

On the Practical Limitations of Electronic Beamsteering using Metamaterials at 28 GHz

Mário Vala
*Instituto de Telecomunicações and
Polytechnic Institute of Leiria*
Leiria, Portugal
mario.vala@co.it.pt

João R. Reis
*Instituto de Telecomunicações and
Polytechnic Institute of Leiria*
Leiria, Portugal
joao.reis@ipleiria.pt

Rafael F. S. Caldeirinha
*Instituto de Telecomunicações and
Polytechnic Institute of Leiria*
Leiria, Portugal
rafael.caldeirinha@ipleiria.pt

Abstract—In this paper, the practical limitations and constraints of electronic (active) beamsteering using metamaterials at 28 GHz, in terms of the parasitic elements introduced by varactor diodes, are addressed. Parametric studies will be presented to ascertain the insertion losses of both series inductance and resistance of the varactor diodes used at unit-cell level, in addition to their bandwidth, frequency of resonance and maximum phase shift yielded. This study and characterisation has been performed in simulation environment using CST Microwave Studio.

Index Terms—Beamsteering, varactor diodes, metamaterials, FSS

I. INTRODUCTION

Fast Electronic beamsteering is currently a hot topic and a key enabling technology for 5G, as it allows for the directing of the antenna beam towards the desired direction without the need of mechanical equipment. Typically, beamsteering is achieved using phased antenna arrays [1], [2], which by effectively controlling the signal phase progression across the antenna elements comprising the array, the beam can be directed to any particular direction. This implies the use of digital or electronic controlled phase shifters which may be cumbersome, since one radio frequency (RF) front-end is required per each antenna element. Consequently, enabling beamsteering in a radio link by means of phased arrays proved to be costly ineffective, bulky and complex, and thus the rationale for studying new alternatives.

One of the preferred solutions as alternative to phased antenna arrays, are transmitarrays. Transmitarrays are often comprised of several similar unit-cells in which the different phase shifts are achieved by the use of p-i-n or varactor diodes, allowing for a simple and cheaper solution when compared to phased antenna arrays.

In fact, it has been demonstrated by the authors in [3], that antenna beamsteering can be performed at 5.2 GHz, using a reconfigurable square-slot frequency selective surface (FSS) transmitarray loaded with varactor diodes. The reconfigurable FSS transmitarray is composed of 5×5 unit-cells and 5 stacked layers. The phase of an incident propagating wave generated by an external radiating source has been demonstrated to be fully controlled when applying specific capacitance patterns throughout the array, and, thus, enabling electronic beamsteering.

Electronic beamsteering using transmitarrays is both timely and topical in the context of 5G [4], particularly when these are applied to single radiating directive sources, such as a horn antenna. In the last years, several transmitarrays have been presented for the 5G operating frequencies at sub- 6 GHz band [5]–[9] and at 28 GHz, as it is the case of the works presented in [10]–[12]. Despite the fact that they are all built with different unit-cells designs, they either employ p-i-n or varactor diodes to enable electronic beamsteering.

With this mindset, an extension of the work presented in [3] has been reported in [13] at 28 GHz, aiming at both 5G and RADAR of the future applications. In this particular work, beamsteering has been demonstrated by employing discrete surface mount capacitors on the re-shaped FSS unit-cell design of [3]. The results of an extensive simulation workout proved that 7 FSS layers are necessary to attain the minimum phase delay of 360° , as opposed to the 5 layer design of [3], to fully control antenna beamsteering. In fact, antenna beamsteering up to $\pm 28^\circ$ in both azimuth and elevation planes has been achieved under simulations in CST MWS at 28 GHz, using a $5 \times 5 \times 7$ transmitarray and lumped elements to mimic an ideal capacitor model (Fig. 1a) to apply in each array element.

Although the simulation study of [13] proved the feasibility and usefulness of the proposed array, some limitations are expected when increasing the complexity of the capacitor model, e.g. by considering the intrinsic parasitics elements typically provided in the manufacturer datasheet, as shown in Fig. 1b, instead of considering just an ideal model of a capacitor. This is of particular relevance when varactor diodes are employed in such structures since they typically present relatively higher series resistance and inductance when compared with a simple discrete capacitor, which will deeply impact the transmitarray performance and de-tune the original unit-cell frequency response, as it is reported in [3].

To this extent, the work reported in this paper will address the influence of a realistic transmitarray when replacing the discrete capacitors considered in [13] by a (complex) varactor diode model. To the authors' knowledge, this kind of study is lacking in the literature. In fact, such effects are mostly ignored when designing such type of structures, which may lead to a discrepancy between simulated and measured results, particularly at high frequencies.

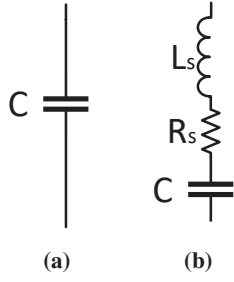


Fig. 1: (a) Ideal capacitor and (b) varactor diode models.

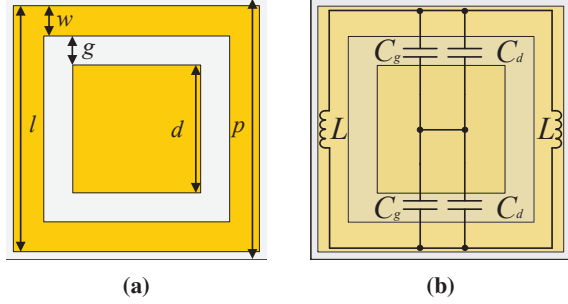


Fig. 2: (a) Unit-cell design and (b) unit-cell equivalent circuit.

II. UNIT-STACKED CELL AND PASSIVE TRANSMITARRAY

The unit-cell considered for this study has already been presented in [13] and is depicted in Fig. 2a. It follows a square-slot FSS design with dimensions of $w = 0.41 \text{ mm}$, $d = 4.06 \text{ mm}$, $g = 0.34 \text{ mm}$, $l = 5.55 \text{ mm}$, $p = 5.75 \text{ mm}$, at 28 GHz. The substrate used was Nelco NX9250 with a thickness of 0.762 mm . Each cell has 2 capacitors, connecting the middle patch to the outer ring, that allow for the control of the phase shift of each cell individually and the pass-band filtering response, following the method described in [3] and [13]. The equivalent circuit for the unit-cell is the one presented in Fig. 2b, where C_d is the capacitance introduced by the capacitor, C_g is the capacitance of the gap and L represents the inductance of the outer loop, the latter two being specified by the FSS dimensions. The circuit presented in Fig. 2b leads to a resonant frequency of the unit-cell, f_c , according to (1).

$$f_c = (1/(\pi \times \sqrt{L \times (C_g + C_d)})) \quad (1)$$

However, with only one layer it is not possible to achieve the 360° phase variation required for beamsteering. By stacking 7 layers of these cells, a bandwidth of 500 MHz (Fig. 3a) at 28 GHz and a maximum phase shift higher than 360° can be achieved, as shown in Fig. 3b.

Employing this cell in a 5×5 transmitarray, and choosing the correct phase shift between adjacent cells according to (2) and the corresponding capacitance value from Fig. 3b, the antenna beam can be directed towards the desired position.

$$\begin{cases} \psi_x = -2\pi \times p \times \cos(El) \times \sin(Az)/\lambda \\ \psi_y = -2\pi \times p \times \sin(El)/\lambda \end{cases} \quad (2)$$

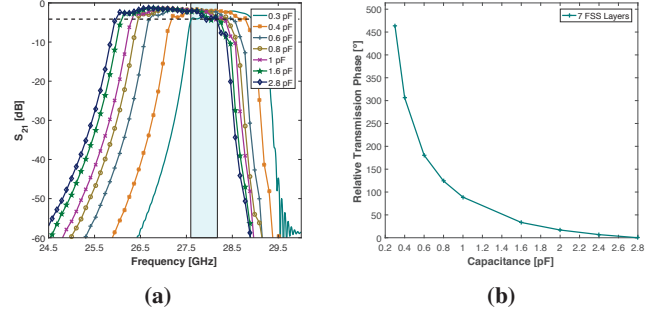


Fig. 3: (a) S_{21} and (b) phase shift for the considered range of capacitance.

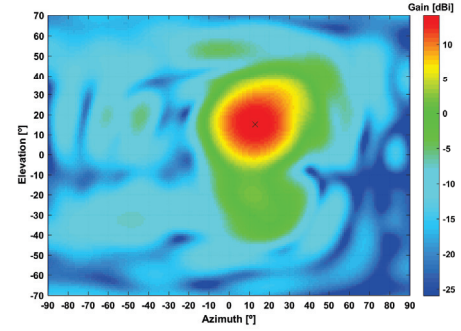


Fig. 4: Example of simulated transmitarray beamsteering capabilities for ideal capacitor model.

where ψ_x and ψ_y are the phase shifts between adjacent cells in the x and y directions, respectively, p is the distance between cell's centres, λ is the wavelength of the incident wave and Az and El are the desired azimuth and elevation angles of the outgoing wave.

An example of beamsteering using the simulated transmitarray is presented in Fig. 4 where the beam was directed towards an azimuth of 15° and an elevation of 15° .

III. UNIT-CELL AND TRANSMITARRAY WITH COMPLEX MODEL

A. Impact on unit-cell frequency response

It has been proved that the unit-cell is capable of beamsteering when considering an ideal model for the capacitor (Fig. 1a). However, when the realistic model of Fig. 1b is considered for C_d of Fig. 2b, several problems arise in terms of unit-cell frequency response.

In fact, the effects arising from considering a realistic model, instead of the ideal model for the capacitors, were analysed in simulation environment. Contrary to the use of discrete capacitors that typically exhibit a resonant behaviour with very low parasitic values (mimicking an ideal model), varactor diodes present parasitic effects that severely affect insertion loss, bandwidth, frequency of operation, as well as total phase shift of the unit-cell. Since the structure presented in [13] works at a higher frequency than the one presented in [3], the parasitic effects typically represented as series resistance and

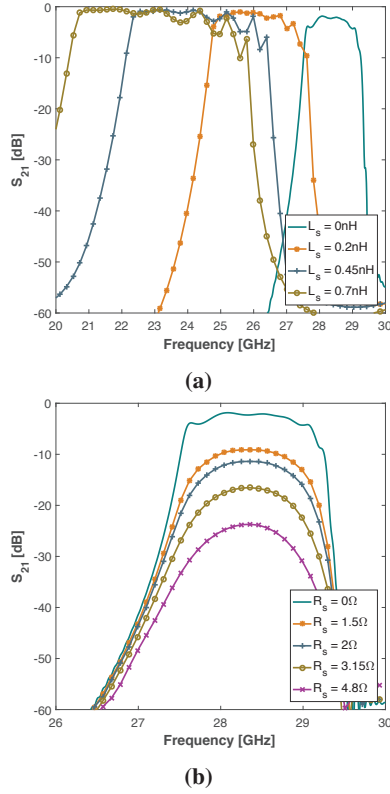


Fig. 5: Effects of: (a) series inductance; and (b) series resistance on S_{21} , for unit-cell at 28 GHz.

series inductance, will have a higher influence on beamsteering performance and, thus, need to be properly considered and characterised.

In order to see if it was possible to use varactor diodes in the unit-cell of [13] in the same way that they were used in [3], a parametric study was performed in CST Microwave Studio. Likewise, lumped elements were used to evaluate the effects of the parasitics in the unit-cell frequency response (S_{21}), while maintaining the same dimensions. The parasitic values used for these studies were the ones most commonly found in the datasheets of the varactor diodes. An individual study was carried for both parasitic inductance and parasitic resistance and the results are depicted in Fig. 5a and Fig. 5b, respectively.

From the presented results, it can be concluded that series inductance leads to a shift in the operating frequency, where the higher the inductance, the lower the operation frequency is observed. This is inline with (1), where the increase of the inductance leads to a smaller resonant frequency. Moreover, the increase of inductance leads to a larger bandwidth and, consequently, a decrease in the total achievable phase delay introduced by each cell, making it impossible to obtain the 360° phase variation required to perform beamsteering, when considering the same range of capacitance values as before. Figure 6 shows the total phase achieved, in the middle of the operating band, for different values of series inductance.

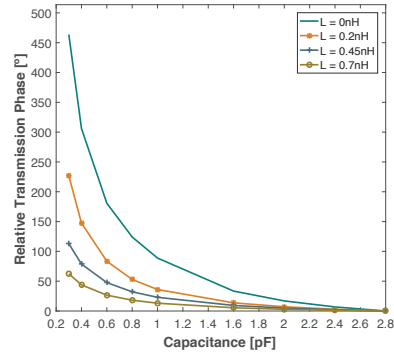


Fig. 6: Comparison of total achieved phase for different values of series inductance.

It can be seen that further increasing the series inductance to e.g. 0.2 nH, the total phase variation varies from 460° to 227° . With only 227° of phase shift, it becomes impossible to have the necessary phase control to allow beamsteering. This tends to worsen when higher inductances are considered, for instances, achieving only 113° and 63° of phase shift for 0.45 nH and 0.7 nH, respectively. However, this effect can be compensated if a different capacitance range is considered, as smaller capacitance values lead to higher phase shifts.

On the other hand, it can be seen from Fig. 5b that series resistance introduces attenuation in the signal that increases with its value. The losses are significant, achieving a total of 25 dB for a series resistance of 4.8 Ω . Even with a series resistance of 0 Ω , the unit-cell still present insertion losses of 3 dB that are caused by the substrate. Contrary to the inductance effects, the effects of the series resistance cannot be compensated.

The introduction of parasitics elements severely affect S_{21} , due to the fact that this unit-cell operates at high frequencies, whereas for smaller frequencies, such effects are less pronounced. In fact, this has been demonstrated in the unit-cell frequency responses (S_{21}) of Fig. 7, where the same study carried out for the unit-cell at 28 GHz [13] was performed for the unit-cell presented in [3] at 5.5 GHz. The differences in both frequencies are easily identified in terms of both parasitic inductance and parasitic resistance. With an inductance of e.g. 0.45 nH, the frequency shift is observed to be 16% for the unit-cell at 28 GHz against 3.6% for the unit-cell at 5.5 GHz. For all these values, the fractional frequency shift was normalised to the initial frequency of operation of the respective unit-cell. In terms of the effects of the series resistance, there is also a large difference between cells at both frequencies. For a resistance of e.g. 4.8 Ω , the unit-cell at 28 GHz exhibits 25 dB of insertion losses while the unit-cell at 5.5 GHz, for the same value of series resistance, exhibits insertion losses of only 12 dB. This study proves that, while the parasitics of the varactor diodes have a huge impact at 28 GHz, contrary to that observed at 5.5 GHz.

Since the objective of this study was to ascertain if it was possible to use varactor diodes at this frequency in the same

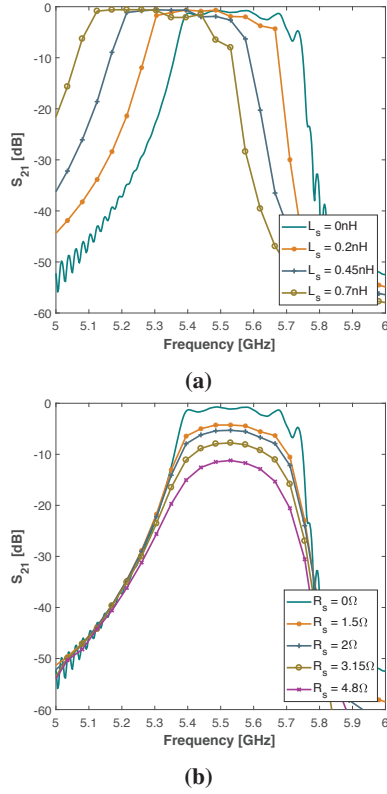


Fig. 7: Effects of: (a) series inductance; and (b) series resistance on S_{21} , for unit-cell at 5.5 GHz.

TABLE I: Parasitics for different varactor diodes.

Varactor	$C_{min} - C_{max}$ (pF)	L_s (nH)	R_s (Ω)	I_{loss} (dB)	Δf (GHz)
SMV2019-079LF [14]	0.3 - 2.22	0.7	4.8	25	7
SMV2019-040LF [14]	0.3 - 2.22	0.45	4.8	25	4.5
SMV2202-040LF [15]	0.31 - 3.14	0.45	3.0	17	4.5
SMV1430-040LF [16]	0.31 - 1.24	0.45	3.15	18	4.5
MPV2100 [17]	0.3 - 3	0.2	2	13	2.5

way as used in [3], a study on the varactor diodes present in the market for the intended range of capacitances, was carried out. Table I summarises the characteristics of some of the existing varactor diodes in terms of their capacitance range, parasitics and expected insertion loss (I_{loss}) and phase shift (Δf) interpolated from Fig. 5. Even when considering the MPV2100 varactor, that exhibits smaller parasitics from among the varactor diodes present in Table I, an insertion loss of 13 dB and a normalised frequency shift of 8.9%, are still obtained.

B. Impact of parasitics on Beamsteering with transmitarray

The main objective of characterising this unit-cell when using the complex model of Fig. 1 was to perceive what are their limitations in terms of beamsteering. As explained in previous sections, to have full control over beamsteering, a total of 360° phase shift is necessary in each cell. It was also proved that when considering this model, the introduction of

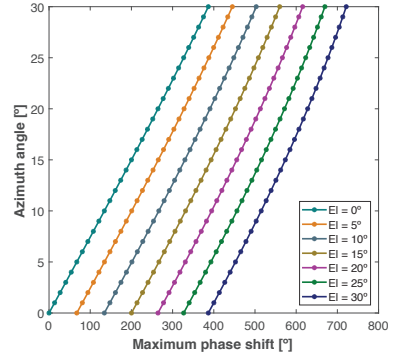


Fig. 8: Total beamsteering range depending on the maximum phase shift obtained by the unit-cell.

TABLE II: Maximum steering angles for different series inductance values considering a 5×5 transmitarray.

Series inductance	Maximum Phase Shift	Maximum 1_D steering angle
0nH	463°	Full control
0.2nH	227°	17°
0.45nH	113°	8°
0.7nH	63°	5°

series inductance would affect the total phase shift achievable by the unit-cell, as depicted in Fig. 6. In this way, using (2) it is possible to better understand limitations of beamsteering according to the unit-cell maximum phase shift, as depicted in Fig. 8.

When the results presented in Fig. 6 are combined with the ones depicted in Fig. 8, the beamsteering angle for the unit-cell with different inductance values can be interpolated. In Table II, a summary of the total achievable phase shift and subsequent maximum beamsteering 1-D range for each of the considered values of inductance, are presented. Even though, in Table II only 1-D beamsteering capabilities are presented, it is still possible to perform 2-D beamsteering. Considering a unit-cell with a series inductance of 0.2 nH, which can only achieve 227° (Fig. 6), it is possible to make a 5×5 transmitarray that can achieve, for example, 5° in azimuth and 10° in elevation.

In order to demonstrate that it is still possible to perform beamsteering despite the parasitics of the varactor diodes, a transmitarray comprised of 5×5 of these cells was simulated similarly to the one presented in II [13]. For this proof-of-concept, it was considered a series inductance of 0.2 nH and a series resistance of 2Ω to simulate the behaviour of a MPV2100 varactor diode. Figures 9a and 9b show the simulated radiation patterns for both the ideal model and the one considering the varactor diodes' parasitics, at 28 and 25 GHz, respectively. It can be concluded that even with series parasitics considered, it is still possible to perform beamsteering, albeit within a smaller angular range.

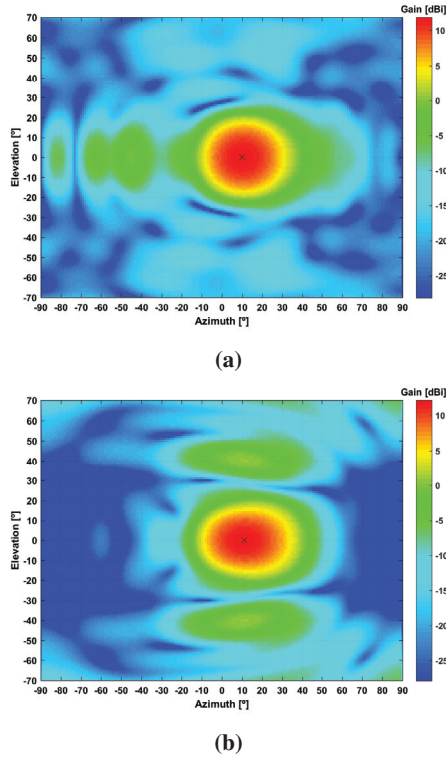


Fig. 9: Simulated radiation pattern for 5x5x7 transmitarray considering (a) capacitor ideal model at 28 GHz and (b) complex model with series inductance (0.2 nH) and resistance (2 Ω) at 25 GHz.

IV. CONCLUSIONS

In this paper, a new study upon the unit-stacked cell in [13] was presented. This study addressed some of the limitations introduced by the use of varactor diodes at high frequencies (particularly at 28 GHz), when compared to discrete capacitors, namely in terms of parasitic series resistance and inductance. The results of this study showed that a higher series inductance of the varactor diode leads to a higher shift in frequency to lower values. The bandwidth is also affected, increasing as the inductance increases. This poses a problem as it leads to a smaller total phase shift achieved in each cell, limiting the range of beamsteering. It was also concluded that the series resistance of the varactor diode does not have impact on the operating band of the unit-cell, despite increasing its insertion losses. The effects of the parasitics were then compared to the unit-cell presented in [3] at 5.5 GHz, being concluded that at higher frequencies the effects of the parasitics were much more notorious.

Finally, a simulation on a 5×5 transmitarray was carried in order to ascertain if the parasitics would impact the transmitarray beamsteering capabilities other than frequency of operation, insertion losses and range of output angle. Simulation results proved that, even with parasitics, it is possible to achieve beamsteering.

Future work will address new studies and possible redesign of the unit-cell to work around the limitations presented

herein and make it fully compliant with e.g. 5G New Radio specifications.

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