Proc. of the 1st International Conference on Electrical, Communication and Computer Engineering (ICECCE)
24-25 July 2019, Swat, Pakistan

A Compact Design of Composite Right/Left-Handed (CRLH) Metamaterial Based Phase Shifter

Muhammad Ayaz
Electrical and Computer Engineering Department
COMSATS University Islamabad, Abbottabad Campus
Abbottabad, Pakistan
FA17-R65-002@cuiatd.edu.pk

Adnan Iftikhar
Electrical and Computer Engineering Department
COMSATS University Islamabad
Islamabad, Pakistan
adnaniftikhar@comsats.edu.pk

Irfanullah
Electrical and Computer Engineering Department
COMSATS University Islamabad, Abbottabad Campus
Abbottabad, Pakistan
eengr@cuiatd.edu.pk

***Abstract*—This paper presents, a composite right-handed/left-handed metamaterial (MTM) based phased shifter design at 2.4 GHz, and its performance is compared with (i) a conventional transmission line material based phase shifter, and (ii) purely left-handed material based phase shifter. The right/left-handed MTM phase shifter is designed using cascaded sections of left-handed lumped element capacitors and inductors and right-handed printed transmission line material. By optimizing the lumped-element component values, the required phase shift can be achieved. To validate the design, three phase shifters (MTM based, conventional and purely left-handed) are simulated using the Agilent-Advanced Design System (ADS) microwave circuit simulator at a design frequency of 2.4 GHz. It is shown that the MTM based phase shifter is compact in size, gives a linear phase response with low Insertion Loss (IL) values.**

***Keywords*—Composite right/left-handed (CRLH), Insertion loss, purely left-handed line, purely right-handed line, metamaterial.**

I. INTRODUCTION

Recently, there has been a strong industrial and academic research in the development of artificial materials called metamaterials (MTM) that demonstrates negative values for both permittivity and permeability. Such MTMs with negative refractive index has found applications in wide range of microwave electronics and devices [1], [4], [6], and [8]. One such microwave component is phase shifter used in many RF applications, for example RADAR and phase array antennas to steer the radiation beam in any desired direction [9]. In the literature [12], [15], [16], [19], phase shifters have been designed using conventional natural materials. However, due to their large size, they are not suitable for compact size requirement applications in today advanced microwave systems. More recently, composite right/left-handed (CRLH) transmission line (TL) shown in Fig. 1 has been used to design compact phase shifter. The length of CRLH TL is denoted as Δp and length of conventional printed TL is denoted as d having characteristic impedance Z_0 and phase constant β_{TL}. C_L and L_L represents purely left-handed (PLH) capacitance and inductance respectively [10],[11],[20]. Classical example of C_L on printed microstrip technology is inter-digital capacitor and that of L_L is microstrip shunted stub [1].

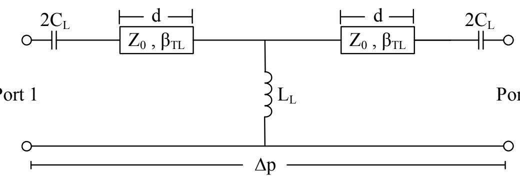

Fig. 1 Schematic of a CRLH TL (T-model) as a unit cell phase shifter unit

Various CRLH metamaterial based phase shifters have been explored recently in [3], [5], [7], [9], [14], and [18]. In this paper the CRLH TL in [9] and shown in Fig. 1 will be used to derive the analytical expressions for phase shifter to give the desired phase shift at 2.4 GHz band. The performance of CRLH phase shifter will then be compared with purely left-handed (PLH) and conventional delay line (also called purely right-handed (PRH)) phase shifters in Agilent-Advanced Design System (ADS) microwave circuit simulator [22] at a design frequency of 2.4 GHz.

The performance comparison metrics are range of phase responses, Insertion loss (IL) and physical size. It is shown that the MTM based phase shifter has compact physical size, gives a linear phase shift response with low IL values. The conventional material based phase shifter can produce only negative phase shift (dependent on structure's length), the pure left-handed material based phase shifter can give only positive phase shift (component values may not be physically realized), while the MTM based phase shifter is capable to produce 0°, positive and negative phase shifts (independent of structure's length with physically realizable component values). The physical compactness and planar design gives the MTM based phase shifter an edge for its easy PCB integration with microwave electronics devices and phased antenna array applications.

The rest of the paper is organized as follows: Section II discusses S-parameters analysis of unit-cell MTM based CRLH phase shifter, section III describes simulation results of single and multi-stage MTM CRLH phase shifters. Performance comparisons of three phase shifters (CRLH, PLH and PRH) are discussed in section IV and section V finally concludes the paper.

II. S-PARAMETERS ANALYSIS

To compute phase shift of symmetrical T unit cell of a CRLH TL in Fig. 1, the two-port network analysis [2] is performed as follows:

- The ABCD parameters of PRH-TL having characteristic impedance Z_0 and phase constant β_{TL} are given below:

$$A_1 = \cos(\beta_{TL}d), B_1 = jZ_0 \sin(\beta_{TL}d), C_1 = jY_0 \sin(\beta_{TL}d), D_1 = A_1 \tag{1}$$

- The ABCD parameters of PLH-TL with element values C_L and L_L are given below:

$$A_2 = 1 + \frac{Z_1}{Z_3}, B_2 = Z_1 + Z_2 + \frac{Z_1 Z_2}{Z_3}, C_2 = \frac{1}{Z_3}, D_2 = 1 + \frac{Z_2}{Z_3} \tag{2}$$

where

$$Z_1 = \frac{1}{j\omega(2C_L)}, Z_2 = Z_1, Z_3 = j\omega L_L \tag{3}$$

- Next the ABCD parameters of cascaded PLH-TL and PRH-TL are given below:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \tag{4}$$

Next converting, the ABCD parameters in (4) to S_{21} parameter gives

$$S_{21} = \frac{2}{A + \frac{B}{Z_0} + CZ_0 + D} \tag{5}$$

The element values C_L and L_L are computed using the matched condition between PLH-TL and PRH-TL [13] in Fig. 1 and the procedure is described as follows: The total phase shift provided by CRLH phase shifter is the sum of phase shifts provided by PRH-TL and PLH-TL, i.e.,

$$\emptyset_{CRLH} = \emptyset_{PRH} + \emptyset_{PLH} \tag{6}$$

where phase shift contribution due to PRH-TL is given by [13]:

$$\emptyset_{PRH} = \beta_{TL}d,\ \beta_{TL} = \sqrt{\mathcal{E}_e}k_0 \tag{7}$$

And phase shift contribution due to PLH-TL is given by [13]

$$\emptyset_{PLH} = \frac{-1}{\omega\sqrt{L_L C_L}} \tag{8}$$

The effective dielectric constant of a microstrip line is given approximately by [2]:

$$\mathcal{E}_e = \frac{\mathcal{E}_r + 1}{2} + \frac{\mathcal{E}_r - 1}{2} \frac{1}{\sqrt{1 + \frac{12t}{W}}} \tag{9}$$

where t is the thickness of the substrate and W is the conductor width. The free space wave number $k_0 = \frac{2\pi f_0}{c}$, f_0 is the design frequency and c is the speed of light.

For matched condition between PRH-TL and PLH-TL, following relation holds true [1]:

$$Z_0 = \sqrt{\frac{L_L}{C_L}} = \sqrt{\frac{L}{C}} \tag{10}$$

where L and C are the inductance and capacitance of PRH-TL. Solving (6) and (8) gives

$$\omega^2 L_L C_L = \frac{1}{(\emptyset_{PRH} - \emptyset_{CRLH})^2} \tag{11}$$

Putting L_L from (10) into (11) and simplifying, we obtain

$$C_L = \frac{1}{\omega Z_0(\emptyset_{PRH} - \emptyset_{CRLH})} \tag{12}$$

And then L_L can be computed using (10) as

$$L_L = {Z_0}^2 C_L \tag{13}$$

Finally, the total phase shift provided by single unit cell in Fig. 1 can be computed by taking phase of (5) and insertion loss is given by

$$IL = -20log_{10}|S_{21}| \tag{14}$$

III. SIMULATION RESULTS OF CRLH PHASE SHIFTER

A. Simulation Results of Single-Stage CRLH Phase Shifter

To validate (5), a unit cell (single stage) phase shifter in Fig. 1 having $\Delta p = 4\,mm$ $(< \lambda/10)$ was designed on FR-4 substrate ($\mathcal{E}_r = 4.6,\ t = 1.6\,mm,\ tan\delta = 0.02$) in ADS Co-simulation environment as shown in Fig. 2. The element values C_L and L_L were computed using (12) and (13) for the desired phase shifts at 2.4 GHz and are tabulated in Table 1 for single stage (single unit cell), 5-stage (cascaded five unit cells) and 10-stage (cascaded ten unit cells) CRLH phase shifters. Then a MATLAB code was written to implement (5) to give desired phase shifts at 2.4 GHz and the results are shown in Fig. 3. As can be see, the analytical and ADS simulation results closely match with each other demonstrating validity of (5). Similarly the results for Insertion loss using (14) and ADS schematic are shown in Fig. 4. The results clearly show that IL is less than 0.5

dB for all phase shifts except for 30° phase shift, where IL is less than 1 dB (ADS schematic result).

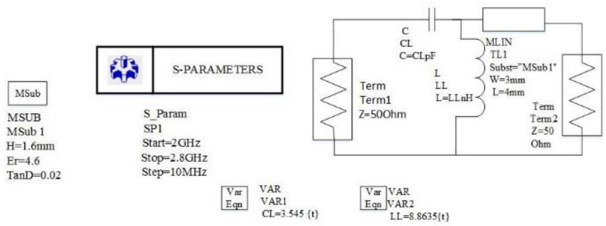

Fig. 2 CRLH unit cell phase shifter unit in ADS schematic

TABLE I. COMPUTED LOADED ELEMENT VALUES

Desired phase shift (degrees)	**Computed values from (12) and (13) for single unit cell CRLH phase shifter**		**Tuned values for cascaded 5 unit cells CRLH phase shifter**		**Tuned values for cascaded 10 unit cells CRLH phase shifter**	
	C_L (pF)	L_L (nH)	C_L (pF)	L_L (nH)	C_L (pF)	L_L (nH)
0	3.545	8.863	3.545	9.195	3.829	8.532
+10	2.417	6.043	3.534	7.711	3.418	8.529
-10	6.646	16.61	3.5	11.59	3.5	10.476
+30	1.477	3.693	2.759	6.988	3.162	7.581

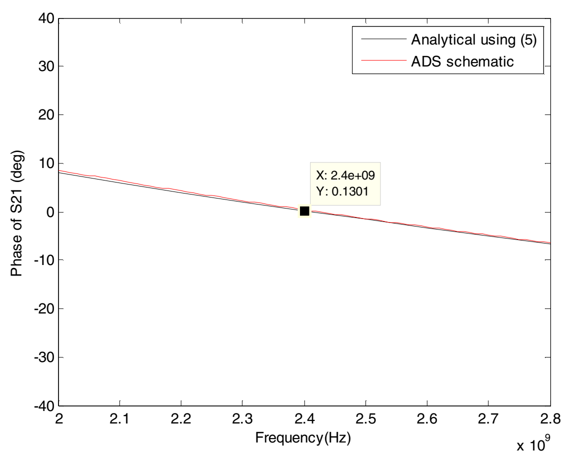

Fig. 3(a) Phase response of unit cell CRLH phase shifter for 0° phase shift

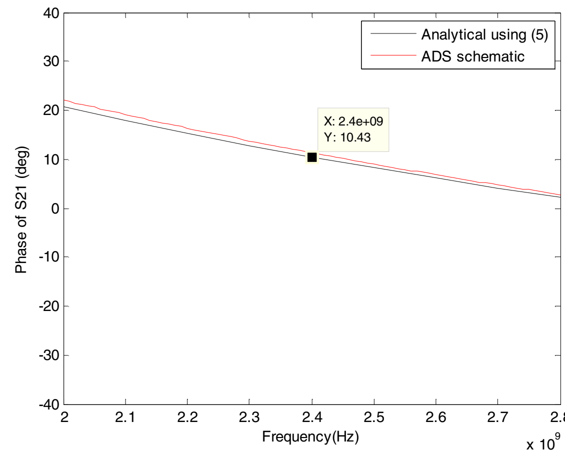

Fig. 3(b) Phase response of unit cell CRLH phase shifter for $+10^{\circ}$ phase shift

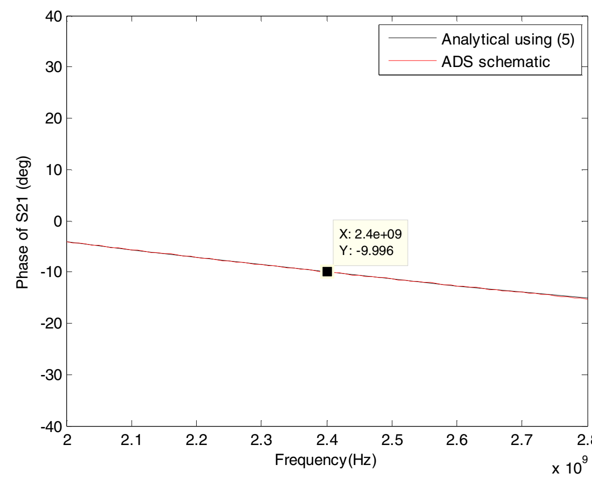

Fig. 3(c) Phase response of unit cell CRLH phase shifter for -10° phase shift

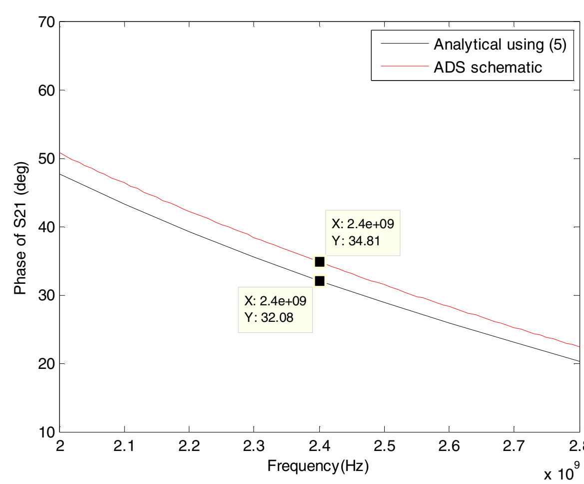

Fig. 3(d) Phase response of unit cell CRLH phase shifter for $+30^{\circ}$ phase shift

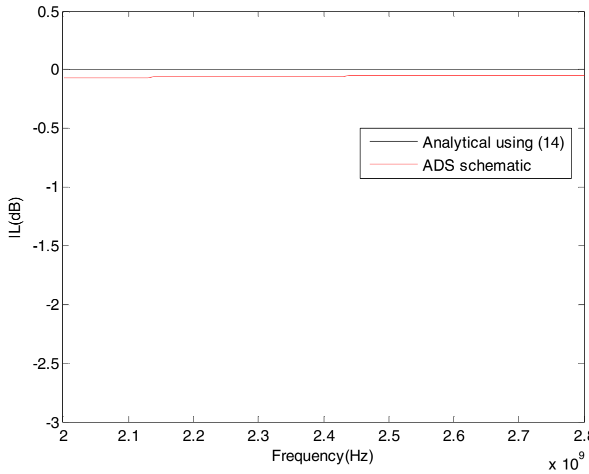

Fig. 4(a) Insertion loss of unit cell CRLH phase shifter for 0° phase shift

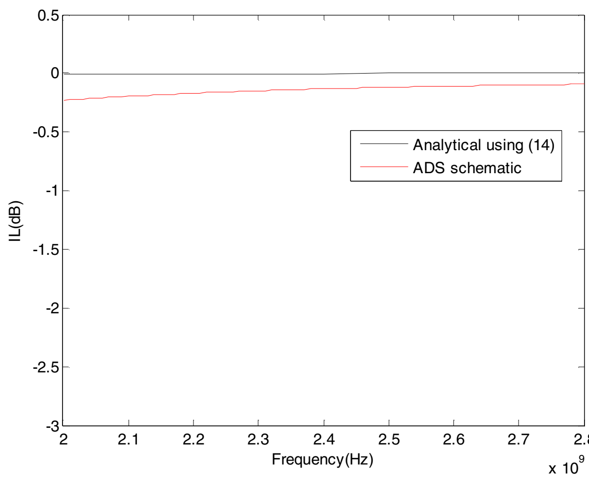

Fig. 4(b) Insertion loss of unit cell CRLH phase shifter for $+10^{\circ}$ phase shift

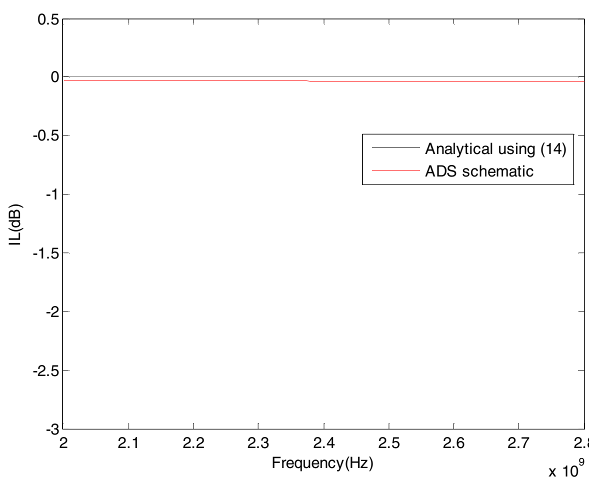

Fig. 4(c) Insertion loss of unit cell CRLH phase shifter for -10° phase shift

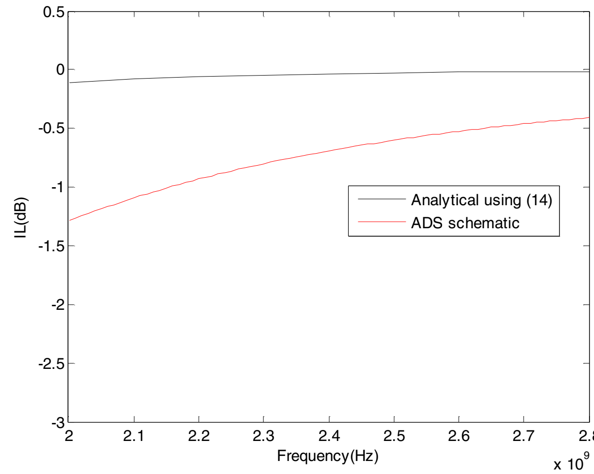

Fig. 4(d) Insertion loss of unit cell CRLH phase shifter for $+30^{\circ}$ phase shift

B. Simulation Results of Multi-Stage CRLH Phase Shifter

Next, five and ten unit cells of Fig. 1 were cascaded in ADS circuit simulator with loading element values given in Table 1 to investigate its dependence on structure size. The results for

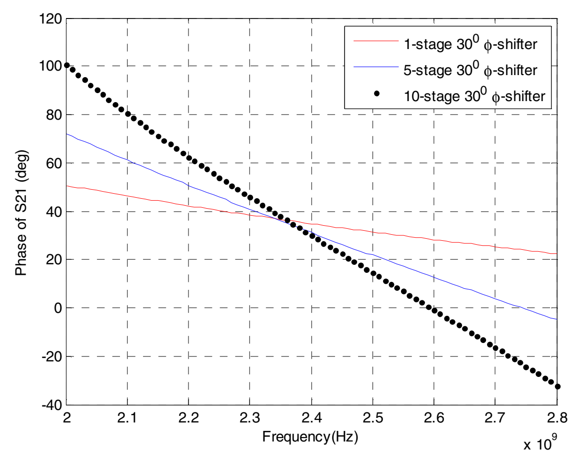

Fig. 5(a) Phase responses of single, five, and 10-stage 30° CRLH phase shifters in ADS circuit simulator

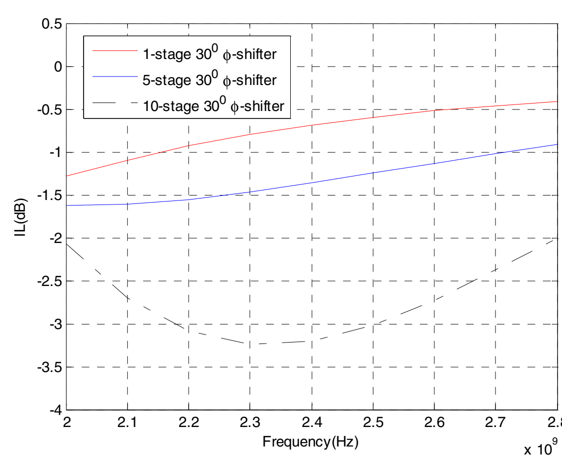

Fig. 5(b) Insertion losses of single, five, and 10-stage 30° CRLH phase shifters in ADS circuit simulator phase responses and insertion losses are given in Fig. 5. Fig. 5(a) shows that the required phase shift is achieved at the design frequency of 2.4 GHz for 1-, 5- and 10-stage phase shifters demonstrating that the performance of metamaterial based CRLH phase shifter is independent of its structure length. In addition, the slope of Fig. 5(a) increases as the number of stages are increased, therefore the size of the phase shifter should be kept to less number of stages for broad-band applications. Similarly the IL results in Fig. 5(b) shows that its values is less than 1.5 dB for 1- and 5-stages phase shifters, while IL is around -3.2 dB for 10-stage phase shifter at 2.4 GHz (IL values 3-4 dB are common for practical phase shifters).

IV. PERFORMANCE COMPARISONS OF VARIOUS PHASE SHIFTERS

In this section, we will compare phase responses, IL and physical size of three phase shifters namely (i) conventional material microstrip delay line phase shifter, (ii) purely left-handed (PLH) metamaterial based phase shifter and (iii) composite right/left-handed (CRLH) metamaterial based phase shifter. The simulated results of phase responses and IL for the three phase shifters are shown in Fig. 6(a) and (b) respectively.

The conventional material based microstrip delay line phase shifter (PRH TL) having physical length of 67 mm at 2.4 GHz on FR-4 substrate with width equal to 3 mm (to match with 50 ohm port) was simulated in ADS Momentum. Its physical length is 16.75 times greater than metamaterial based CRLH phase shifter (4 mm), and its phase response shows that its slope is greater than metamaterial based PLH and CRLH phase shifters indicating its unsuitability for broadband applications.

Then PLH TL based phase shifter comprising C_L and L_L only (TL sections of length 'd' removed) in Fig. 1 was simulated in ADS circuit simulator with loading element values of $C_L = 2.533\ pF$ and $L_L = 6.332\ nH$ for 30° phase shift and the results are shown in Fig. 6. Fig. 6(a) clearly shows that PLH-TL based phase shifter can give only positive phase shifts for any loading element values, that is the graph of phase response always remain above 0. This can also be explained using (6) and (8) as any positive traveling wave will always produce positive phase shift (phase advance) $e^{-j\emptyset_{PLH}}$ because $\emptyset_{PLH}$ from (8) is negative.

Finally, metamaterial based CRLH phase shifter of Fig. 2 was simulated in ADS circuit simulator for -10° and 30° phase shifts with $\Delta p = 4\ mm$ and loading element values given in Table 1. The results in Fig.6(a) clearly shows that CRLH phase shifter is capable to give positive or negative desired phase shifts by simply changing loading element values C_L and L_L computed from (12) and (13). The results in Fig. 6(b) shows that the IL of -10° CRLH phase shifter is less than -360°TL and PLH TL phase shifters at 2.4 GHz.

The above discussion concludes that metamaterial based phase shifter is capable to produce 0°, positive and negative phase shifts (independent of the length of structure), and its compact size of 4 mm on FR-4 substrate is 94% less than conventional delay line phase shifter.

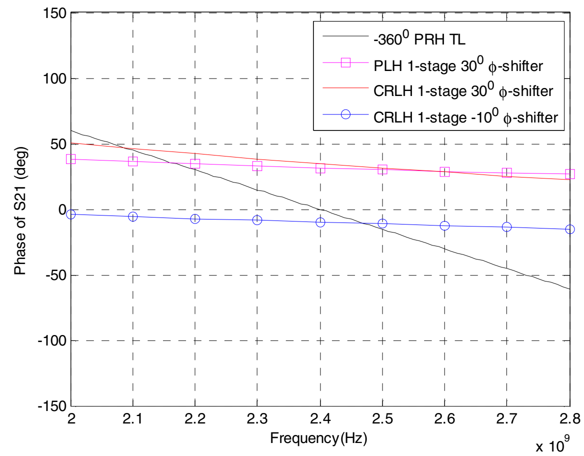

Fig. 6(a) Phase responses of -360° PRH, single stage PLH and single stage CRLH phase shifters in ADS circuit simulator

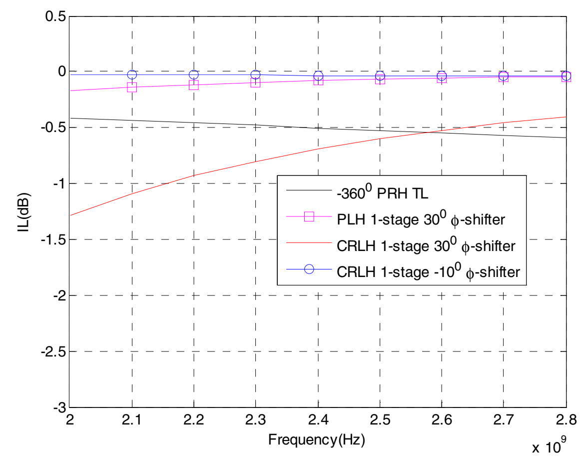

Fig. 6(b) Insertion losses of -360° PRH, single stage PLH and single stage CRLH phase shifters in ADS circuit simulator

V. CONCLUSION

Analytical expressions were derived to compute the required phase shift and insertion loss of a unit cell metamaterial (MTM) based composite right/left-handed (CRLH) phase shifter at a design frequency of 2.4 GHz. The analytical results were compared with ADS circuit simulator results, both with close agreement. Then using single stage CRLH phase shifter, 5-stage and 10-stage MTM phase shifters were designed on FR-4 substrate in ADS circuit simulator. Their phase responses, insertion losses and physical sizes were compared with conventional microstrip material based phase shifter and purely left-handed phase shifter. It was shown that MTM based CRLH phase shifter can produce zero, positive and negative phase shifts independent of its size. The purely left-handed phase shifter is capable to produce only positive phase shifts, while conventional delay line phase shifter can give only negative phase shifts. The size of MTM based CRLH phase shifter (4mm) on FR-4 substrate was found to be 94% less than its conventional delay line counterpart (67 mm) to achieve the desired phase shifts at 2.4 GHz band.

REFERENCES

[1] C. Caloz and T. Itoh, "Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications," John Wiley and Sons, Inc., Hoboken, NJ, 2006, pp. 86-246.

[2] David M. Pozar, "Microwave Engineering", 4th Ed, John Wiley & Sons, Inc., Hoboken, New Jersey February 2012.

[3] S. Simion, R. Marcelli, G. Bartolucci, F. Craciunoiu, A. Lucibello, G. D. Angelis, A. A. Muller,A. C. Bunea and G. I. Sajin, "Composite Right/Left Handed (CRLH) based devices for microwave applications,"Advanced Microwave and Millimeter Wave Technologies: Semiconductor Devices, Circuits and Systems, In Tech Publishing Company, Inc., 2010.

[4] C. Caloz and T. Itoh, "Metamaterials for High-Frequency Electronics," Proceedings of the IEEE, vol. 93, no. 10, Oct. 2005.

[5] A. Sanada, C. Caloz and T. Itoh, "Novel zeroth-order resonance in composite right/left-handed transmission line resonator," Proceedings of the Asia-Pacific Microwave Conference, pp.1588-1591, Nov. 2003.

[6] C. Caloz, "Metamaterial dispersion engineering concepts and applications," Proceedings of the IEEE, vol. 99, no. 10, May 2011.

[7] A. Sanada, C. Caloz and T. Itoh, "Characteristics of the composite right/left-handed transmission lines," IEEE Microw. and Wireless Compon. Lett.,vol. 14, no. 2, Feb. 2004.

[8] R. Marques, F. Martin and M. Sorolla, Metamaterials with Negative Parameters: Theory, Design and Microwave Applications, John Wiley and Sons Inc., Hoboken NJ, 2008.

[9] B. D. Braaten, S. Roy, Irfanullah, S. Nariyal, B. Ijaz, M. M. Masud,S. A. Naqvi and A. Iftikhar, "A Cascaded Reconfigurable RH/CRLH-Zero-Phase Microstrip Transmission Line Unit Cell, "Proceedings of the IEEE Intern. Conf. on Wireless Infor. Tech. and Systems, Maui, Hawaii, November 11th - 16th, 2012.

[10] Chrirtophe Caloz and Tatsuo ltoh, "Application of the transmission line theory of left-handed (LH) materials to the realization of a microstrip "LH line"," IEEE International Symposium on Antennas and Propagation, June 2002.

[11] Hongjoon Kim, Alexander B. Kozyrev, Abdolreza Karbassi, and D. W. van der Weide, "Linear Tunable Phase Shifter Using a Left-Handed Transmission Line," IEEE Microwave and Wireless Component Letters, vol. 15, no. 5, May 2005.

[12] F. Ellinger, H. Jäckel, and W. Bächtold, "Varactor-loaded transmission line phase shifter at C-band using lumped elements," IEEE Trans. Microw. Theory Tech., vol. 51, no. 4, pp. 1135–1140, Apr. 2003.

[13] M. A. Antoniades and G. V. Eleftheriades, "Compact linear lead/lag metamaterial phase shifters for broadband applications," IEEE Antennas Wireless Propag. Lett., vol. 2, pp. 103–106, 2003.

[14] Christian Damm, Martin Schüßler, Jens Freese, and Rolf Jakoby, "Artificial Line Phase Shifter with separately tunable Phase and Line Impedance," Proceedings of the 36th European Microwave Conference, Manchester UK, 2006.

[15] C. Damm, M. Schüßler, M. Oertel, and R. Jakoby, "Compact tunable periodically LC loaded microstrip line for phase shifting applications," in Microwave Symposium Digest. IEEE MTT-S International, June 12-17 2005, pp. 2003–2006.

[16] C. Weil, S. Muller, P. Scheele, Y. Kryvoshapka, G. Lussem, P. Best, and R. Jakoby, "Ferroelectric- and liquid crystal tunable microwave phase shifters," in 33rd European Microwave Conference, October 7-9 2003, pp. 1431–1434.

[17] ZOU Yong-zhuo, LIN Zhi-li, LING Ti, YAO Jun, HE Sailing, "A new broadband differential phase shifter fabricated using a novel CRLH structure," Journal of Zhejiang University SCIENCE A, vol.8, no.10, 2007, pp. 1568-1572.

[18] Youn-Kwon Jung. Bomson Lee, "Compact Metamaterial-Based Tunable Phase Shifter at 2.4 GHz," Journal of electromagnetic engineering and science, vol. 13, no. 2, pp. 137-139, June 2013.

[19] X. Tang and K. Mothaan, "Design considerations for octave-band phase shifters using discrete components," IEEE Transactions on Microwave Theory and Techniques, vol. 58, no. 12, pp. 3459-3466, Dec.2010.

[20] H. Kim, A. B. Kozyrev, A. Karbassi, and D. W. vander Weide, "Linear tunable phase shifter using a left-handed transmission line," IEEE Microwave and Wireless Components Letters, vol. 15, no. 5, pp. 366-368, May 2005.

[21] www.rogerscorp.com

[22] www.agilent.com