Analytical Modeling and Simulation of Tapered Distributed Analogue Tunable Phase Shifter

M. Ould-Elhassen, M. Mabrouk, P. Benech, A. Ghazel

Abstract—**In this work, the electrical modeling and simulation of phase shifter based on distributed CPW transmission lines structure is presented. It presents an analytical study followed by circuit simulation of the phase shifting, the insertion loss and the return loss of proposed phase shifter. The expression of phase shifting is obtained through a global ABCD matrix of 9-sections of proposed phase shifter then obtained by circuit simulation on Matlab. This study is compared with characterized phase shifter.**

Index Terms—**Phase Shifter, Modeling, Simulation, Linear Taperisation, Distributed Loaded Line.**

I. INTRODUCTION

Nowadays, Radio Frequency (RF) and microwave systems have become important parts of modern life, particularly in wireless communications, multi path systems and phased array technologies. Phase shifter is a microwave device that presents many enhancements of features of microwave systems and enables them to provide new beneficial functions thanks to its ability to adjust the phase of signal as desired.

Properly, we can define phase shifter as device that can adjust the phase of an input signal and in the best case providing low insertion loss, and equal amplitude in all phase states. It can be reciprocal, meaning that it works effectively on signals passing in either direction [1-2].

We can also define controllable phase shifters that can be tunable electrically, magnetically or mechanically [3]. Most of the phase shifters are passive reciprocal networks and most of them are electrically-controlled. While the applications of microwave phase shifters are numerous, perhaps the most important application is within a phased array antennas system, in which the phase of a large number of radiating elements are controlled to force the electro-magnetic wave to add up at a particular angle to the array.

In our case we present a distributed analogue phase shifters fabricated with transmission lines which are periodically loaded by Surface Diode Varactor. This phase shifter was only experimentally characterized and reported by [4]. This distributed phase shifter is consists of 9 cells where two high impedance lines, at input and output, that are loaded by periodic cascaded lumped capacitive impedances.

II. MODELING

The electrical equivalent circuit of the phase shifter distributed structure is shown in Figure 1. A CPW transmission line of characteristic impedance Z_c and electrical length θ is periodically loaded by varactors (ideally modeled by a variable capacitance C_2), in series with inductors L. The input and output T-sections are different from the central sections, with a transmission line having an electrical length θ' and variable capacitance C_1. The only difference with figure 1 of [4] is C_b which is used only when V_{bias} is applied.
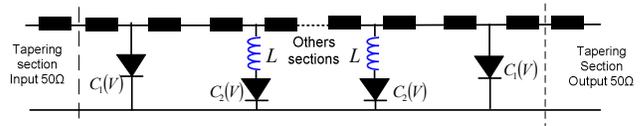
Fig. 1. Electrical equivalent circuit of studied distributed phase shifter

A. Coplanar Waveguide Transmission Line Theory

Coplanar Wave Guide (CPW) technology is used for fabricating phase shifter. It has some immediate advantages. First, both ground and signal lines are on the same side of substrate affording easy access for shunt mounting of elements without drilling. Second, CPW has a canonical closed forms model [5] that can be used to obtain design equations.

The CPW transmission line is characterized by its effective permittivity ε_{eff} and characteristic impedance Z_c. Equation (1) shows how to calculate the effective permittivity of our CPW line and equation (2) shows the characteristic impedance [6].

$$\varepsilon_{eff} = 1 + \frac{\varepsilon_r - 1}{2}\left[\frac{K(k')}{K(k)}\frac{K(k_1)}{K(k_1')}\right] \quad (1)$$

$$Z_c = \frac{30\pi}{\sqrt{\varepsilon_r}}\frac{K(k')}{K(k)} \quad (2)$$

Where the functions $\frac{K(k)}{K(k')}$ and $\frac{K(k)}{K(k')}$ are defined as following [6]:

$$\frac{K(k)}{K(k')} = \frac{1}{\pi} Log\left(2\frac{1+\sqrt{k}}{1-\sqrt{k}}\right) \text{ For } 0.707 \le k < 1 \qquad (3\text{-}a)$$

$$\frac{K(k)}{K(k')} = \pi \Big/ Log\left(2\frac{1+\sqrt{k'}}{1-\sqrt{k'}}\right) \text{ For } 0 \le k < 0.707 \qquad (3\text{-}b)$$

$$k = \frac{W}{W+2G} \qquad (3\text{-}c)$$

$$k_1 = \frac{\sinh\left(\dfrac{\pi W}{4H}\right)}{\sinh\left(\dfrac{\pi(W+2G)}{4H}\right)} \qquad (3\text{-}d)$$

$$k' = \sqrt{1-k^2} \qquad (3\text{-}e)$$

Where W is a CPW width, G is the gap and H is substrate thick.

B. Input and tapering sections

The figure 2 shows the scheme of tapering section at the input of phase shifter. This section consists of CPW transmission line portion loaded by a capacity that the value can be adjust.
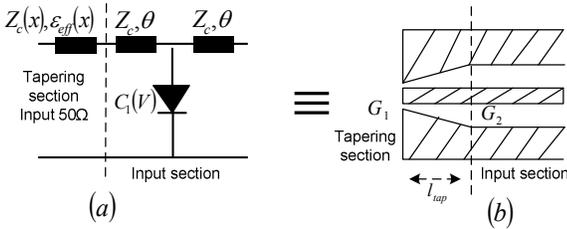
Fig. 2. Electrical equivalent circuit of tapering section (a) input section (b)

For the tapering section Fig. 2(a) of our phase shifter, we define the gap variation as linear shape and as function of the tapering length (l_{tap}) as following:

$$G_2(x) = mx + G_1 \qquad (4\text{-}a)$$

Where m is $m = \dfrac{G_2 - G_1}{l_{tap}} \qquad (4\text{-}b)$

The following figure gives the variation of characteristic impedance Z_c and the effective permittivity ε_{eff} as function of the tapering length l_{tap} and relative permittivity ε_r of substrate. In this case, we use the equations (1-3) to calculate Z_c and ε_{eff}. The variation of tapering section's gap function of length, yield a variation of both Z_c and ε_{eff}. In our Matlab program, we vary tapering length and relative permittivity of used substrate and we give the behaviour of tapering section's parameters.
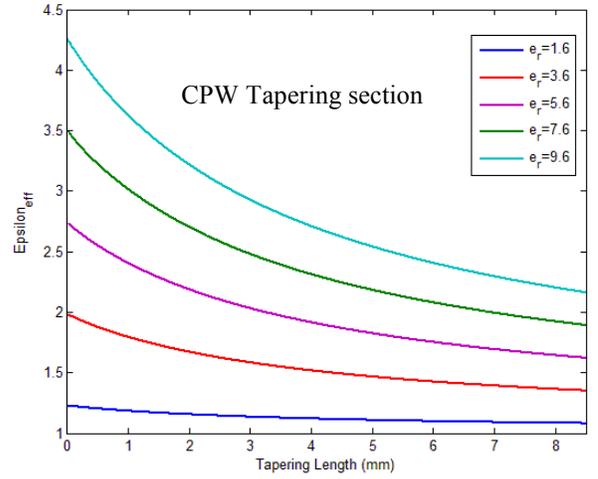
(a)
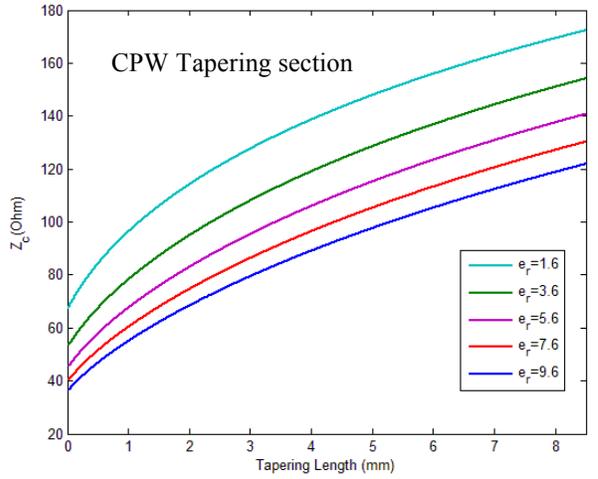
(b)

Fig. 3. Effective permittivity variation vs length (a) , Characteristic impedance variation vs length (b) for different values of relative permittivity.

In this section, we will calculate the ABCD matrix of tapered section. For the TEM mode of propagation in transmission line, the voltage $V(x)$ and the current $I(x)$ equations are given in by as following [7]:

$$\frac{d^2V}{dx^2} - \frac{1}{Z}\frac{dZ}{dx}\frac{dV}{dx} - ZYV = 0 \qquad (5\text{-}a)$$

$$\frac{d^2I}{dx^2} - \frac{1}{Y}\frac{dY}{dx}\frac{dI}{dx} - ZYI = 0 \qquad (5\text{-}b)$$

Where Z and Y are series impedance and shunt admittance per unit of length of line, respectively, and are continuous functions of x. For the linearly tapered transmission, we assume:

$$Z(x) = Z_{01}(1+mx) \qquad (6\text{-}a)$$

$$Y(x) = Y_{01}(1+mx)^{-1} \qquad (6\text{-}b)$$

Where m is a measure of taper [7] defined by equation 4-b. Substitution of equation (6-a) in (5-a) gives:

$$\frac{d^2V}{dx^2} - \frac{m}{1+mx}\frac{dZ}{dx}\frac{dV}{dx} - \gamma^2 V = 0 \quad \text{where} \quad \gamma = \sqrt{ZY} \qquad (7)$$

By referring to the work reported by [8], the particular solutions of (7) are given by:

$$p(x) = -(1+mx)J_1\left(\left(\frac{\beta}{m}\right)(1+mx)\right) \qquad (8\text{-}a)$$

$$q(x) = -(1+mx)\left(N_1\left(\left(\frac{\beta}{m}\right)(1+mx)\right) + 2jJ_1\left(\left(\frac{\beta}{m}\right)(1+mx)\right)\right) \qquad (8\text{-}b)$$

Where, J_1 and N_1 are the Bessel functions of the first and second kind respectively.

By using the expression given in [7] and [8] the transfer matrix parameters ABCD are obtained as:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_{tap} = \frac{2(1+ml)}{\pi\beta/m}\begin{pmatrix} \frac{1}{1+ml}(J_1(a)N_0(b)-J_0(b)N_1(a)) & jZ_0(J_1(a)N_1(b)-J_1(b)N_1(a)) \\ \frac{j}{Z_0(1+ml)}(J_0(a)N_0(b)-J_0(b)N_0(a)) & (J_1(a)N_0(b)-J_0(b)N_1(a)) \end{pmatrix} \qquad (9)$$

After calculating the ABCD matrix of tapering section, the ABCD matrix of input section can be written as following:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_{input} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{tap}\begin{pmatrix} \cos(\theta) & jZ_c\sin(\theta) \\ \frac{j\sin(\theta)}{Z_c} & \cos(\theta) \end{pmatrix}\begin{pmatrix} 1 & 0 \\ jC_1(V)\omega & 1 \end{pmatrix}\begin{pmatrix} \cos(\theta) & jZ_c\sin(\theta) \\ \frac{j\sin(\theta)}{Z_c} & \cos(\theta) \end{pmatrix} \qquad (10)$$

C. Central section

Each of central-sections of the phase shifter consists of CPW transmission line elements loaded by parallel LC circuit that we can also vary the values. The electrical equivalent circuit of one central section is showed in figure 5.
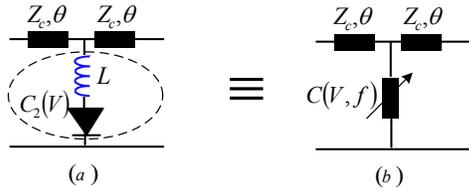
Fig. 4. (a) Electrical equivalent circuit of central section (b) Equivalent capacitance

The input and output sections are tapered and an inductance is added in series with the varactors. The tapering allows matching the phase shifter over a large variation of the capacitance C. Series inductances allow improvement of the C_{max}/C_{min} varactor ratio, allowing to have more efficient varactors, a low number of sections, and so short phase shifters [4].

First, we show how the series inductance improves the varactor's behavior. We propose a design procedure for the phase shifter.

The equivalent impedance of the series LC network is written as:

$$Z_{eq} = jL\omega + \frac{1}{jC\omega} \qquad (11\text{-}a)$$

$$Z_{eq} = \frac{1-LC\omega^2}{jC\omega} \qquad (11\text{-}b)$$

$$Z_{eq} = \frac{1-(\omega/\omega_0)^2}{jC\omega} \quad \text{Where} \quad \omega_0 = 1/\sqrt{LC} \qquad (11\text{-}c)$$

We assume that $\omega < \omega_0$, the equivalent capacitance

$$C_{eq} = \frac{C}{1-(\omega/\omega_0)^2} \qquad (12)$$

So we can assume that we have a capacitance C_{eq} function of frequency and voltage.

The ratio $y_{eq} = C_{eq\,max}/C_{eq\,min}$ where

$$C_{eq\,max} = \frac{C_{max}}{1-(\omega/\omega_{0\,min})^2} \quad \text{and} \quad C_{eq\,min} = \frac{C_{min}}{1-(\omega/\omega_{0\,max})^2} \qquad (14)$$

With $\omega_{0\,max} = \dfrac{1}{\sqrt{LC_{min}}}$ and $\omega_{0\,min} = \dfrac{1}{\sqrt{LC_{max}}}$

$$y_{eq} = \frac{C_{max}}{C_{min}}\left(\frac{1-(\omega/\omega_{0\,max})^2}{1-(\omega/\omega_{0\,min})^2}\right) \qquad (15)$$

$$y_{eq} > y = C_{max}/C_{min} \qquad (16)$$

In the next section, we prove that in the case of added inductance L we can improve the performances of the phase shifter and we get also lower phase shifter means low sections number.

The ABCD matrix of each central section can be written as following:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_{central} = \begin{pmatrix} \cos(\theta) & jZ_c\sin(\theta) \\ \frac{j\sin(\theta)}{Z_c} & \cos(\theta) \end{pmatrix}\begin{pmatrix} \frac{jC_2(V)\omega}{1-\left(\omega/\omega_0\right)^2} & 0 \\ 1 & 1 \end{pmatrix}\begin{pmatrix} \cos(\theta) & jZ_c\sin(\theta) \\ \frac{j\sin(\theta)}{Z_c} & \cos(\theta) \end{pmatrix} \qquad (17)$$

D. The whole of the Phase Shifter

In this part, in order to determine the characteristics of our phase shifter, the cell unit of our phase shifter showed in the figure (5-a) by the electrical equivalent LC circuit showed in the figure (5-b) where L_d and C_d are series inductance and shunt capacitance per unit of length of line, respectively. C_{var} is the varactor capacitance that varies with voltage.
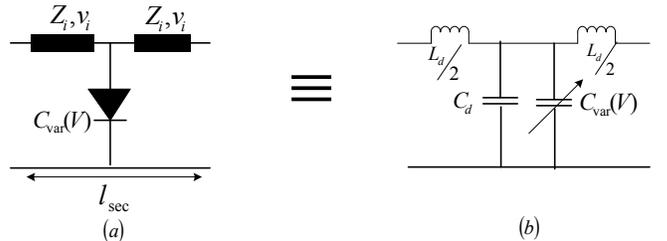
Fig. 5. (a) Cell unit of our distributed phase shifter; (b) Equivalent circuit of Varactor loaded line [9]

The parameters of equivalent LC circuit (5-b) can be determined by using the transmission line parameters: velocity

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v_i, the characteristic impedance Z_i and the effective permittivity [9-14]:

$$L_d = \frac{l_{sec}}{v_i} Z_i, \ C_d = \frac{l_{sec}}{Z_i v_i} \ \text{and} \ v_i = \frac{c}{\sqrt{\varepsilon_{eff}}} \tag{18}$$

To determine characteristic impedance for the CPW line of ABCD matrix, we must set the determinant of following matrix to zero and the relation $AD - BC = 1$ [9]:

$$\begin{pmatrix} A - e^{-\gamma l} & B \\ C & D - e^{-\gamma l} \end{pmatrix} \tag{19}$$

That gives the relation $\cosh(\gamma l) = (A + B)/2$ and the characteristic impedance can be determined by $Z_{ABCD} = \sqrt{B/C}$. By using the LC equivalent electrical circuit given by the figure 5-b, much simpler ABCD matrix can be given as following:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & J\omega \frac{L_d}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ jC\omega & 1 \end{pmatrix} \begin{pmatrix} 1 & J\omega \frac{L_d}{2} \\ 0 & 1 \end{pmatrix} \tag{20}$$

From the previous matrix, we can determine the following expressions by using these expressions of $Cosh(\gamma l)$ and Z_{ABCD} given above. From the equation (20) we can obtain:

$$\omega^2 = \frac{2}{L_d C}(1 - \cosh(\gamma l)) \tag{21}$$

$$Z_{ABCD} = \sqrt{\frac{L_d}{C} - \frac{\omega^2 L_d^2}{4}} \tag{22-a}$$

The lumped element transmission line periodic model shown in the figure 1 is limited by Bragg frequency, so named for the similarity to optical Bragg diffraction. In transmission lines the Bragg frequency corresponds to the frequency where $Z_{ABCD} = 0$ or $Cos(\beta l)=0$, that means, if the wavelength approaches of the spacing length l_{sec}. At the Bragg frequency there is no power transfer from one port to the other. For this reason, this frequency has to be good practical limit for the phase shifter operation of such structure [15].

$$Z_{ABCD} = \sqrt{\frac{L_d}{C_d + C_{var}}} \sqrt{1 - \left(\frac{\omega}{\omega_{Bragg}}\right)^2} \tag{22-b}$$

$$f_{Bragg} = \frac{\omega_{Bragg}}{2\pi} \tag{23}$$

$$f_{Bragg} = \frac{1}{\pi \sqrt{L_d (C_d + C_{var})}} \tag{24}$$

$$f_{Bragg}^{min} = \frac{1}{\pi \sqrt{L_d (C_d + C_{max})}} \tag{25}$$

The Bragg frequency is inversely proportional to L_d, C_d and varactor diode capacitance C_{var}.

From equation (22-b), the characteristic impedance is written as function of Bragg frequency, it is evident that for frequency well below the Bragg frequency $f \ll f_{Bragg}$ the characteristic can be simplified to the equation (26).

The phase shifter is assumed as loaded transmission line characterized by Z_L and v_{phase} that can be defined as following [15]:

$$Z_L = \sqrt{\frac{L_i}{C_i + C_{var}/l_{sec}}} \ \text{With} \ L_i = \frac{L_d}{l_{sec}} \ \text{and} \ C_i = \frac{C_d}{l_{sec}} \tag{26}$$

$$v_{phase} = \frac{1}{\sqrt{L_i \left(C_i + C_{var}/l_{sec}\right)}} \tag{27}$$

$$v_{phase} = \frac{v_i}{\sqrt{1 + \frac{C_{var}/l_{sec}}{C_i}}} \tag{29}$$

The first key of design relationship is obtained by imposing the constraint that when the varactor is in its maximum capacitance state [15].

We define the ratio:

$$x = \frac{C_{max}/l_{sec}}{C_d} \ \text{and} \ y = \frac{C_{max}}{C_{min}} \tag{30}$$

By using the equations (26) and (30), the characteristic impedance of each portion of transmission line, the phase velocity, the minimum Bragg frequency and the section length can be written as function of x as following:

$$Z_i = Z_L \sqrt{1 + x} \tag{31}$$

$$v_{phase} = \frac{v_i}{\sqrt{1 + x}} \tag{32}$$

$$f_{Bragg}^{min} = \frac{v_i}{\pi l_{sec} \sqrt{1 + x}} \tag{33}$$

$$l_{sec} = \frac{v_i}{\pi f_{Bragg}^{min} \sqrt{1 + x}} \tag{34}$$

The phase shift generated by one unit cell can be also defined as following:

$$\varphi = 2\pi f \frac{l_{sec}}{v_{phase}} \tag{35}$$

In order to design our phase shifter, we must consider the cases that we have the minimum and the maximum of varactor capacitor, so the maximum differential phase shifting which can be obtained by one cell unit is:

$$\varphi_{max} = 2\pi f \frac{l_{sec}}{v_i}\left(\sqrt{1 + x}\right) \ \text{and} \ \varphi_{min} = 2\pi f \frac{l_{sec}}{v_i}\left(\sqrt{1 + xy}\right) \tag{36}$$

$$\delta\varphi = 2\pi f \frac{l_{sec}}{v_i}\left(\sqrt{1 + x} - \sqrt{1 + xy}\right) \tag{37}$$

The equation (38) allows us to determine the number of section of phase shifter. To get a differential phase shifting of 360° at a specified frequency f and voltage V, the correspondence number of sections is given by:

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$$n_{\text{sec}} = \frac{2\pi}{\delta\varphi} \tag{38}$$

In order to calculate the phase shift of the studied entire phase shifter, we use the global matrix ABCD principle, composed of (n) cascaded sub-matrices.

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_{global} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{input} \times \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{central}^{n\_sec} \times \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{output} \tag{39}$$

The phase shift is the argument of S_{21} parameter of studied phase shifter.

$$S_{21} = \frac{2}{A + \dfrac{B}{Z_0} + CZ_0 + D} \tag{40}$$

The equation (40) shows the expression of the parameter S_{21} with Z_0 the reference impedance.

E. Schottky Diode modelling

Schottky diodes are voltage variable capacitors or tuning diodes, are best described as diode capacitors employing the junction capacitance of a reverse biased PN junction [16]. The capacitance of these devices varies inversely with the applied reverse bias voltage and is used to vary the centre frequency of the resonator. The equivalent circuit of a typical Schottky varactor together with the package parasitic is shown in Figure 6.
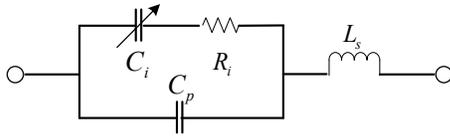
Fig. 6. Schottky Diode Model [16]

In our case we use a mathematical model of simulated varactor diode and it is given by the equation (41), this Schottky model is studied and modeled by [16].

$$C(V) = \frac{C_{j0}}{\left(1 - \dfrac{V}{\phi}\right)^M} + C_p \tag{41}$$

Where C_j is the fitted junction capacitance, C_{j0} is the zero-bias junction capacitance, V is the junction potential, ϕ is the fitted barrier potential, and M is the grading coefficient.

III. DESIGN OF WHOLE PHASE SHIFTER AND VALIDATION MODEL

A. CPW line model

In order to verify our CPW transmission line synthesis results, we have calculated the effective permittivity ε_{eff} and characteristic impedance Z_c values from both equations (1) and (2) using our own Matlab program. The table 1 shows below these values and those performed with the help of LineCalc of ADS© [17], AppCAD© [18] and our Matlab program. Good agreement is obtained between all of these results which are used for designing the CPW transmission lines sections of our phase shifter prior simulation.

TABLE 1
EFFECTIVE PERMITTIVITY AND CHARACTERISTIC IMPEDANCE COMPUTED ON APPCAD, MATLAB AND ADS

Parameters	LineCalc	AppCAD	Matlab
ε_{eff}	1.372	1.37	1.376
Z_c	178.387Ω	177.1Ω	179.79Ω

In this part, we calculate the parameters of tapered transmission line section.

The input gap $G_1=0.2mm$, $G_2=5mm$, the taper parameter $m= 0.5765$ and tapering section length $l_{tap}=8.5mm$.

B. Diode Model

The Schottky diode that was used by [4] is silicon MACOM (MA46H071) one. The characteristic of these diodes [19] are depicted on figure 7. The zero-bias capacitance is $C_{j0}=C_{max}=2.45pF$, the ratio $C_{max}/C_{min}=7$, the series resistance Rs=0.4Ω, and the parasitic series inductance is Ls=1.3 nH.
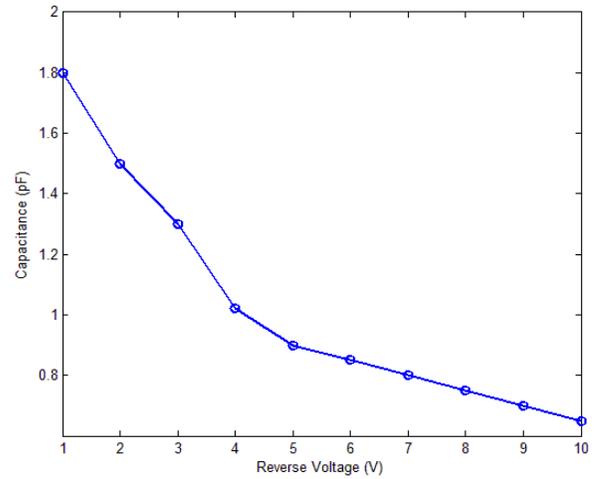
Fig. 7. Capacitive vs Reverse Voltage [19]

From the datasheet we can read and see $C_{max}=2.45pF$ and $C_{min}=0.45pF$. Table 2 gives the value of voltage variation used for our simulation and the values of capacitance.

TABLE 2
CAPACITANCE VALUE VS TENSION OF VARACTOR DIODE

Reverse voltage	1V	2V	3V	4V	5V	6V	7V	8V	9V	10V
Capacitance (pF)	1.8	1.4	1.3	1.02	0.9	0.85	0.8	0.75	0.7	0.65

C. Phase shifter design

In this part, we proceed to determine the design's

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parameters of our phase shifter. In this purpose we use the key design parameter as x and thus we can determine the other parameters (Z_i, l_{sec} and n_{sec}).

For $x=5$, we used a MACOM (MA46H071) diode, and Rogers substrate RO4003 [ε_r = 3.36, H = 813.0μm, tg(δ)=1.5*10^{-3}], and the design parameters are: Z_i = 122 Ω C_d=0.4pF, and l_{sec}=8.9mm. Then these parameters are entered into our Matlab program, along with the MA46H071 diode parameters provided by datasheet, to simulate this phase shifter. We computed dimensions for CPW impedance of 179Ω, and the corresponding geometrical dimensions are : $W=1.34mm$ and $G_2 = 5mm$.

TABLE 3
CHARACTERISTICS PARAMETERS FOR CENTRAL SECTION

	x	Z_i	l_{sec}	y	n_{sec}	F
Without L	5	122	5mm	7	13	1GHz
$L=2.7\ nH$	5	122	5mm	9.12	12	1GHz

From table 3 and figure 8, we can see that if we use series inductor L with the varactor diode, we can get low number of sections (12) and thus a short phase shifter operating at 1.0 GHz. That confirms what was reported by [4].
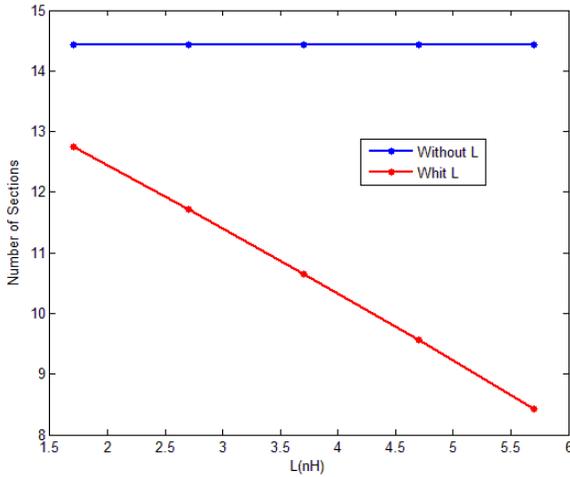
Fig. 8. Number of section vs added inductance

IV. SIMULATION RESULTS

In our both simulations, we used the same parameters published by [4]. The tapering section length is 17.0mm and central section length is 10.0mm. For our simulations, we have implemented our Matlab program for ABCD matrix calculating from DC to 1.2GHz. Then we deduce the argument of S_{21} parameter which is the phase shift and both modules of S_{21} and S_{11}.
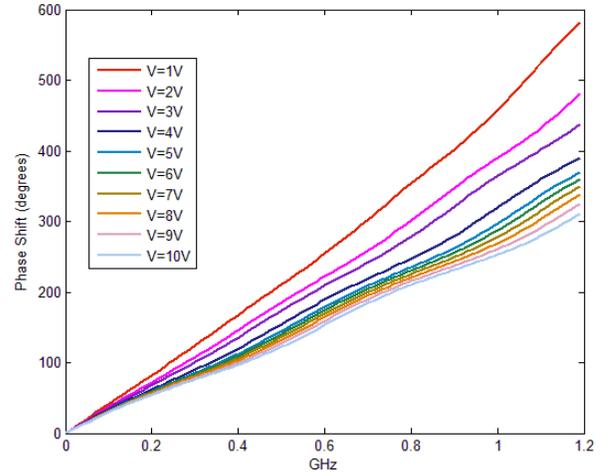
Fig. 9. Simulation results of phase shifting

Figure 9 shows the simulation results of phase shifting. These results show a good agreement with the reported and published measurements in [4]. We have at 1GHz a phase shifting up to 500° for a voltage $V=1V$.
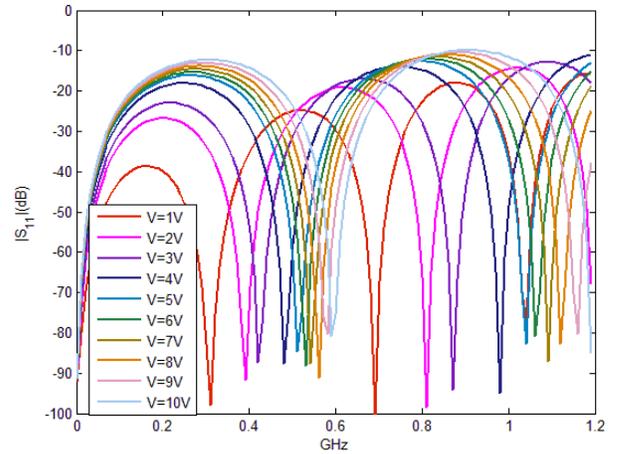
Fig. 10. Simulated return loss S_{11} of Phase shifter
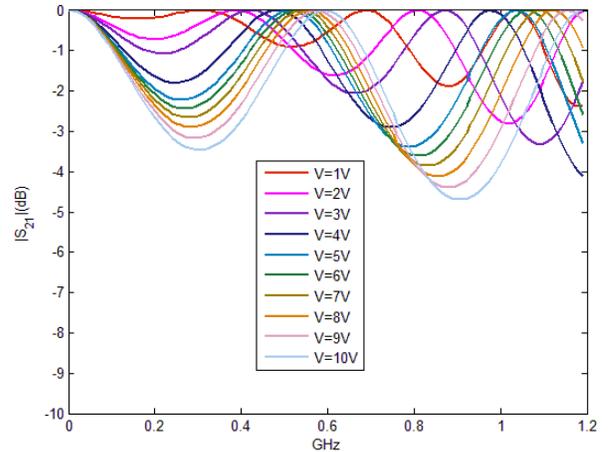
Fig. 11. Simulated insertion loss S_{21} of Phase shifter

The depicted results of figures 10 and 11 show a great

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improvement compared to those presented in [4]. The maximum of insertion losses is about 4.5dB. The return loss is better than 12.0 dB. These both results constitute a good validation of the addition of an inductance in series with the varactors and the tapering of the input and output sections to improve performances of our studied phase shifter.

V. Conclusion

In this work, we have developed an analytical model based on ABCD matrix concept of an analogue distributed phase shifter using varactors diodes. The measurement results of this phase shifter were already published in [4]. Although our goal isn't to improve but to confirm the studied and published structure of [4], we can say that our modeling and simulation confirm good improvement of phase shifter performances. We have developed our own Matlab software in order for simulating S_{21} and S_{11} parameters of our phase shifter, and then deduce its phase shifting which is the S_{21} argument. All of our simulation results are correlating with published measurements.

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