the low current-bias region (0–2 μA) varies from -15 to -10 degrees, whereas the phase of the reflected signal in the high current-bias region varies from 118 to 125 degrees.

The existence of the low reflection region of the PIN diode in Figure 4 is used in the design of a variable directional coupler. The PIN diode of Figure 2 is connected to the coupled port of the coupler of Figure 3, and the S-parameters are measured for

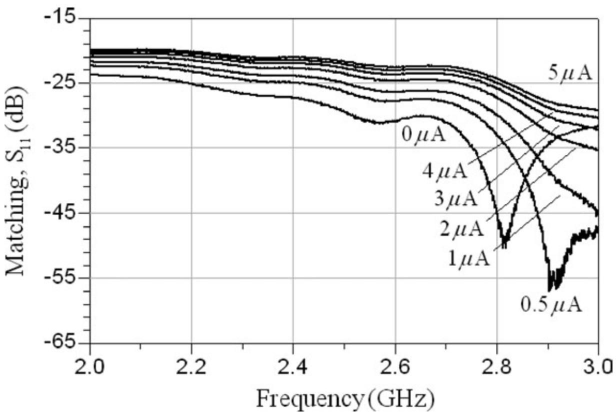

Figure 6 Measured input reflection coefficient of proposed coupler versus bias current

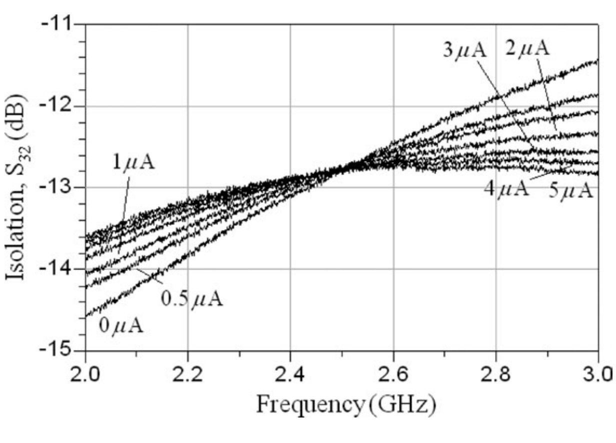

Figure 7 Measured isolation of proposed coupler versus bias current

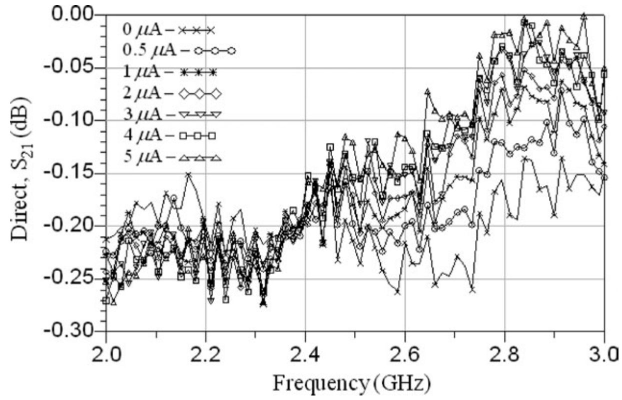

Figure 8 Measured insertion loss in direct arm of proposed coupler versus bias current

TABLE 1 Power Consumption of Variable Directional Coupler for Different Coupling Levels Indicated by Figure 5

I_g (μA)	0	0.5	1	2	3	4	5
P (μW)	0	0.27	0.58	1.23	1.9	2.58	3.27

the cases when the bias current is varied from 0 to 10 mA. The bias current is supplied through a wideband bias tee, at Port 3.

The measured performance of the coupler is presented in Figures 5–8, for the case when the bias current is varied within 0–5 μA. The measurements at higher bias currents are not presented as they mirror the performance at lower bias currents with respect to the high attenuation region at 5 μA. The measured coupling coefficient S_{31} shows a variation of nearly 20 dB across the frequency range of 2–3 GHz, while the measured variation of the insertion loss is about 0.2 dB. The reflection coefficient at the input S_{11} shows that matching levels below -17 dB are maintained throughout the indicated frequency range, while isolation, S_{32}, is lower than -11 dB.

The power consumption of the PIN diode for the coupling levels indicated by Figure 5 is given in Table 1. The power consumed by the PIN diode is dependent on the coupling coefficient, and the maximum power consumed by the PIN diode is 3.27 μW at a bias current of 5 μA, which coincides with lowest coupling levels of about 30 dB.

4. CONCLUSION

The design and performance of a PIN diode-based variable directional coupler has been presented in this article. In this design, the normally coupled port of a loosely coupled directional coupler is terminated in a PIN diode, while the output was taken from the usually isolated port. The PIN diode in the circuit of the coupled port provides a means of control of the amount of RF power emanating from the isolated port by either absorbing reflection or absorption. The fabricated variable directional coupler shows that a variation of the voltage transmission coefficient of over 18 dB is possible over a frequency range of 2–3 GHz, with a negligible change of the insertion loss in the direct arm of the coupler. This device is useful as a means of power monitoring in RF front-ends.

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DESIGN OF LOG-PERIODIC DIPOLE ARRAY INSPIRED ANTENNA WITH VERY WIDE BANDWIDTH

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ABSTRACT: *A parallel-strip line fed antenna with very wide bandwidth is presented in this article. This wideband antenna is designed as a combination of two individual antenna elements that are connected in a way inspired by the log-periodic antenna array technique. To miniaturize the size of the structure, metamaterial-based antennas are used as the basic radiating elements. The proposed antennas are designed on FR4 substrate and measured results show that it has a very wide bandwidth from 0.68 to 120 GHz with a VSWR < 3 for frequency range from 0.68 to 3.2 GHz and VSWR < 2 for the remaining bandwidth, with relative stable radiation characteristics.* © 2012 Wiley Periodicals, Inc. Microwave Opt Technol Lett 54:2646–2650, 2012; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.27150

Key words: *log-periodic antenna; metamaterial-based antenna; parallel strip; ultrawideband antenna*

1. INTRODUCTION

Ultrawideband (UWB) technology due to its high speed data rate communications, high accuracy radars, excellent immunity to multipath interference, and large bandwidth has been attracting enormous interest worldwide. In general, UWB system is not restricted to a single frequency band but can transmit over a broad range of frequencies. This characteristic differentiates it from other wireless technologies. The broad spectrum makes it resistant to interference, jamming, and accurate ranging. One of the key technologies in the UWB system that has been widely investigated by both academia and industries is the antenna design. Several antenna designs have been proposed since the release of the UWB spectrum by Federal communication commission in 2002 to satisfy this spectrum requirement.

Recently, there has been a significant interest in developing low profile, light-weight, and easy to manufacture wideband antennas. Meanwhile, different types of log-periodic antennas due to its frequency-independent characteristics have been proposed to work over a wide range of frequencies. The implementation of log-periodic principles in microstrip antennas is presented in Refs. 1 and 2, the characteristic of microstrip antenna is improved by log-periodic technique. In Ref. 3, an array of rectangular microstrip patches were arranged in log-periodic way and coupled to a microstrip feed line. A dual feed log-periodic antenna with high gain and bandwidth was presented in Ref. 4. However, the size of these antennas is large due to the usage of multiple radiating elements.

In this article, we propose a new concept for designing wideband antennas based on the concept of log-periodic antenna array technique. Metamaterial-based antennas are used as the radiating elements. These radiating elements are connected together and fed using parallel strip transmission lines. The antenna performance is simulated by the full-wave electromagnetic simulator. The proposed wideband antennas with its increased bandwidth not only can support the UWB spectrum but also can be used for many other electronic/communication systems including GSM, GPS, PCS, and Bluetooth. Moreover, the proposed antenna may find applications in radar systems, target sensing, locating, tracking, and indoor geo-location systems. Among all these applications, it can be specifically useful for indoor geo-location (where the probability to suffer from multipath effect is very high) to improve the sensing accuracy.

This article is organized as follows. The design of the individual antenna elements used in the proposed wideband antennas is described in section 2. Simulated and measured results along with parametric analysis have been discussed in section 3 and the article is concluded in section 4.

2. ANTENNA DESIGN

The proposed antenna design is based on the concept of log-periodic antenna array technique, where an array of radiating elements with narrow bandwidth is arranged in a log-periodic way to increase the bandwidth [1–4]. In this article, we present a very wide band antenna that is a combination of two individual antenna elements arranged in a log-periodic way. For this purpose, independent metamaterial-based wideband antenna elements have been designed covering different radiating frequencies to give more bandwidth. The basic design of the antenna element used in the proposed antenna is based on the concept of composite right/left-handed (CRLH) metamaterials antenna [5]. Figure 1 shows the structure of the single antenna element used in the proposed antenna. This antenna element consists of a circular patch, a semicircular portion with wings, and a straight section to which the power is delivered through a parallel-strip line (this feeding line will be discussed later). The semicircular portion feeds the circular patch through capacitive coupling.

The gap between the circular patch and the semicircular patch has to be designed carefully so that there is enough generation of capacitance, which is essential to get a better matching throughout the entire bandwidth. If this capacitive coupling is too tight, the radiation performance will be adversely affected.

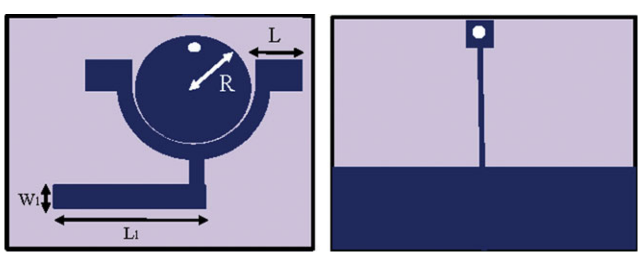

Figure 1 Topology of antenna element used in the proposed wideband antenna. (a) Top view and (b) bottom view. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]