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A Novel Metamaterial Microelectromechanical Systems Phase Shifter with High Phase Shift and High Bandwidth

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ABSTRACT

In this paper, new topology of phase shifter is proposed that uses advantage of metamaterial and MEMS technology. The phase shifter is switched between two states of RH- and LH-TL having frequency passband unlike other proposed metamaterials which create the maximum phase shift from one unitcell. Analysis and design approach of the phase shifter is presented and the structure is simulated using 3D simulator. The phase shifter creates 180 degree phase shift with return loss and insertion loss that are better than 15 dB and 0.25 dB in both states at frequency ranges of 1.4-4.4 GHz. Therefore, low loss, high bandwidth and high phase shift are the advantages of the new proposed phase shifter.

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1. INTRODUCTION

Phase shifters are two-port device to change transmission phase of RF systems such as phased array. Phased array uses many phase shifter elements that are effective factor in the cost of the phased array system. Two methods used for minimizing the system cost are implementation of low loss and small size phase shifter. A phase shifter with low loss eliminates power amplifier device in phased array system and its low size decreases the substrate area. Low RF loss, low weight, high linearity and negligible DC power consumption are several advantages of microelectromechanical systems (MEMS) over other technologies such as ferroelectric and monolithic microwave integrated circuits (MMIC) [1], [2].

A wide range of microwave devices with enhanced performances have been developed using the particular of the composite right/left handed transmission line (CRLH-TL) structure [3–5]. One key advantage of electromagnetic metamaterial lies in its subwavelength resonator making them suitable for miniaturization of RF circuits and components [6]. A 3-states reconfigurable phase shifter using CRLH transmission line has been proposed in literature [4]. In fact it is based on LH nature due to using capacitance in horizontal line and inductance in vertical line. For simulation, the ideal switches were used for changing the capacitance and inductance. However, LH-TL such as RH-TL has limited phase shift in light of impedance matching considerations. The proposed phase shifter in literature [5] is based on CRLH-TL. MEMS capacitor was used for changing transmission line from RH to LH nature. This method creates phase shift that is larger than conventional method. Gholizadeh et al. [7] proposed phase shift much larger than Perruisseau-Carrier et al. [5] because of it changes both elements of transmission line simultaneously that solve impedance matching consideration problem.

In this paper, a new structure is proposed that creates the maximum phase shift of 180 degree because it uses new metamaterial transmission line that can be justified as RH- and LH-TL with desirable frequency range using MEMS technology. The conventional metamaterial uses

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RH- and LH-TL with high and low frequency bands, respectively. Therefore, they create low phase shift in common design frequency of RH- and LH-TL, because of they have minimum phase at their minimum and maximum frequency band, respectively. However, in new structure, RH- and LH-TL are bandpass that can be designed at the same frequency band. Therefore, they have maximum phase shift in common design frequency.

2. PROPOSED TOPOLOGY

Proposed phase shifter is based on artificial TL unitcell which can be used as RH or LH (see Figure 1). The RH and LH nature of the unitcell is simply understood from two states. One state is when capacitance C_1 is much larger than C_2. At this condition, the unitcell does not pass low frequency. In the middle frequency, C_1 is dominant and the unitcell is the same as real TL that is consisted of horizontal inductances and vertical capacitance; then it works as RH. By increasing frequency the effect of C_2 increases and it acts like as short circuit. Therefore, the unitcell stop band will be created. Other state is when capacitance C_2 is much larger than C_1. This condition in which C_2 is short circuit was considered in literature [8]. It is shown that the unitcell has LH nature in the state of C_2 is larger than C_1. RH and LH nature of the unitcell can be shown by extracting TL characteristics. In the following section two states of the unitcell will be analyzed in details.

RH and LH nature of the unitcell create negative and positive phase constant, respectively. Thus the unit cell can be used as phase shifter to create 180 degree by adjusting capacitance ratio. It can be realize physically using MEMS technology that is shown in Figure 2. The phase shifter is consisted of coplanar stripline. Two signal lines have been split and then the capacitance C_1 using MEMS bridge and oxide layer is created between signal lines. Two MEMS bridges and oxide layers are used for constructing the capacitance C_2. Two bridges have been connected using high impedance line.

3. ANALYSIS

First, the unitcell is converted to T-model for standard periodic analysis that shown in Figure 3. Dispersion is obtained as follows [9]:

$$\cos(\beta l) = 1 + zy \tag{1}$$

where β is the equivalent phase constant of the unit cell (having periodic nature), l is the unit cell length, z is horizontal branch line impedance and y is vertical branch line admittance. They are described as follows:

$$z = j\omega(2L) - \frac{j}{\omega C_1} \tag{2}$$

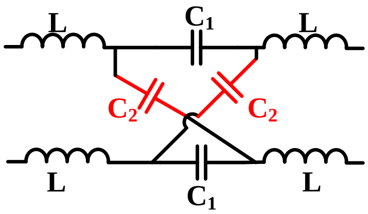


Figure 1. Proposed artificial TL unitcell

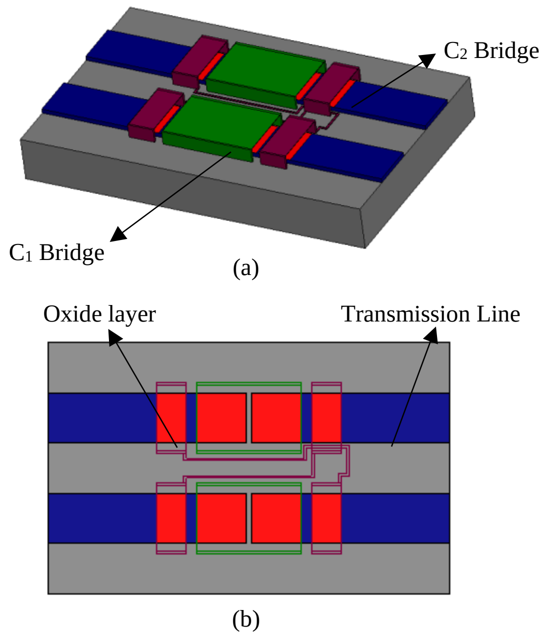


Figure 2. (a) proposed phase shifter (b) top view with transparent bridges

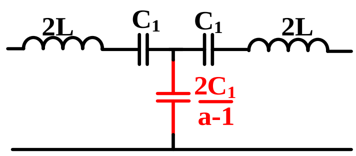


Figure 3. T-model equivalent circuit of proposed artificial TL unitcell

$$y = j\omega\left(\frac{2}{a-1}\right)C_1 \tag{3}$$

$$a = \frac{C_1}{C_2} \tag{4}$$

Therefore the dispersion relation of proposed TL unitcell is obtained as:

$$\beta l = \cos^{-1}\left(1 + \frac{2}{a-1}(1 - 2\omega^2 LC_1)\right) \tag{5}$$

For positive vertical branch line capacitance (RH nature, a>1), the frequency band is:

$$\frac{1}{\sqrt{2LC_1}} \le \omega \le \frac{\sqrt{a}}{\sqrt{2LC_1}} \tag{6}$$

It shows that the unitcell has capability of high-pass frequency operation. For negative vertical branch line capacitance (LH nature, 0<a<1), the frequency band is:

$$\frac{\sqrt{a}}{\sqrt{2LC_1}} \le \omega \le \frac{1}{\sqrt{2LC_1}} \tag{7}$$

It shows that the unitcell has capability of low-pass frequency operation. For further analysis and impedance matching consideration, the characteristics impedance of the proposed unitcell will be obtained. Using standard periodic analysis, the equivalent characteristic impedance (Z_{ol}) of artificial TL is given by [9]:

$$z_{ol} = \sqrt{\frac{2z}{y}}\sqrt{1+\frac{zy}{2}} \tag{8}$$

By substituting Equations (2-4) I ntothe above equation, it is reformulated as:

$$z_{ol} = \sqrt{\frac{2L}{C_1}}\sqrt{\left(1-\frac{a}{2\omega^2 LC_1}\right)\left(1-2\omega^2 LC_1\right)} \tag{9}$$

4. PHASE SHIFTER DESIGN

Electrical model of proposed phase shifter is shown in Figure 4a. It is different from first electrical model (Figure 1); because of the transmission line is used instead of lumped inductance which is also consisted of line capacitance of C_l. Phase shifter has two states corresponding to capacitance ratio of a in regard to the above mentioned analysis. The new T-models of the phase shifter is shown in Figure 4b. The new capacitance ratio (b) in T-model is defined as follows:

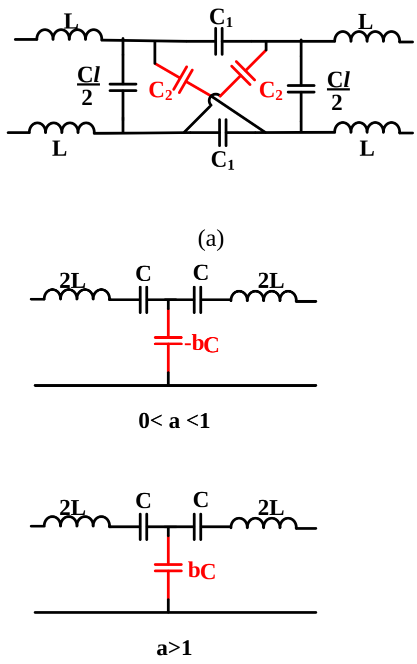
$$C = C_1 + \frac{C_l}{2} \tag{10}$$

$$b = \frac{2C_2 + C_l}{|C_1 - C_2|} \tag{11}$$

The same as above analysis, transmission phase (φ) is obtained as follows:

$$\begin{cases} 1)\ \varphi = \pi - Cos^{-1}\left(-1 - b + 2b\omega^2 LC\right), \ a > 1 \\ 2)\ \varphi = Cos^{-1}\left(1 - b + 2b\omega^2 LC\right) \quad , 0 < a < 1 \end{cases} \tag{12}$$

where the frequency band and c parameter is defined as follows:



(b)

Figure 4. Proposed phase shifter (a) electrical model (b) T-model equivalent

$$\begin{cases} 1)\ \omega_L = \frac{1}{\sqrt{2LC}} \le \omega \le \frac{\sqrt{\frac{b+2}{b}}}{\sqrt{2LC}} = \omega_H\ , \ a > 1 \\ 2)\ \omega_L = \frac{\sqrt{\frac{b-2}{b}}}{\sqrt{2LC}} \le \omega \le \frac{1}{\sqrt{2LC}} = \omega_H , 0 < a < 1 \end{cases} \tag{13}$$

$$c = \frac{f_L}{f_H} \tag{14}$$

where f_L and f_H are low and high frequency of unitcell pass band; respectively and c is defined as their ratio. Phase shifter characteristic equation can be approximated for simplicity of the design. Thus Equation (12) was simplified using Taylor series for parameters of a and c as follows:

$$\begin{cases} 1) \quad \varphi = -2c\sqrt{\left(\frac{f}{f_L}\right)^2 - 1} \ \ , \ a > 1 \\ 2) \quad \varphi = \pi - 2c\sqrt{\left(\frac{f}{f_L}\right)^2 - 1} \ , \ 0 < a < 1 \end{cases} \tag{15}$$

The approximated Characteristic impedance (Z_{ol}) near its extremum value is:

$$Z_{ol} = \frac{Z_o f_L}{f_C}\left[\frac{1-c}{c} + \frac{2c}{c-1}\left(\frac{f}{f_L} - \frac{1}{\sqrt{c}}\right)^2\right] \tag{16}$$

$$\frac{f_L}{f} = \sqrt{c} \tag{17}$$

where parameter of f_c can be defined as follows:

$$f_C = \frac{1}{2\pi\sqrt{LC_l}} = \frac{1}{\pi l\sqrt{2L_t C_t}} = \frac{f_{cl}}{l} \tag{18}$$

where L_t and C_t are inductance and capacitance per length of transmission line. For a>1:

$$\frac{f_C}{f_L} = \sqrt{1 + \frac{2C_1}{C_l}} \tag{19}$$

$$\frac{f_C}{f_H} = \sqrt{1 + \frac{2C_2}{C_l}} \tag{20}$$

For 0<a<1:

$$\frac{f_C}{f_L} = \sqrt{1 + \frac{2C_2}{C_l}} \tag{21}$$

$$\frac{f_C}{f_H} = \sqrt{1 + \frac{2C_1}{C_l}} \tag{22}$$

Using the above equations, the phase shifter was designed at frequency of 3 GHz. The design parameters are shown in Table 1. Two states of phase shifter can be created by capacitance changing using MEMS technology. They have introduced as $C_{1,2u}$ and $C_{1,2d}$ for two states. C_{1u} and C_{2d} are defined for state of a<1. C_{1d} and C_{2u} are defined for state of a>1.

4. RESULTS AND DISCUTION

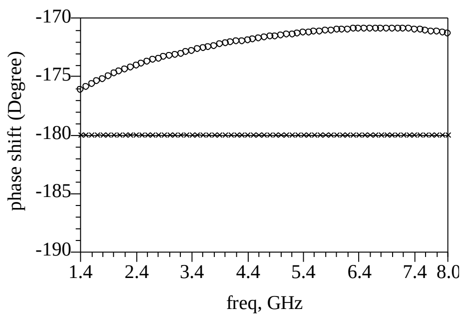
The proposed phase shifter has been simulated using Ansoft HFSS 3D simulator which solves Maxwell equations on the structure. Table 2 shows physical dimension of the structure used in 3D simulation. In addition, ADS circuit model simulation and analytical results would be shown to compare analysis accuracy. Figure 5 shows phase shift characteristic with two states transmission phase. It can be seen that, presented results of analysis and circuit simulation are very close at 1.4-4.4 GHz frequency band which is near design frequency of 3 GHz. But HFSS result is a slightly different with other results, because the circuit model is very simple.

TABLE 1. Design parameters of the circuit model

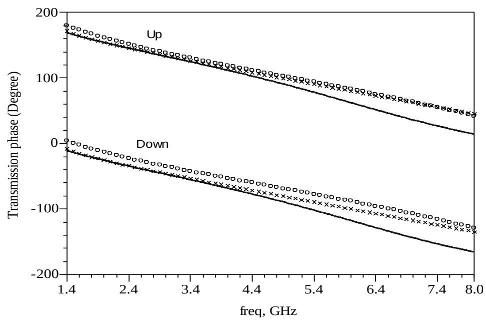
Parameters	Value	Parameters	Value
f(GHz)	3	$f_{L1,2}$ (GHz)	1.32
f_c(GHz)	12.1	$f_{H1,2}$ (GHz)	6.85
f_{cl}(MHz)	67.1	$\varphi\Delta^\circ$	180
$Z_o(\Omega)$	110	$Z_{ol1,2}(\Omega)$	50
ε_{eff}	2.02	l(mm)	5.5
L_t(nH)	260.7	C_t(pF)	43.1
L (pH)	721.4	C_l(fF)	238.5
$C_{1,2d}$(pF)	10	$C_{1,2u}$(fF)	256.8

TABLE 2. Physical dimension of the 3D structure

Parameters	Value	Parameters	Value
Substrate dielectric constant	3.55	Copper Conductivity	58 s/µm
Substrate thickness	0.3 mm	Bridge gap	2.85 um
Loss tangent of the substrate	0.0027	Dielectric constant of capacitances	4
Conductor material	copper	Dielectric thickness of capacitances	0.3 um
Conductor thickness	0.01mm	MEMS bridge width of C_1	565um
Conductor width	300um	MEMS bridge width of C_2	283um
Conductor space	100um	Structure size	$5.5\times1.4mm^2$



(a)

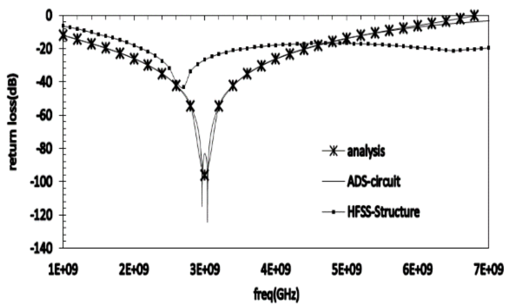


(b)

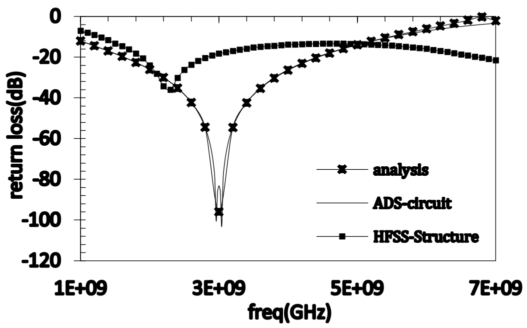
Figure 5. (a) Phase shift characteristic (b) Transmission phase result of ADS (-), HFSS (○) and Analysis (×) for two state of up (where C_1 is up (a<1)) and down (where C_1 is down (a>1))

The models of MEMS bridge and transmission line are not accurate, because they are not consisted of marginal capacitance and inductance. The simulation results also showed that, depend on capacitance ratio, the phase can be positive or negative and this emphasizes RH an LH behavior of proposed artificial unitcell.

Figures 6 and 7 show scattering parameters of proposed phase shifter for two states. It can be seen that the return loss and insertion loss are better than 15 dB and 0.25 dB in both states at frequency ranges of 1.4-4.4 GHz. The analysis and HFSS results are very close, except in the end of the pass band, because of the propagation condition is not exactly true. Therefore, the simulation results show the proposed phase shifter had very good characteristics. It has very low loss and high bandwidth.

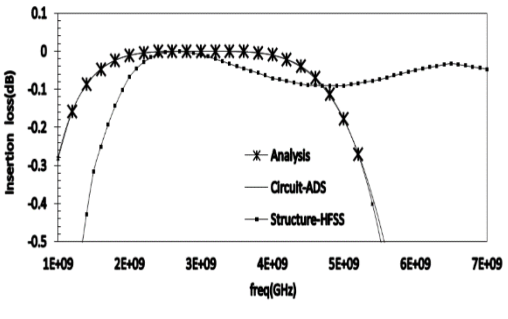


(a)

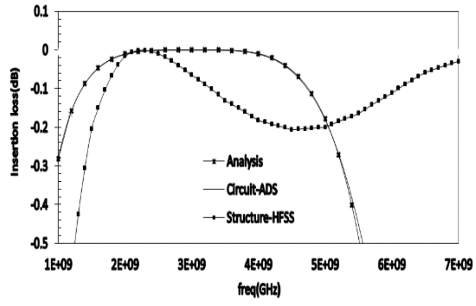


(b)

Figure 6. Return loss (a) in one state which C_1 is up (a<1) (b) in another state which C_1 is down (a>1)



(a)



(b)

Figure 7. Insertion loss (a) in one state which C_1 is up (a<1) (b) in another state which C_1 is down (a>1)

6. CONCLUSION

In this paper, the new structure has been proposed with maximum phase shift of 180 degree using one unitcell. It uses new metamaterial transmission line that can be justified as RH- and LH-TL with desirable frequency range using MEMS technology with the same frequency band operation. Therefore, they have maximum phase shift in common design frequency. The analysis and design of phase shifter have been presented and then the structure was simulated using 3D simulator. The analysis results are good agreement with simulation result around 1.4-4.4 GHz frequency band which is near the design frequency of 3 GHz. The phase shifter has return loss and insertion loss better than 15 dB and 0.25 dB in both states. The results illustrate that the proposed phase shifter has low loss, high band width and high phase shift.

7. ACKNOWLEDGMENT

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چکیده

در این مقاله شیفت‌دهنده فاز با توپولوژی جدید با استفاده از تکنولوژی MEMS و متامتریال ارائه می‌شود. این شیفت‌دهنده فاز بین دو خط انتقال RH و LH که برعکس بقیه متامتریال‌ها دارای باندگذر هستند سوئیچ می‌شود و سبب ایجاد بیشترین شیفت فاز در یک سلول واحد می‌شوند. تحلیل و روش طراحی شیفت‌دهنده فاز ارائه می‌شود و سپس با استفاده از شبیه‌ساز 3D شبیه‌سازی می‌شود. شیفت‌دهنده فاز دارای شیفت فاز ۱۸۰ درجه است و در هر دو حالت دارای تلفات برگشتی و عبوری بهتر از ۱۵ dB و ۰/۲۵ dB در باند فرکانسی ٤/٤–١/٤ GHz است و در نتیجه تلفات پایین، شیفت فاز و پهنای باند بالا از مزایای شیفت‌دهنده فاز ارائه شده، است.

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