A Novel Insertion Type Phase Shifter Using Conductor-Backed Coplanar Waveguide

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Abstract

We present the first insertion type phase shifter based on a conductor-backed coplanar waveguide transmission line structure. We designed a scale model varactor-tuned phase shifter on a microwave print circuit board and performed empirical calculations and several computer simulations. This new phase shifter shows significant performances with very low insertion loss of < 2 dB, high bandwidth of > 1 GHz, and large phase change of ~ 20°. The proposed phase shifter candidates for several applications in both RF and microwave communications and measurement systems.

Keywords : Microwave phase shifter, insertion type, varactor-tuned, conductor-backed, coplanar waveguide.

1. Introduction

Phase shifters are extensively used in phased-array antennas, modulation and demodulation circuits, and measurement systems in the present day. The mechanical phase shifter was proposed with a hollow waveguide structure [1]. This phase shifter is bulky and requires a rotating part (inertia is a concern), therefore it has never been used in any modern RF and microwave systems. All electronic phase shifters using both passive and active components (*i.e.* PIN diodes, varactors, and FETs) are generally employed. When comparing with the mechanical phase shifters, electronic phase shifters can provide inertialess phase change with minimal switching time. Digital electronic phase shifters [2-4] normally use switches to alter the electrical phase length, whereas analog electronic phase shifters [5-7] vary a device reactance continuously to control the phase angles.

Current analog phase shifters usually provide high resolution of phase changes limited only by the control circuits but narrow bandwidth and high losses. In order to achieve broadband operation, however, a low-Q structure is required. To reduce losses, the structure should be distributed rather than simply resistive. To achieve monolithic integration, varactor diodes rather than ferromagnetic components should be the variable phase elements.

This research paper proposes a new analog phase shifter with insertion type structure using conductor-backed coplanar waveguide (CBCPW) transmission line loaded with varactor diodes. Using this phase shifter would overcome the drawbacks of both mechanical and the present analog phase shifters. Figs.1 (a) and (b) show a schematic and its lossless equivalent circuit of the insertion type phase shifter with a very short transmission line section, when L_t and C_t are inductance and capacitance per unit length of the transmission line, respectively, and C_v(V) is the voltage dependence varactor capacitance.

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2. Theory and Design

2.1 Conductor-backed Coplanar Waveguide

A variety of transmission line structures can be used to form phase shifters such as coaxial, microstrip and coplanar waveguide (CPW) lines. Only microstrip and coplanar wavegide are extensively utilized when fabricating monolithic microwave integrating circuits (MMICs), nevertheless, using microstrip suffers from disadvantages of high dispersion, high insertion loss, and via holes requirement.

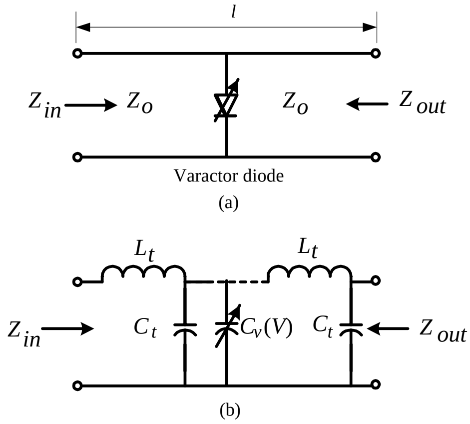

Fig. 1 An insertion type phase shifter (a) a schematic of a transmission line loaded with varactor diode and (b) its equivalent circuit.

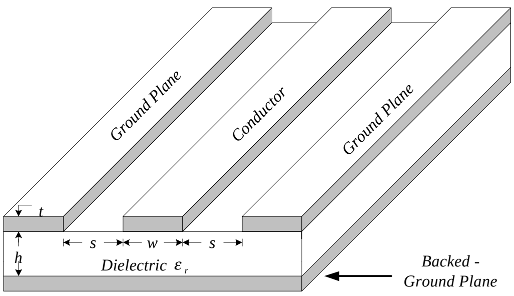

Fig. 2 A CBCPW transmission line.

To overcome these problems, this paper studied a phase shifter structure based on CPW transmission lines. Additionally, to improve the characteristics of the phase shifter, the conductor-backed coplanar waveguide (CBCPW) was chosen due to its potential advantages over ordinary CPW, including superior mechanical strength, high power-handling capability and smaller size [8-9].

Fig.2 shows a structure of conductor-backed coplanar waveguide (CBCPW) consisting of a center conductor and ground planes on both sides of the print circuit board. The characteristic impedance of the CBCPW line can be calculated as [10-11]

$$Z_{o(line)} = \frac{60\pi}{\sqrt{\varepsilon_{re}}} \frac{1}{K(k_1)/K'(k_1) + K(k_2)/K'(k_2)} \quad (1)$$

where K(k_i) and $K'(k_i)$ are the complete elliptic integrals of the first kind and its complement, respectively (when i = 1 and 2).

The ratio of K/K' can be determined as

$$\frac{K(k_i)}{K'(k_i)} = \frac{\pi}{ln\left[2\left(1+\sqrt{k_i'}\right)/\left(1-\sqrt{k_i'}\right)\right]}$$

$$\text{for } 0 \le k_i \le 0.707 \quad (2)$$

$$\frac{K(k_i)}{K'(k_i)} = \frac{1}{\pi} ln\left[2\left(1+\sqrt{k_i}\right)/\left(1-\sqrt{k_i}\right)\right]$$

$$\text{for } 0.707 \le k_i \le 1 \quad (3)$$

where $k_i' = \sqrt{1-k_i^2}$ and

$$k_1 = \frac{w}{w+2s} \quad (4)$$

$$k_2 = \frac{\tanh(\pi(w/2)/2h)}{\tanh\left(\pi\left(w/2 + s\right)/2h\right)}. \quad (5)$$

The effective dielectric constant (ε_{re}) of the CBCPW transmission line can be obtained as

$$\varepsilon_{re} = 1 + q(\varepsilon_r - 1) \quad (6)$$

where

$$q = \frac{K(k_2)/K(k'_2)}{K(k_1)/K(k'_1) + K(k_2)/K(k'_2)}. \quad (7)$$

The phase velocity of wave on the transmission line can be calculated to be (c is the velocity of light)

$$v_{phase(line)} = \frac{c}{\sqrt{\varepsilon_{re}}}. \quad (8)$$

These equations will be employed for determining the series transmission line matching at the input and output of the proposed phase shifter.

2.2 CBCPW Phase Shifting Section

In this work, insertion type CBCPW phase shifter was optimally designed and built. A CBCPW line loaded with varactor diodes forms an artificial transmission line (its lossless equivalent circuit is depicted in Fig.1). The capacitance per unit length of the artificial transmission line has contributions from the unloaded line capacitance (C_t) and the varactor capacitance (C_v). The inductance per unit length (L_t) of the artificial line is unchanged from that of the unload line. The characteristic impedance and phase velocity for the varactor diode-loaded line are given in the following equations [12-14]

$$Z_o(V) = \sqrt{\frac{L_t}{(C_t + C_v(V)/l)}} \tag{9}$$

$$v_{phase}(V) = \sqrt{\frac{1}{(L_t(C_t + C_v(V)/l))}} \tag{10}$$

where

$$L_t = \frac{l}{v_{phase(line)}} Z_{o(line)} \tag{11}$$

$$C_t = \frac{l}{Z_{o(line)} v_{phase(line)}} \tag{12}$$

$$C_v(V) = C_{jo}\sqrt{\frac{1}{1 - V/m}} \tag{13}$$

when l is the length for obtaining an equivalent varactor capacitance per unit length, C_{jo} is the zero-bias capacitance, V is the reverse biasing voltage which is negative, and m is a factor depending on the semiconductor structure and properties of the varactors.

It is obvious that the varactor capacitance can be changed when varying the reverse bias across the diodes, resulting in altering of the phase velocity or phase angle of the incoming signals. Nevertheless, changing the capacitance per unit length also changes the characteristic impedance of the artificial transmission line. Therefore, we must be careful for designing the phase shifter by reducing the variation in total capacitance to make the change in the characteristic impedance very small.

2.3 Phase Shifter Realization

A microwave substrate of RO3006 with relative permittivity of 6.15±0.05 and dielectric thickness of 50 mil (1mil = 1/1000 inch) from Rogers Corp. was utilized to built up the phase shifter. Varactor diodes of MSV-38 (R_s=1.7 Ω, C_{jo} = 1.26 pF, and $m \approx 0.5$) with beamlead packages from the Metelics Corp. were used as reactive elements. The proposed phase shifter was then designed on the CBCPW structure. In this work, a section of CBCPW with two varactor diodes was designed to be a phase shifting part, and series of CBCPW lines were used to be matching elements at its input and output. The simulation program with all previous equations was employed to optimize the phase shifter. The optimized dimensions of the phase shifter were obtained when input and output impedances were found to be $Z_{in} = Z_{out} \approx 50$ Ω. Fig.3 shows the phase shifter schematic (top view layout) comprising of a main phase shifting section at the middle, 3 input matching sections and 3 output matching sections. Table 1. depicts optimized dimensions for all CBCPW transmission line sections of the phase shifter. The scattering parameters (S_{11} and S_{21}) were then calculated using empirical formulas elsewhere.

The proposed phase shifter was built on the RO3006 microwave substrate with the optimized dimensions. A microcomputer-controlled milling machine (LPKF model) was employed to etch the designed circuit patterns on the substrate with the maximum error of ±1 mil. The etched circuit was then connected with 50 Ω SMA connectors at its input and output ports. The connectors were also used to join the upper and lower ground planes. The completed phase shifter is shown in Fig.4.

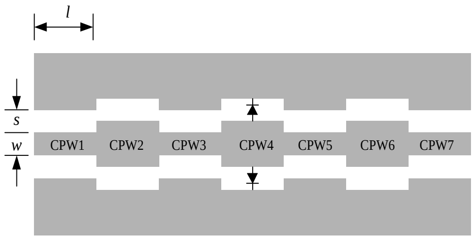

Fig. 3 The proposed insertion type CBCPW phase shifter (top view).

Table 1 The optimized dimensions of the proposed phase shifter.

Section	w (mil)	s (mil)	l (mil)	$Z_{o(line)}$
CPW1	97.52	100.00	242.80	43.04
CPW2	129.49	109.97	387.58	36.06
CPW3	91.55	109.97	353.00	44.96
CPW4	147.79	95.01	534.35	32.72
CPW5	80.65	109.97	377.94	48.45
CPW6	118.20	109.97	392.17	38.30
CPW7	97.52	100.00	242.80	43.04

Fig. 4 The completed insertion type CBCPW phase shifter on the RO3006 microwave substrate with two shunted-varactors.

3. Experimental results

The constructed phase shifter was then tested using a calibrated network analyzer (HP8720D). The simulated and measured scattering parameters (S_{11} and S_{21}) of the phase shifter agree well, as clearly shown in Fig.5, where the discrepancies are believed to be due to the parasitics associated with the diode package, CBCPW transmission line interconnections, and the effects of dimension errors. The scattering parameters from measurement show that the proposed phase shifter has < 2.0 dB insertion loss (S_{21}) and < -10 dB return loss (S_{11}) over the frequency range from 4.0 to 5.0 GHz. Finally, the measurement of phase changes at continuous reverse bias voltages was performed employing a network analyzer. Biasing for the varactors was achieved by using external bias tees connected at input and output ports of the phase shifter. The phase change versus reverse bias voltage at the operating frequency of 4.5 GHz was then plotted in Fig.6. The total phase change of ~ 20° was obtained when biasing the varactor diodes from 0 to 10 V. The insertion loss of the phase shifter at the same frequency was also measured (Fig.6).

4. Discussions

This phase shifter is a very promising device for microwave communications and measurement applications. The total phase changes can be easily increased by adding up the number of varactor diodes on the CBCPW lines, for example, using 14 diodes, this phase shifter could alter the phase angle from 0 to 360°, resulting in the useful phase shifter for translating frequency. Nevertheless, the performance of the proposed phase shifter is limited by the capacitance value and the physical size of the beamlead diodes. To increase the operating frequency, the varactor diodes with smaller capacitance values and shorter CBCPW transmission line lengths must be employed. Therefore, for very high-frequency applications, monolithic integrated fabrication is essentially required. The monolithic fabrication not only reduces the cost of the phase shifter, but also reduces the parasitics associated with commercial diode packages.

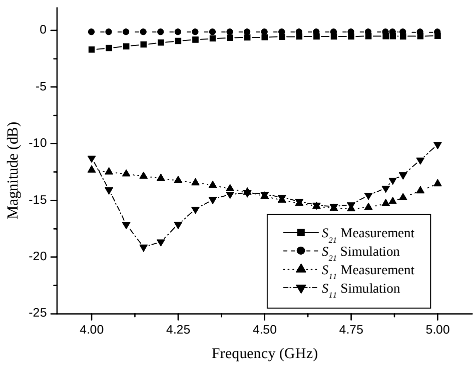

Fig. 5 Simulated and measured scattering parameters of the phase shifter at zero bias.

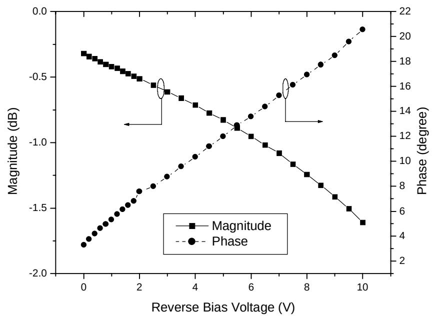

Fig. 6 Measured magnitude and phase change of S_{21} vs. reverse bias voltages at the frequency of 4.5 GHz.

5. Conclusions

The new insertion type phase shifter based on a CBCPW structure proposed in this paper has shown the excellent performances of low insertion loss and large bandwidth. A wide range of phase changes can be obtained by using the reverse bias tuning. This phase shifter is a viable candidate for applications in communications and measurement because it offers a clear path toward complete integration into MMICs. The integrated version is rigorously expected to have improved performances and reduced size and cost.

6. Acknowledgment

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