Linear Tunable Phase Shifter Using a Left-Handed Transmission Line

Hongjoon Kim, Alexander B. Kozyrev, Abdolreza Karbassi, and D. W. van der Weide

***Abstract*—We demonstrate a compact, linear, and low loss variation hybrid phase shifter using a left-handed (LH) transmission line. For frequencies from 4.3 to 5.6 GHz, this phase shifter gives a nearly linear phase variation with voltage, with a maximum deviation of $\pm 7.5^\circ$. Within this frequency range, the maximum insertion loss is 3.6 dB, and the minimum insertion loss is 1.8 dB over a continuously adjustable phase range of more than 125°, while minimum return loss is only 10.2 dB. Furthermore, this phase shifter requires only one control line, and it consumes almost no power.**

***Index Terms*—Left-handed (LH) transmission lines, metamaterials, phase shifter, varactor.**

I. INTRODUCTION

TO BE useful in microwave systems, a phase shifter should exhibit low loss, low loss variation with phase state change, low return loss, low power consumption, and linear phase variation for precise control of its phase state. Many analog and digital phase shifters have been reported in the literature: for example, Ellinger *et al.* [1] have compared the performance of various phase shifters, and they demonstrate a very compact phase shifter using lumped elements that shows better performance (in terms of insertion loss and return loss) than previously-reported phase shifters. However, the control linearity of this transmission type phase shifter is highly dependent on the diode capacitance–voltage (C–V) relation and, consequently, it does not exhibit a highly linear phase variation with abrupt or hyper-abrupt doped diodes.

Recently there has been a great deal of interest in artificial metamaterials, which are also known as left-handed (LH) materials. One way to realize left-handed materials uses planar transmission lines that are loaded with series capacitors and shunt inductors. These structures have been suggested in the literature previously, and several applications have been reported [2]–[5]. The phase shifter in this work is implemented by combining this LH transmission line concept with varactor diodes. As a result of this combination, the phase shifter can be very compact, and it can exhibit a linearly tunable performance across a broad frequency range with low loss and low loss variation.

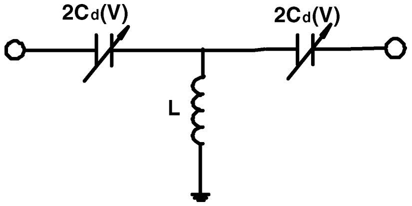

Fig. 1. Unit cell of a LH phase shifter circuit.

II. THEORETICAL CONSIDERATIONS FOR LH PHASE SHIFTERS

A. Basic Phase Shifting Unit Cell in LH Transmission Line

Fig. 1 shows the unit cell of a LH phase shifter. This structure has two diode capacitors ($2C_d(V)$) in series, and an inductor (L) between them. A simple analysis from [5] reveals the dimensionless propagation constant which represents phase change per section (β) for this structure

$$\sin^2\left(\frac{\beta}{2}\right) = \frac{1}{4\omega^2 L \cdot C_d(V_R)}. \tag{1}$$

Here, V_R is reverse bias voltage across the diodes.

If we cascade several unit cells together, we observe a periodic cutoff frequency (also known as the Bragg frequency, ω_{B}) [2]

$$\omega_{\mathrm{B}} = \frac{1}{2\sqrt{L \cdot C_d(V_R)}}. \tag{2}$$

Because this is a high-pass filter structure, the operating frequency must be higher than the Bragg frequency. For $\omega \gg \omega_{\mathrm{B}}$, β becomes very small. Then we can approximate β as

$$\beta \approx -\frac{1}{\omega\sqrt{L \cdot C_d(V_R)}}. \tag{3}$$

Now we will use (3) to explain the response of our LH phase shifter circuit.

The characteristic impedance (Z_0) also can be approximated as (4) when $\omega \gg \omega_{\mathrm{B}}$

$$Z_0 \approx \sqrt{\frac{L}{C_d(V_R)}}. \tag{4}$$

To minimize reflections, we set $Z_0 = 50\ \Omega$ so the diode capacitance values are required to satisfy the following equations ($C_{ls} =$ large signal diode capacitance)

$$C_{ls} = \frac{\int_{V\min}^{V\max} C_d(V_R)dV_R}{V_{\max} - V_{\min}}. \tag{5}$$

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Here, $V_{\max}$ and $V_{\min}$ are the maximum and minimum reverse bias voltages respectively. Thus, phase shift variation per section due to bias voltage change ($\Delta\beta$) and total phase variation ($\Delta\phi$) are given as

$$\Delta\beta = \frac{1}{\omega\sqrt{L}}\left(\frac{1}{\sqrt{C_d(V_{\max})}} - \frac{1}{\sqrt{C_d(V_{\min})}}\right) \tag{6}$$

and

$$\Delta\phi = \Delta\beta \cdot n \tag{7}$$

where n is the number of identical unit cells.

B. Linear Phase Variation According to Voltage

A key motivation for the use of LH phase shifters is their linear phase variation with voltage. The diode capacitance variation ($C_d(V_R)$) goes as

$$C_d(V_R) = \frac{C_{j0}}{\left(1 + \frac{V_R}{V_{bi}}\right)^m}. \tag{8}$$

Here, C_{j0} is the zero-bias diode capacitance and m is a junction doping grading parameter.

When $m = 2$, we can have perfect linear phase variation according to voltage because we will have β as follows in this LH transmission line structure:

$$\beta(V_R) = A\left(1 + \frac{V_R}{V_{bi}}\right) \tag{9}$$

where $A = -1/(\omega\sqrt{LC_{j0}})$.

From the diode capacitance (8), when $m \neq 2$, the LH phase shifter does not exhibit perfect linearity. However, when we put (8) into (3), the β–V relation becomes very linear for most abrupt and hyper-abrupt diodes. This means the LH phase shifter structure can effectively compensate such a nonlinear capacitance-voltage (C–V) relation of most abrupt and hyper-abrupt diodes. Fig. 2 shows a C–V relation of the diode used in this letter and its theoretical phase constant variation in LH transmission line. For comparison, an ideal C–V curve for linear phase variation is also shown.

III. REALIZATION OF THE PHASE SHIFTER

Our phase shifter (Fig. 3), was realized on Rogers RT/Druid 3010 board ($\varepsilon_r = 10.2$). MACOM hyper-abrupt junction GaAs flip-chip varactor diodes (MA46H120) were attached using conductive silver epoxy. After thru-reflect-line (TRL) calibration, we measured the diode capacitance variation at 5 GHz using a network analyzer. The C_{j0} of the diode, as described in the manufacturer's data sheet, is 1.1 pF, close to the measured C_{j0} of the diode, 1.47 pF. The discrepancy may arise from the package capacitance, the parasitics of the silver epoxy, or process variation in manufacturing. The diode C–V curve was given in Fig. 2. From this curve we calculate $C_{ls} \approx 1$ pF. Because two diodes are in series in each section, the total diode capacitance is halved. Thus, to have characteristic impedance of 50 Ω with a $C_{ls} \approx 1$ pF, the inductance must be 1.25 nH from (4).

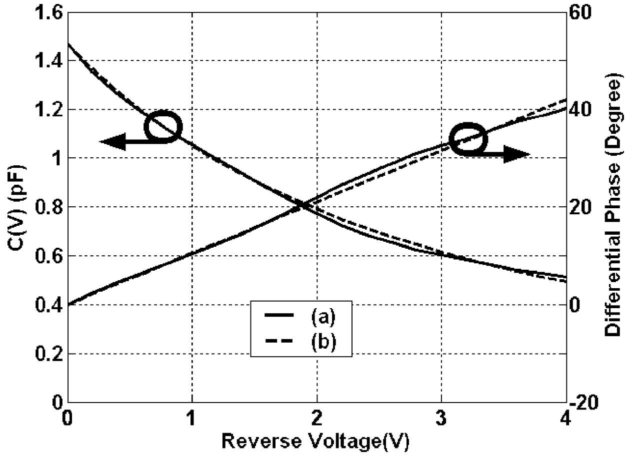
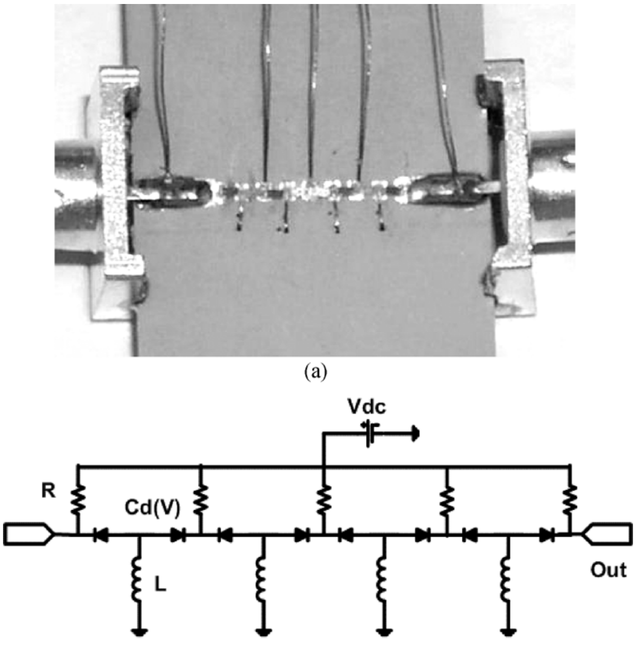


Fig. 2. Diode C–V curves along with theoretical phase variation curves for a section of LH transmission line. (a) Hyper-abrupt diode used in this work (MACOM MA46H120 [measured at 5 GHz]). (b) An ideal diode with perfect linear phase variation in LH transmission line [C_{j0} =1.47, in (8)]. Phase variation graph is drawn for f = 5.2 GHz and L = 1.25 nH.



(a)

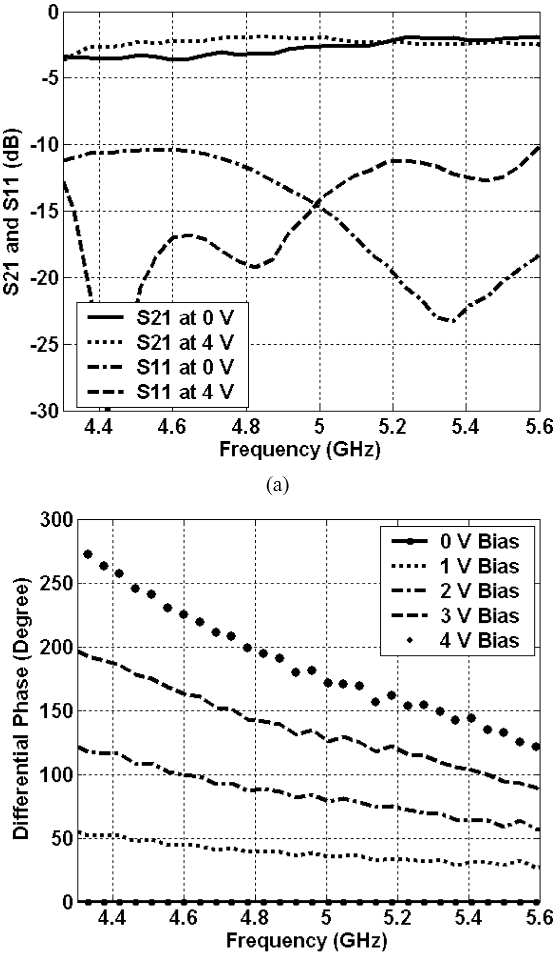
(b)

Fig. 3. (a) Fabricated LH phase shifter. (b) Equivalent circuit.

Inductances were implemented by connecting 0.12 mm diameter copper wire to the ground plane on the back side of the board. DC bias wires are connected with 3 kΩ resistors between diodes as shown in Fig. 3(b). Our final circuit had four sections of the unit cell shown in Fig. 1, and total circuit was 1 cm × 2 mm, neglecting the connectors and bias wires.

IV. MEASUREMENTS AND DISCUSSION

Equation (2) predicts a cut-off frequency of 2.63 GHz and 4.46 GHz for 0 V bias and 4 V bias, respectively. Measurement indicated −6 dB cut-off frequencies at 2.7 and 4.1 GHz, respectively. Our circuit is also expected to show a high-pass filter response such that we could use this phase shifter at any frequency



(a)

(b)

Fig. 4. Insertion loss, return loss and phase variation VS. control voltages. (a) Insertion loss and return loss variation for 0 and 4 V. The insertion loss variation is very small (< ± 0.9 dB) across the whole frequency range. (b) The phase variation from 0 to 4 V (set S_{21} phase to 0° for all frequencies at 0 V). The lines on the graph are drawn for voltage differences of 1 V, and the phase state variation per voltage step at any particular frequency is nearly constant.

above the Bragg frequency. However, we require a small pad for attachment of the diodes, inductors and bias wires. The small pad capacitance to ground operates as a low-pass filter, making the whole circuit behave more like a band-pass filter. Thus, the stop band begins above 5.6 GHz. Finally, at frequencies between 4.3 and 5.6 GHz, this circuit shows excellent phase shifting performance [see Fig. 4(a) and (b)]. A maximum insertion loss of 3.6 dB, a minimum of 1.8 dB, and a minimum return loss of 10.2 dB across all phase states over 4.3 GHz to 5.6 GHz. The maximum deviation of phase from linear is just $\pm 7.5^\circ$. Note also that the gap between the phase states, from one voltage to the next, is uniform at any frequency in Fig. 4(b).

At 5.2 GHz, which can be used for indoor wireless LAN, this phase shifter shows excellent performance. The maximum insertion loss is only 2.36 dB, and the insertion loss variation is within ± 0.2 dB as seen in Fig. 5. The maximum phase deviation from a straight line is only $\pm 4.2^\circ$. Given these low insertion loss and insertion loss variations, this circuit could be used in phase shift keying (PSK) applications.

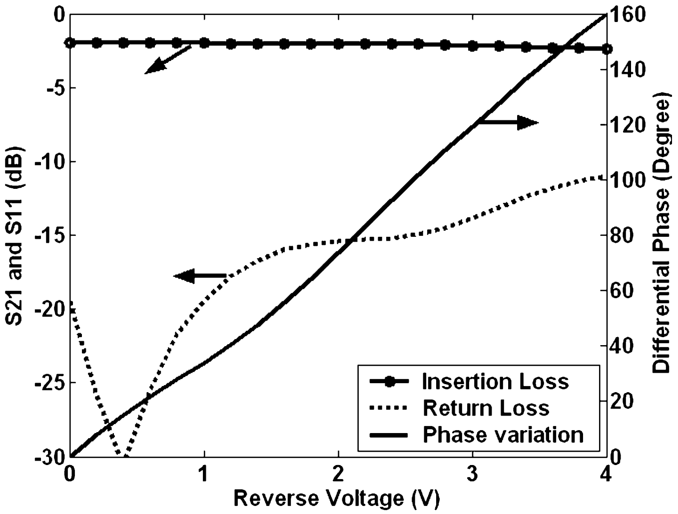


Fig. 5. Insertion loss, return loss and phase variation with voltage at 5.2 GHz (set S_{21} phase at 0° at 0 V). The insertion loss maximum is 2.36 dB and the minimum is 1.98 dB. The return loss is better than 11 dB and phase variation is nearly linear.

V. CONCLUSION

We have demonstrated a new type of phase shifter at high frequencies, and supplied the elementary theory that describes it. Our phase shifter shows low loss, low loss variation, low return loss, negligible power consumption, and very linear phase variation with voltage. This phase shifter can be made broadband and compact in size, and it exhibits good performance despite its hybrid implementation. This is possible because of the high-pass filter structure inherent in the LH phase shifter design. We note that adoption of MMIC fabrication processes for this phase shifter could minimize the low-pass filter effect, thus allowing for even higher frequency operation.

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