Electronically Reconfigurable Two-Stage Schiffman Phase Shifter for Ku Band Beam Steering Applications

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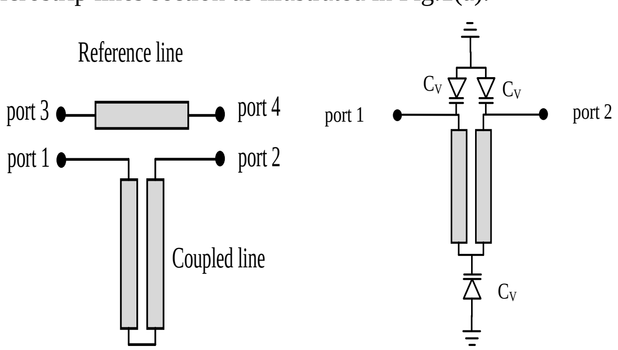
***Abstract*—An electronically reconfigurable phase shifter using two Schiffman sections is performed for beam steering applications in Ku band. The proposed phase shifter consists of only two cascaded coupled-line sections with the reference line removed. This circuit is loaded by varactor diodes that ensure its tunability over a wide bandwidth. By supplying these varactor diodes with suitable bias voltages, a phase shift is continuously adjusted and reached up to 168° at 12.7 GHz with low insertion losses according to the simulations. Thus, the proposed two-stage phase shifter is able to reach a beam steering angle of 28.6° at 12.7 GHz with only one control voltage. The proposed structure exhibits that our phase shifter has a compact size and a large phase shifting range throughout the Ku band. The tunable phase shifter is prototyped and the measurement results are presented.**

***Keywords*—Schiffman phase shifter; reconfigurable; varactor diode; beam steerability; Ku-band**

I. Introduction

Differential phase shifters are frequently exploited in communication systems such as phased array antennas and microwave control devices. This appliance is made of main and reference lines which produce a constant differential phase shift between them [1-3].

One of the most appealing types of differential phase shifters is the Schiffman structure [4-8] due to its simple topology and wideband characteristic. For this configuration, the differential phase shift is provided by a parallel-coupled microstrip lines section as illustrated in Fig.1(a).



(a) Conventional Structure. (b) Tunable Structure.

Fig. 1. Schematic Design of the Single Stage Schiffman Phase Shifter.

Recently, the tunable differential phase shifters have become increasingly beneficial to achieve the beam steering functions using compact structures [9, 10]. In the case of steerable antenna arrays, a large phase shifting range is required to control the direction of the radiation pattern. To that end, a various design of reconfigurable phase shifters suitable for beam steering applications has been mentioned in literature [11-13]. These phase shifters generally contain some kind of active devices offering an adjustable phase shift throughout a large frequency band [12]. One of the prominent tuning components is the varactor diode which has a high phase variation by continuously adjusting the voltages [13].

The Schiffman phase shifter compensated with varactor diodes is a good candidate for beam steering applications because of its potential to achieve a continuously variable phase shift throughout a large frequency band keeping the compactness of the design [14]. This phase shifter model showed in Fig. 1(b), is proposed and developed in [15]. This new approach has some attractive features such as the simplicity of the structure in a planar configuration, the compact size, the wide bandwidth and the large phase shift range with easy adjustment of the phase shift.

Nevertheless, some of the tunable single stage phase shifters produce a restricted range of phase shift variation. Therefore, to resolve this problem, a cascade configuration of phase shifters seems to be an interesting solution to achieve a large phase shift response [16-21]. In this respect, few Ku-band tunable phase shifter designs are referenced in the literature. Therefore, a new structure with both compact size and large phase variation range in Ku band is favored to meet the requirements of beam steering applications.

This letter reports the design, for the first time, of a compact configuration of tunable phase shifter using two Schiffman sections operating especially in Ku band for beam steering applications. To accomplish the continuous tunability of the phase shifter, varactor diodes are introduced to the structure, which includes two pairs of cascaded coupled lines. In the phase shifter structure, it is suggested to cascade the Schiffman sections as a means of increasing the phase shift variation while maintaining the compactness of the phase shifter.

The novelty of this work is proposing a phase shifter that provides an electronically adjustable phase shift through changing the bias voltages of the diodes over the Ku band without increasing the phase shifter size.

The aim of this work is to integrate, as part of a larger ongoing project, our tunable phase shifter in a compact feeding network of the phased arrays antenna, allowing it to continuously steer its beam towards geo-satellites for Ku-band television broadcasting.

II. Phase Shifter Design

Many modified Schiffman phase shifters were proposed for different purposes, such as bandwidth enhancement, and circuit miniaturization [5]. Many researches suggest many structures such as the double-coupled lines [6, 7], cascaded coupled lines, parallel coupled lines [4], and multi-section coupled lines structures [8]. In our proposed design, the original Schiffman phase shifter is amended to develop an accordable phase shifter, having coupled lines charged by varactor diodes without reference line.

So as to enlarge the phase shift variation, two single stage phase shifters are connected in cascade. Each one has a Schiffman structure loaded with three varactor diodes (Cv) to produce a continuously adjustable phase shift by controlling the diode's voltage.

Pursuing simplicity, three identical varactor diodes (MA46H120) are used in the layout of the suggested single stage phase shifter. In fact, two varactor diodes were placed in series, and another one was linked with the ground plane [18]. This diode was selected because of its high speed and its large capacitance variation. According to the instructions provided by the manufacturer, its capacitance value varies from 1.15 pF to 0.15 pF when the diode is biased from 0 to 18 Volts. The measured S-parameters of the varactor diode and its equivalent electrical circuit are reported to utilize them during the optimization step.

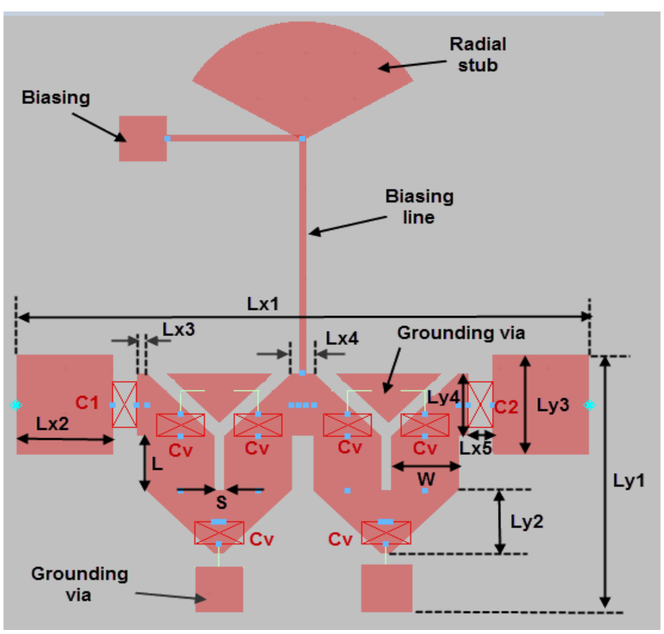


Fig. 2. Design of the Two-Stage Tunable Schiffman Phase Shifter.

TABLE I. Design Parameters and Dimensions Values for the Suggested Phase Shifter

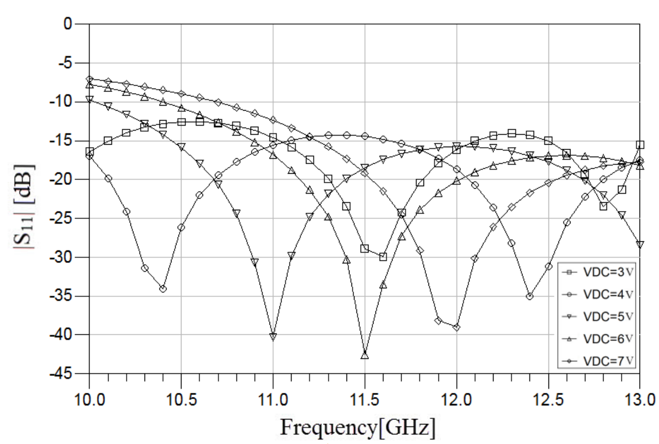
Parameters	Value[mm]	Parameters	Value[mm]
L	1.2	Ly4	1.4
W	1.4	Lx1	11.8
S	0.2	Lx2	2
Ly1	5.7	Lx3	0.2
Ly2	1.4	Lx4	0.45
Ly3	2.23	Lx5	0.5

The placement of the diodes was carefully considered with the aim of getting only to get only one feed line for the whole phase shifter. Thus, the two single stage phase shifters do not need to be individually biased. In this case, one bias line is connected to the phase shifter where the voltages are applied to polarize the six varactor diodes. In addition, the design includes two capacitances C1 and C2 which serve to uncouple the input power in the phase shifter from the supply line.

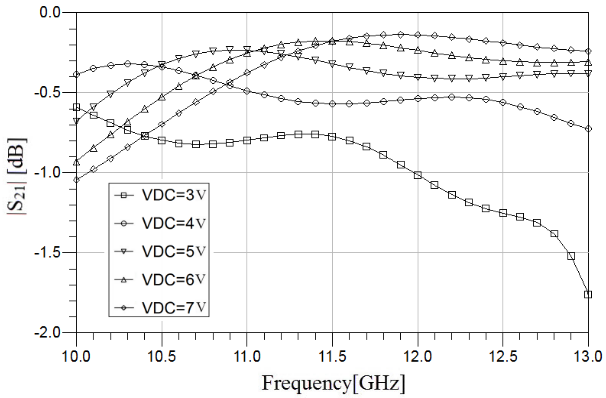
The phase shifter was implemented on a Teflon substrate having a relative permittivity of 2.55 and a thickness of 0.8 mm. It is designed using microstrip technology and simulated through the ADS simulator in the frequency range 10.7-12.7 GHz. The design of the proposed phase shifter is illustrated in Fig. 2 and its dimensions are enumerated in Table I.

III. Results and Discussions

The simulated S-parameters of the two-stage Schiffman phase shifter for different control voltages are presented in Fig. 3. In accordance with this figure, it is noted that the phase shifter is well matched over the entire operating frequency band and the return and insertion losses present good performances at different polarization voltage values. In fact, the return loss remains below -10 dB in the whole operating band when the voltages change from 3 V to 7 V, as illustrated in Fig. 3(a). In addition, the insertion loss reaches the maximum value of -0.57 dB while the voltages exceed 4 V along the Ku band in accordance with Fig. 3(b). Furthermore, as can be seen in Fig. 4, a linear variation of the simulated phase shift is obtained for all frequencies by altering the control voltages from 3 V to 7 V. Our phase shifter achieves a phase shift variation of 112.88° and 168° at 10.7 and 12.7 GHz, respectively.



(a) |S11|



(b) |S21|

Fig. 3. Simulated S Parameters of the Tunable Phase Shifter for Different Control Voltages.

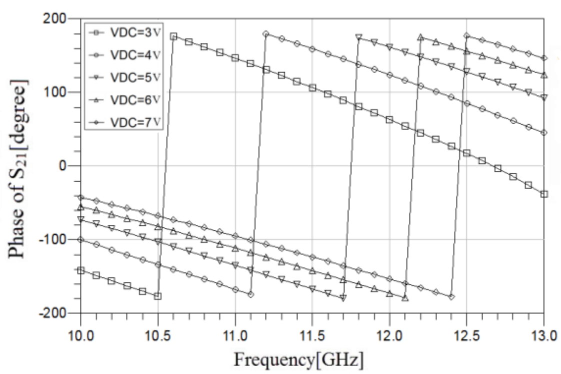
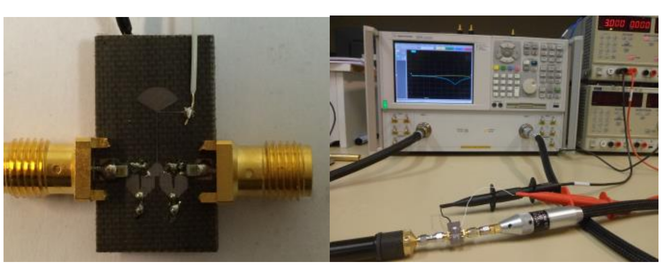


Fig. 4. Simulated Phase Shifts of the Tunable Phase Shifter for Different Control Voltages.

The performances of the tunable phase shifter are qualified regarding its beam steering capability. This latter is characterized by the beam steering angle which depends on the phase shift difference conforming to the following equation:

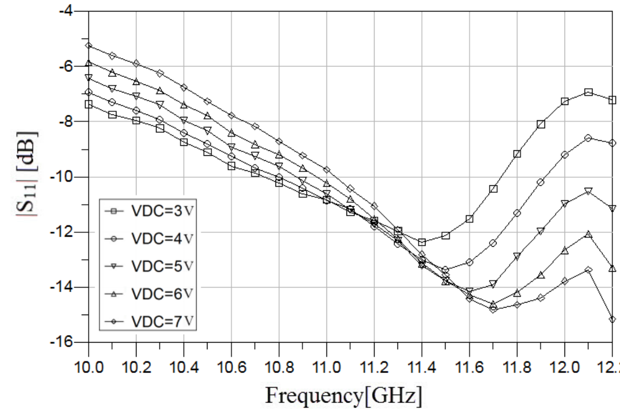
$$\theta = \sin^{-1}\frac{-\Delta\phi\,\lambda}{2\pi d} \quad (1)$$

Where θ is the beam steering angle, d is the distance between two antennas, λ is the wavelength (C/F) and Δϕ is the phase shift difference. When this difference of phase shift is created by the array of two antenna distant by 23 mm, the beam of the antenna array is steered continuously by 22.4° and 28.6° at 10.7 and 12.7 GHz respectively, by adjusting the control voltage throughout the Ku band. To validate the functioning concept, the phase shifter is manufactured and tested. Fig. 5 illustrates the phase shifter prototype.

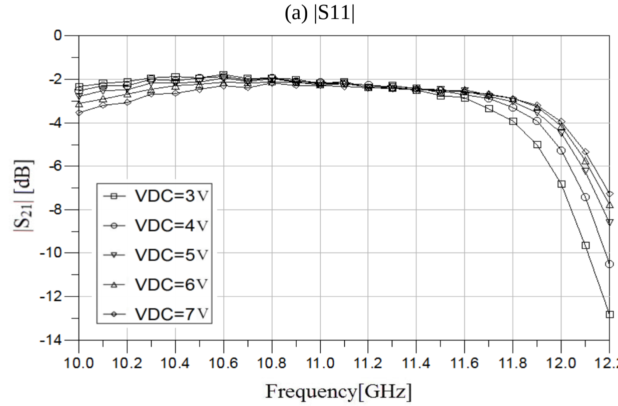


(a) Manufactured Prototype. (b) Prototype Under Test.

Fig. 5. Photograph of the Two-Stage Tunable Phase Shifter.



(a) |S11|



(b) |S21|

Fig. 6. Measured S Parameters of the Tunable Phase Shifter for Different Control Voltages.

Measurements were performed using a network analyzer and the measured S-parameters are provided in Fig. 6 for different control voltages. By adjusting the voltages from 3 V to 7 V, the return loss is less than -10 dB over the frequency band from 11 GHz to 11.7 GHz, as presented in Fig. 6(a). Furthermore, from Fig. 6(b), the maximum insertion loss is around -2 dB over the bandwidth extending from 10.7 GHz to 11.7 GHz for all voltage values.

Fig. 7 displays the measured phase shifts of the proposed phase shifter for different control voltages.

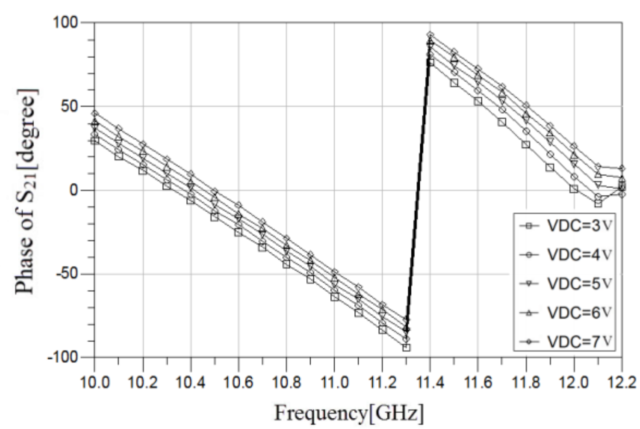


Fig. 7. Measured Phase Shifts of the Tunable Phase Shifter for Different Control Voltages.

From this figure, it can be seen that the phase shift variation of this phase shifter follows the variation of the voltages along the operating bandwidth. Also, when the voltages move from 3 V to 7 V, we can observe that the measured difference phase shifting range is about 15° and 21.13° at 10.7 and 11.7 GHz, respectively.

Inserted in the feed network of two antennas distant by 23 mm, the phase shifter can steer the beam electronically by 3° and 3.75° at 10.7 and 11.7 GHz respectively, by tuning the control voltages. Unfortunately, the measurement results are not close to the simulation results. This degradation is due to the effects of the soldering temperature or exposure time during the diode mounting step.

Despite the limitations of the manufacturing process, the continuous beam steering behavior is approved by adjusting the diode voltage even if the phase shift variation is very low. The future works need to focus on improving the phase variation range of the phase shifter to achieve the full cycle azimuthal scanning when integrated into a large phased antenna array.

The characteristics of the proposed phase shifter were compared to recently issued phase shifters. Only the phase shifters made by the printed circuit board with varactor diodes were taken into consideration. The comparison is outlined in Table II.

TABLE II. PERFORMANCE COMPARISON OF VARACTOR-BASED PHASE SHIFTERS

Ref	**Num. diodes**	**Num. section**	**Freq (GHz)**	**Max. IL (dB)**	**Max. PS (°)**	**Approach**
[17]	6	3	11.5-12.5	2.3	360	RTPS
[18]	6	2	6.7-7.7	4.2	380	All-pass network
[19]	4	2	1.8-2.6	1.5	380	RTPS
This paper	6	2	10.7-12.7	0.57	168	Schiffman PS

Num: number, IL: insertion loss, PS: phase shift, RTPS:Reflection-type phase shifters

Compared to the reported phase shifter performing in the Ku band [17], our phase shifter has the most compact size allowing it to be inserted in a large antenna array for beam steering applications. Indeed, the reflection-type phase shifter have a bulky structure because it consists of a 3 dB/90° coupler combined with reflective circuits [17]. Other structures [18, 19], which are based on coupled lines section charged by varactor diodes, are limited to providing a large phase shift variation across a narrowband at low frequencies.

The above features indicate that our phase shifter offers a compactness and a phase variation throughout 2 GHz of bandwidth in Ku band even with a short phase shift range.

IV. CONCLUSION

In this article, an electronically reconfigurable phase shifter operating in Ku band is designed, fabricated and measured. The proposed design, with the reference line removed, is based on the combination of two Schiffman sections embedded with varactor diodes. The two-stage phase shifter yields a continuously adjustable phase shift over a wide frequency range with just one control voltage. The cascade structure provided in the phase shifter circuit results in the increase of the phase shift variation keeping the compactness of the phase shifter. The measured results clearly validate the tunability of the proposed phase shifter.

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