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Design of Electrically Tunable Phase Shifter for Antenna Arrays Operating in Ku-band

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Abstract—This paper deals with the modeling and simulation of a wideband analog phase shifter for Ku applications. The structure adopted is based on a 90° branch-line coupler loaded by varactor diodes used to provide a wide phase shift range. The main idea of this work is to integrate controlled phase shifters in the antenna array in order to control its main beam between different satellites. Several circuits have been tested and optimized using ADS software from Agilent Technologies to obtain a wide bandwidth and wide phase shift range with low insertion loss over the Ku band.

Keywords—wideband phase shifter; varactor diodes; antenna array; continuous beam steering.

I. INTRODUCTION

The demands on beam steerable antennas for reception of Direct Broadcast from Satellite (DBS) have quickly increased over the last few years.

Actually, the parabolic antennas which are used for receiving TV signals from satellite have a fixed main lobe to point on a single satellite.

Furthermore, the current trend in DBS systems is to develop electronically steerable antennas at low cost and low weight, eventually able to realize functions of search and automatic pointing towards the satellite television programs.

For this, the controllable phase shifter has the function to control the pointing of antenna arrays and avoid degradation of the RF signal in its multidirectional propagation. Moreover, it allows controlling electronically the radiation pattern by modifying the amplitude and the phase of feed of the base antennas.

In the literature, many tunable phase shifters have been used for beam steering in phased array antenna, which have different range of phase shift according to the bandwidth. Several approaches are developed in order to switch beam antennas.

Reference [1] proposes a low cost phase shifter based on a cascaded reconfigurable defected microstrip structure which is able to realize a phase shift of 17° by controlling the working states of PIN diodes.

We can also find in [2] a design and simulation of reconfigurable switched line Microstrip phase shifters for phased array antenna. The reconfigurability is achieved by loading phase shifter using high frequency PIN diodes which acts as microwave switches. The designed phase shifter can be used for 360° beam steering in phased array antenna. Another work describes an analogue phase shifter based on distributed CPW transmission lines loaded by Varactor diodes [3]. A significant phase shift of approximately 800° at 2 GHz can be generated using a loaded line phase shifter. It is also possible to introduce a phase shifter by using varactor diodes to steer the beam direction [4]. Experimental results show that a beam steering angle of about 7 degrees was achieved for the 24-element beam-steerable antenna at 60 GHz. To achieve switched beam antenna, numerous researches propose a feed network for phased arrays which integrates functions of power divider and phase shifter into one structure. Its feeding circuit consists of a branch-line coupler phase shifter using varactor diodes to independently control the output phases [5-8].

This paper proposes a design of a controllable phase shifter for DBS applications operating in the Ku-band. The advantages of our structure are: simplicity, compact size and large phase shift range. By introducing the phase shifter in the feed network of the antenna array, electronically beam steering can be achieved. We present details of the proposed phase shifter and discuss the obtained results: return loss, insertion loss and phase shift.

II. PHASE SHIFTER DESIGN

Our proposed phase shifter consists of a 90° branch-line coupler with a single varactor diode in each adjusting arm. The varactor diode has the feature to behave as a capacitor whose capacitance varies depending on the voltage applied to its terminals when it is reverse biased. The main characteristic of a varactor diode is its capacity variation range for a given reverse voltage range. A varactor diode can be considered as a variable capacitor controlled by a voltage. The coupler is designed with microstrip transmission lines on the Teflon substrate with a relative permittivity of 2.55 and a thickness of 0.8 mm. The structure and the dimensions of the phase shifter are presented in Fig. 1.

A thin branch line (150Ω) connected to the main transmission line is used to provide bias DC voltage for varactor diodes and decouple DC supply and microwave circuit. The corresponding geometrical dimensions of our phase shifter are given as follows: $W = 6.7$ mm, $L_1 = 4.3$ mm and $L_2 = 4.2$ mm.

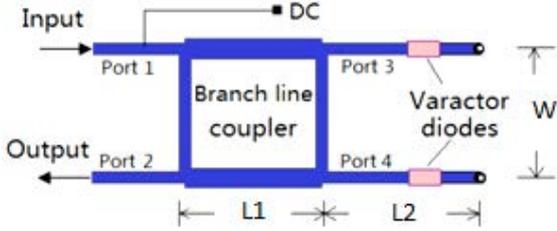


Fig. 1. Phase shifter topology.

The varactor diode is used as an active element tuning the phase shifting by adjusting the input DC voltage. Fig. 2 gives the equivalent electrical circuit of the varactor diode [9].

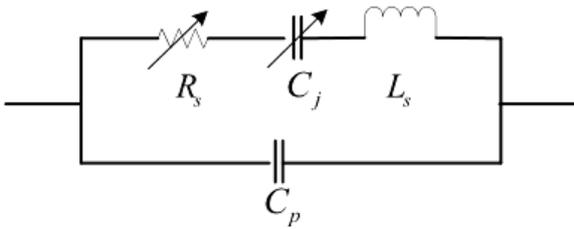


Fig. 2. Equivalent model of the varactor diode.

To use a varactor in simulation, we just need to identify the same values of the parameters that give a similar behavior of the diode to that given by the manufacturer [10].

The junction capacitance C_j of the diode varies with the reverse voltage applied to its terminals. It is given by the following formula:

$$C_j(V_j) = \frac{C_{j0}}{\left(1 - \frac{V_j}{\phi}\right)^M}$$

where V_j is the reverse voltage applied across the diode, and C_{j0} , ϕ and M are the zero bias junction capacitance, the fitted barrier potential and the gradient coefficient, respectively.

We used in the designing of the phase shifter, a reference diode varactor MA46580-1209 manufactured by M/A-COM company. From instructions given by the manufacturer, we have determined the characteristic of this diode: $C_{\max} = 1.56$ pF and $C_{\min} = 0.1$ pF. When the diode is biased from 0 to 18V, C_p have been assessed at 0.02 pF. The parasitic series resistance $R_s = 2.2 \Omega$, and the parasitic series inductance is $L_s = 0.105$ nH.

III. RESULTS AND DISCUSSION

When designing this type of phase shifter, we must optimize the geometrical parameters reflecting his behavior and influencing its performance to achieve more than 360 degrees phase shift in the Ku-band keeping the phase shift depending on the frequency. We present below the simulation results of the phase shifter and the excitation network of the antenna array. In all simulations, we used the same parameters available in [10].

A. Phase shifter with capacitance

At first, a 0.7 pF capacitance value were incorporated in each output branch, Fig. 3, to see its influence on the phase shift. Then, we varied the value of the capacity from 0.1 pF to 1.56 pF to see the variation of the phase shifter depending on the frequency.

We used Ansoft Designer software to simulate the circuit model and tune the capacitance. We deduce the argument of S_{21} parameter, which is the phase shift, and the modules of S_{11} and S_{21} .

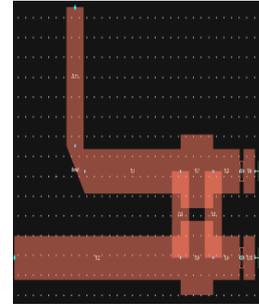


Fig. 3. Layout of the phase shifter with controllable capacity.

From Fig. 4, we can notice that the phase shifter is well matched with a reflection coefficient remaining below -10 dB along the required band [10.7-12.7] GHz and the transmission coefficient is around -0.9 dB.

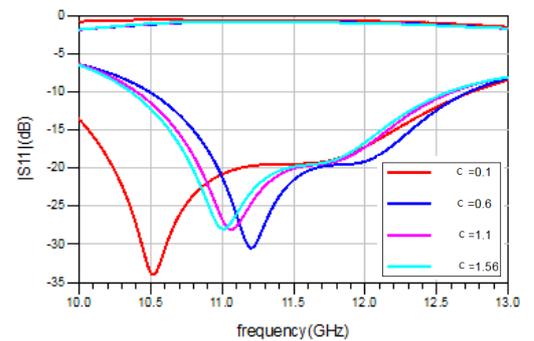


Fig. 4. Return and insertion losses for different values of the capacitance.

The simulated phase shift versus frequency is shown in Fig. 5. We have a phase shifting up to 102° and 151° at 10.7 and 12.7 GHz, respectively for a capacitance $C = 0.7$ pF. For $C = 0.1$ pF, the maximum value of the differential phase shift is about 180°. If we increase the value of the capacitance, we obtain a lower range of the phase.

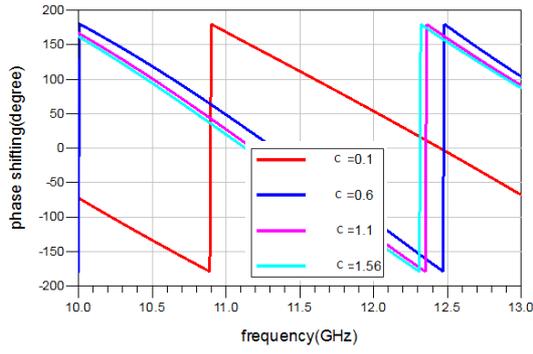


Fig. 5. Phase shifting for different values of the capacitance.

B. Phase shifter with varactor diode

As shown in Fig. 6, a varactor diode is incorporated in each branch of the coupler in order to change the phase and a bias is added to polarize the diode. In simulation and regarding the varactor diode, we used its equivalent model presented in Fig. 2.

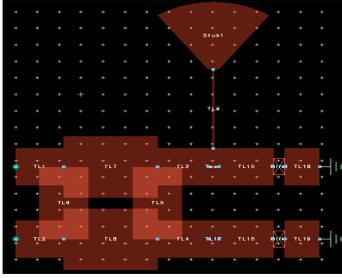


Fig. 6. Layout of the phase shifter with tuning varactor diode.

The design of the phase shifter has been optimized under ADS software to have more phase shift with low insertion loss in the Ku-band.

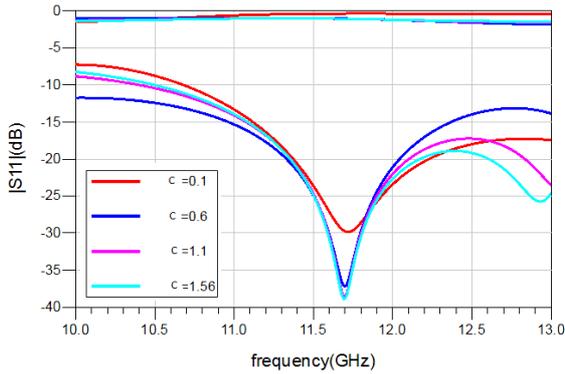


Fig. 7. Return and insertion losses with varactor diode for different values of the capacitance.

Fig. 7 exhibits the S-parameters and illustrates good performances for the phase shifter. By varying the capacitance from 0.1 pF to 1.56 pF, the return loss remains lower than -10 dB at the desired frequency range from 10.7 to 12.7 GHz. It achieves -29 dB at 11.7 GHz. The losses of the

phase shifters are less than 2 dB and the maximum of the insertion loss is about 0.4 dB.

Fig. 8 presents the simulated phase shift with varactor diode as a function of the frequency. For $C = 0.1$ pF, the maximum value of the differential phase shift is about 285° at 10.7 GHz. We can conclude that when we increase the value of the capacitance, the phase shift decreases.

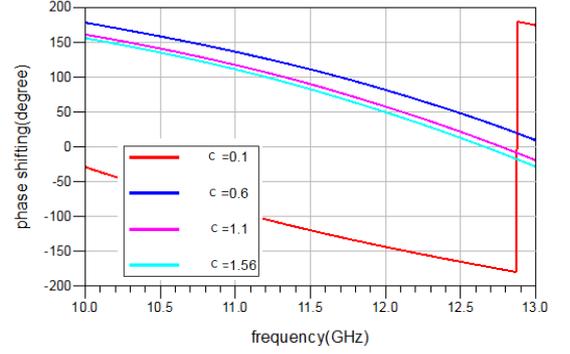


Fig. 8. Phase shifting with varactor diode for different values of the capacitance.

By tuning the capacitance of the varactor diode from 0.1 to 1.56 pF, the phase shift varies linearly in function of different values of the capacitance for the three frequencies (10.7, 11.7 and 12.7 GHz). The difference of the phase shift is 158° at 10.7 GHz and reaches 190° at 12.7 GHz, Fig. 9. The phase shift obtained has a quadratic variation from 0.1 pF up to 0.6 pF, and it is linear from 0.6 pF up to 1.56 pF.

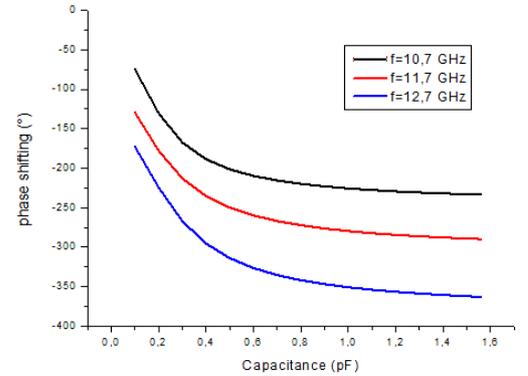


Fig. 9. Phase shift versus capacitance for different frequencies of the proposed phase shifter.

According to the phase law (1), the depointing of the beam is generated in a continuous way.

$$\theta_0 = \sin^{-1} \frac{\Delta\phi\lambda}{2\pi d} \quad (1)$$

where θ_0 is the beam steering angle,
 d = distance between two antennas,
 λ = wavelength (C/F),
 $\Delta\phi$ = difference of the phase shift.

By examining Fig. 10, we can confirm that the angle of depointing of our phase shifter moves with the variable capacitance (from 0° to 44°) and keeps the same behavior. The phase shifter provides a maximum of depointing of 44° at 12.7 GHz. The difference in the depointing for the three frequencies (10.7, 11.7 and 12.7 GHz) is 4.8° . It should be noted that it is necessary to have a depointing of the constant beam irrespective of the frequency where it does not exceed 3° of difference (beam aperture angle).

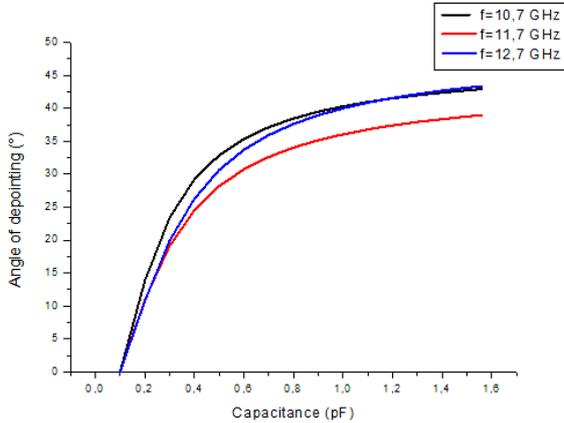


Fig. 10. Depointing versus capacitance of the proposed phase shifter for different values of the frequency.

IV. BEAM SWITCHED ANTENNA ARRAY

The design stage when completed will be followed in the final phase by networking the phase shifters and the excitation network to have a complete array. The proposed geometry consists of 1×4 array feed network employing phase shifters and wideband Wilkinson power dividers. For implementing the excitation network for the phased array antenna depicted at Fig. 11, we have used the same substrate (Teflon) as that of the phased array antenna. By designing the feed network, every two antenna ports are connected to a branch, and one branch-line phase shifter is used to adjust the phase over the other two antennas. We use a phase shifter for every two antennas in order to minimize the number of the phase shifters in the antenna array. In this circuit, we use two capacitances to decouple the input power in each branch from two supply lines for DC voltages of the corresponding branch-line phase shifters.

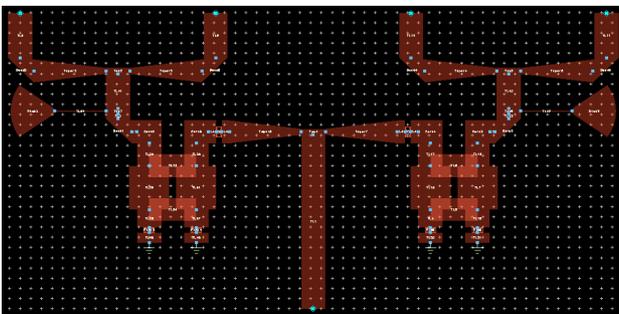


Fig. 11. Electronically steerable beam antenna array with varactor diode.

The entire structure of the feeding network and phase shifter for the antenna array can be simulated with ADS software. In Fig. 12, we present simulated results of the proposed network of phase shifters in terms of return loss and insertion loss.

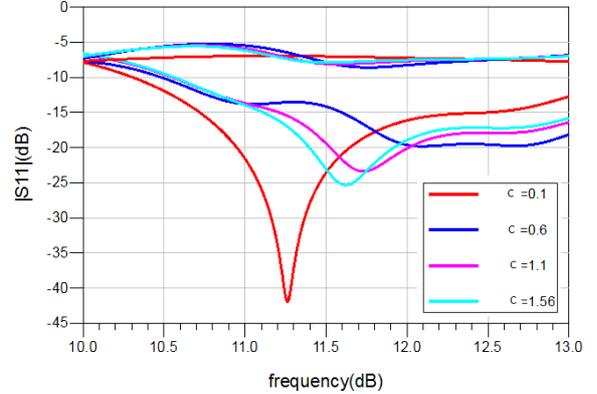


Fig. 12. Return and insertion losses for different capacitance values.

According to this figure, we can confirm that the entire network is adapted throughout the Ku-band and the values of return loss and insertion loss keep good performances for all capacitance values. Indeed, the return loss is less than -20 dB between 10.7 and 12.3 GHz, but it increases to reach -10 dB in the higher frequency. The insertion loss is less than 1 dB throughout the band of operating frequencies. Moreover, as can be seen in Fig. 13, the simulated phase shift changes linearly as a function of the frequency. So, the phase shift decreases when the value of the capacitance increases.

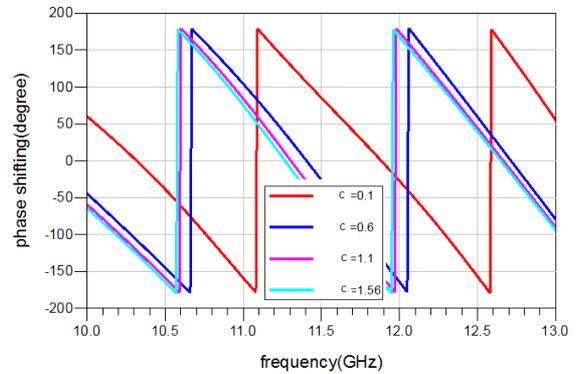


Fig. 13. Phase shifting for different values of the capacitance.

Afterwards, we choose to tune the varactor diodes integrated in one of the phase shifters in order to provide a phase shift between two antenna couple. While tuning the capacitance of the varactor diode from 0.1 to 1.56 pF, a linear phase is obtained for three frequencies: 10.7, 11.7 and 12.7 GHz. We can observe in Fig. 14 that the phase shifting of our network keeps approximately the same appearance over different frequency bands. Our network provides 124° phase shift at 10.7 GHz and near 160° phase shift for 11.7 and 12.7 GHz. As branch-line, the phase shifter provides a continuous phase shifting by altering the value of the

capacitance. The 1x4 array is thus expected to obtain a good continuous beam steering performance. When 160° phase difference is added in the feed network, Fig. 15 shows that the beam can be steered about ±18° with a difference of depointing not more than 3° for the three frequencies previously indicated.

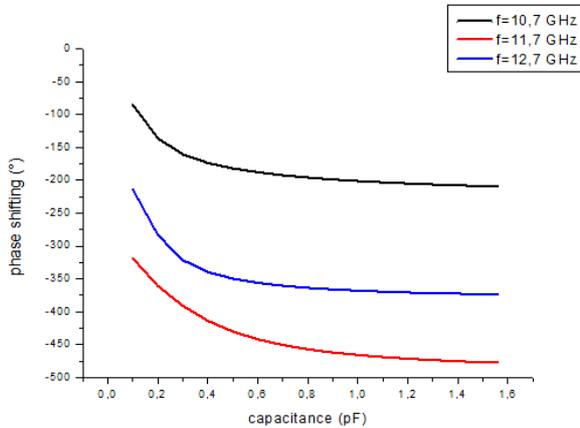


Fig. 14. Phase shift versus capacitance for different frequencies of network depointing.

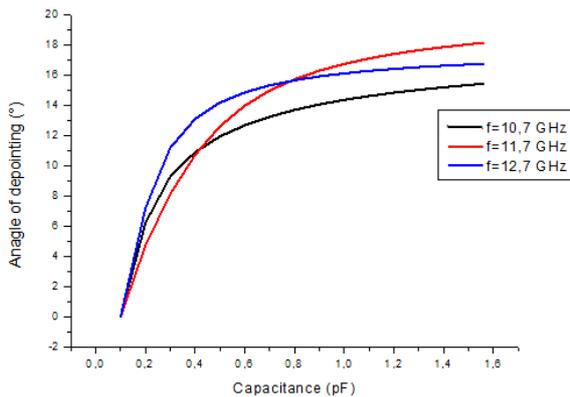


Fig. 15. Depointing versus capacitance for different frequencies of network depointing.

Therefore, we conclude that the branch-coupler with varactor diodes gives good performance and provide 18° of beam depointing when it is integrated with Wilkinson power dividers, but this remains still insufficient for a larger antenna array to switch the beam in all directions. That said, we must find a more effective solution that really ensures the continuous phase shift of the signal between 0° and 360°. In addition, although the optimized phase shifter can provide more phase shifts, its size is still significant and does not allow it to be integrated in our large network of antennas. That is why we must seek a more suitable phase shifter for our requirements.

V. CONCLUSION

In this work, we have presented a wideband analog phase shifter loaded by varactor diodes operating in the Ku-band, which is suitable for beam steering and phased array antennas.

The proposed phase shifter is able to provide continuous tunable phase shifts only by adjusting the capacitance.

We have implemented the circuit using Electromagnetic simulator and obtained good performance in terms of insertion loss, return loss and phase shift.

By inserting the proposed phase shifter in a feed network of four antennas, the main beam of the antenna array is then electrically steerable from -18° to +18°, which can be suitable for Ku applications.

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