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# Triple-Slot Phase-Shifting Cell of Reduced Size for Reflectarray Applications

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**Abstract**—This paper presents an enhanced version of the triple-slot phase-shifting cell topology previously studied. It consists in reducing the size of the unit cell in order to enlarge its bandwidth and to minimize the detrimental effect of the angle of incidence on its behavior. Simulations demonstrate that the cell preserves a satisfying performance over a wide frequency band, even when it is illuminated with a high angle of incidence in both polarizations.

**Index Terms**—reflectarray antennas, phase-shifting cell, single linear polarization.

## I. Introduction

Microstrip printed reflectarrays have been extensively studied in the past two decades. They offer the possibility of forming complex radiation patterns with relative simplicity, low cost, low losses and low profile.

In passive structures, the unit cell usually uses patches [1], slots [2] or stubs [3] to control the phase of the reflected wave. These structures suffer generally from two major limitations: the insufficient phase range and the limited bandwidth. This second limitation has confined for a long time this type of antennas to narrowband applications. In order to overcome these limitations, several resonators are generally combined on a single layer or a multilayer substrate [4, 5]. However, single layer solutions are preferable as they result in a simpler technological process.

In active reflectarrays, the reflected phase has to be controlled dynamically with a reduced number of reconfigurable elements, such as *PIN* diodes [6], *varicap* diodes [7] and *MEMS* switches [8], loading the unit cell. This permits to preserve a low cost antenna.

While designing a reconfigurable reflectarray, one of the main challenges is thus to design a phase-shifting cell whose phase can be controlled dynamically over a  $360^\circ$  range with a reduced number of reconfigurable elements and over a large bandwidth. A possible candidate is the triple-slot phase-shifting cell presented in [9].

In [10], it has been shown that the bandwidth of the unit cell can be improved by reducing its size. Here, we demonstrate that this reduction on the size of the cell can also enhance its robustness versus the angle of incidence as it will be shown on the triple-slot topology.

## II. Impact of the Incidence on the Behavior of the Cell

### A. Initial Performances of the Cell Under Normal Incidence

The proposed cell, illustrated in Fig. 1, is identical to the cell presented in [9]. The only difference lies in the variable capacitance loading the central slot. It is modeled here with a lumped element (in red) instead of the gap capacitance of variable length. The cell is 35mm in size ( $m=35\text{mm}$ ), printed on a substrate with 2.17 dielectric constant and 1.6mm thickness, suspended 15.7mm above a square metallic cavity. It is simulated using HFSS<sup>®</sup> electromagnetic simulator assuming an infinite periodic array. Initially, the cell is supposed illuminated with a plane wave under normal incidence. Four uniformly distributed phase states can be obtained respectively for the values  $\{10\text{fF}, 57\text{fF}, 77\text{fF}$  and  $123\text{fF}\}$  of the variable capacitance loading the central slot (Fig. 2). The bandwidth of the cell is defined for losses less than 1dB and for a phase resolution better than 1.79 equivalent bit. This resolution corresponds to a phase standard deviation [11] better than  $30^\circ$ . In our case, Fig. 3 clearly shows that losses are less than 1dB all over the band, and the phase standard deviation (Fig. 4) takes values less than  $30^\circ$  between 5GHz and 5.65GHz which results in 12.2% of bandwidth.

### B. Performances of the Cell Under Oblique Incidence

A unit cell must operate over a range of angle of incidence representative of the real illumination conditions of the array. To assess this effect, the cell is now placed in an infinite periodic array. It is illuminated with a plane wave under oblique incidence (Fig. 5). Fig. 6 and Fig. 7 clearly show that when the cell is illuminated with an oblique incidence, in both TE and TM polarizations, the variation of the phase standard deviation versus the frequency is deteriorated. This demonstrates the detrimental effect of the oblique incidence on the behavior of the cell and on the bandwidth. Indeed, for a  $30^\circ$  angle of incidence, the phase standard deviation quickly tends to  $30^\circ$  in TE polarization and the bandwidth is reduced to 4.8% (5-5.25GHz). The situation is even worse for TM polarization as no frequency point complies with the standard phase deviation requirements when the incidence angle is  $30^\circ$ . Hence the need to improve the robustness of the cell regarding

oblique incidence. To do so, the size of the cell has to be reduced as it will be demonstrated in the next section.

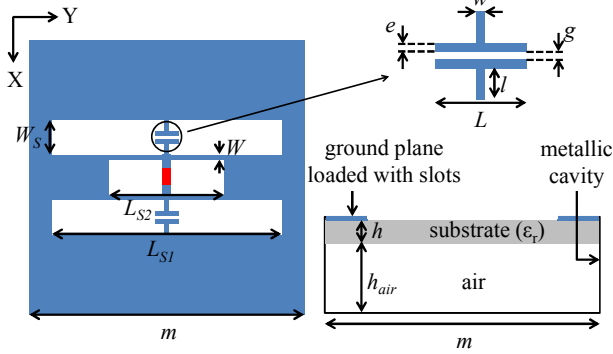


Fig. 1. Phase-shifting cell:  $L_{S1}=23\text{mm}$ ,  $L_{S2}=11\text{mm}$ ,  $W_S=5\text{mm}$ ,  $W=0.2\text{mm}$ ,  $w=0.5\text{mm}$ ,  $e=g=0.2\text{mm}$ ,  $l=2.2\text{mm}$ ,  $L=1\text{mm}$ ,  $h=1.6\text{mm}$ ,  $\epsilon_r=2.17$ ,  $h_{air}=15.7\text{mm}$

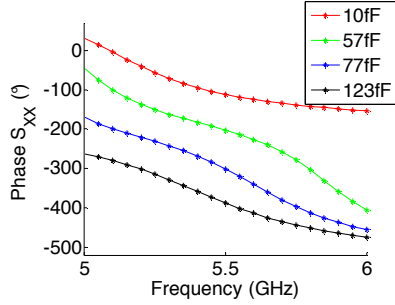


Fig. 2. Reflected phase versus frequency, of the cell of size  $m=35\text{mm}$ , for the four states obtained with the convenient values of the variable capacitance

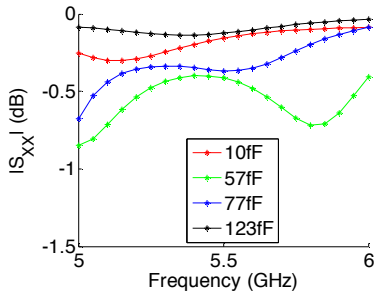


Fig. 3. Losses versus frequency, of the cell of size  $m=35\text{mm}$ , for the four states obtained with the convenient values of the variable capacitance

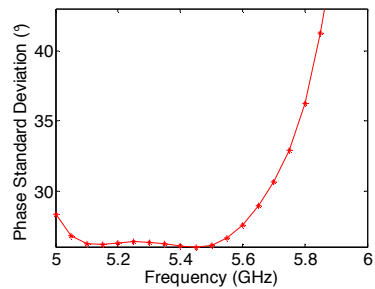


Fig. 4. Phase standard deviation versus frequency of the cell of size  $m=35\text{mm}$

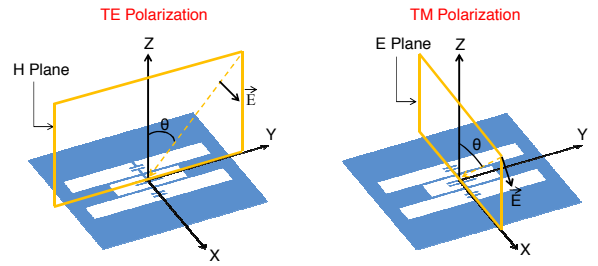


Fig. 5. Phase-shifting cell under oblique incidence (considering x-polarization)

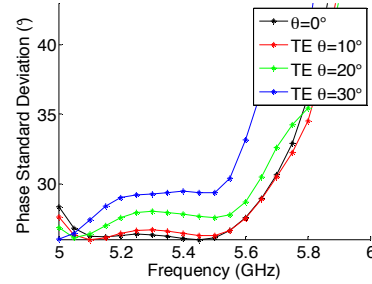


Fig. 6. Phase standard deviation versus frequency, of the cell of size  $m=35\text{mm}$ , for different angle of incidence in TE polarization

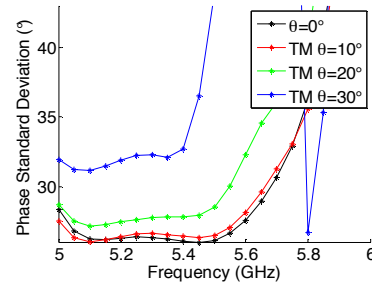


Fig. 7. Phase standard deviation versus frequency, of the cell of size  $m=35\text{mm}$ , for different angle of incidence in TM polarization

### III. Phase-Shifting Cell of Reduced Size

The size of the cell, illustrated in Fig. 1, is now  $m=28\text{mm}$  instead of  $35\text{mm}$ , and the other dimensions ( $L_{S1}$ ,  $L_{S2}$ ,  $W_S$ ,  $W$ , etc...) are maintained identical. The cell is simulated in an infinite periodic array and illuminated with a plane wave under normal incidence. The four new convenient values of the central slot capacitance, for which four uniformly distributed phase states are obtained, are  $\{10\text{fF}, 42\text{fF}, 62\text{fF}$  and  $150\text{fF}\}$  (Fig. 8). The bandwidth for which losses (Fig. 9) are less than  $1\text{dB}$  and the equivalent bit number is better than  $1.79$  (Fig. 10) is here  $15.65\%$  ( $5.3\text{-}6.2\text{GHz}$ ) instead of  $12.2\%$  when  $m=35\text{mm}$ . Moreover, Fig. 11 and Fig. 12 clearly show that reducing the size of the cell permits to preserve a satisfying bandwidth even for high angle of incidence. Indeed, a minimum bandwidth of  $12\%$  ( $5.45\text{-}6.15\text{GHz}$ ) is obtained for an incidence of  $30^\circ$  in TM polarization.

## iv. Conclusion

In this paper we demonstrated that the initial triple slot phase-shifting cell suffers from a major limitation. Its bandwidth is severely reduced when it is illuminated under an oblique angle of incidence. Reducing the size of the cell can improve its robustness regarding this effect. A minimum bandwidth of 12% is demonstrated for a 30° angle of incidence, even for TM polarization (the most critical one). In the final version of the article, a complete interpretation of the effect of the angle of incidence on the behavior of the cell will be presented. Moreover, an auto-correction technique of the effect of the incidence will be given.

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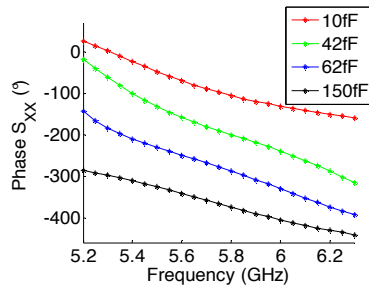


Fig. 8. Reflected phase versus frequency, of the cell of size  $m=28\text{mm}$ , for the four states obtained with the convenient values of the variable capacitance

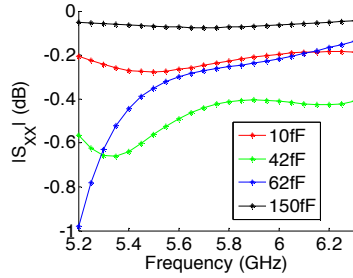


Fig. 9. Losses versus frequency, of the cell of size  $m=28\text{mm}$ , for the four states obtained with the convenient values of the variable capacitance

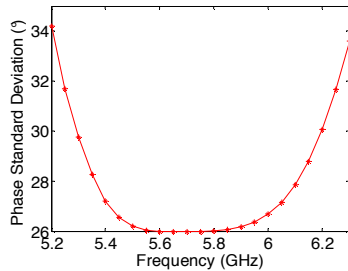


Fig. 10. Phase standard deviation versus frequency of the cell of size  $m=28\text{mm}$

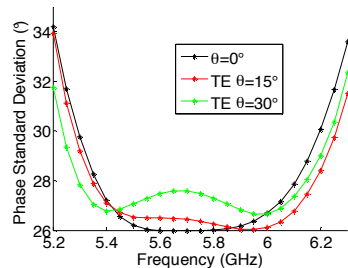


Fig. 11. Phase standard deviation versus frequency, of the cell of size  $m=28\text{mm}$ , for different angle of incidence in TE polarization

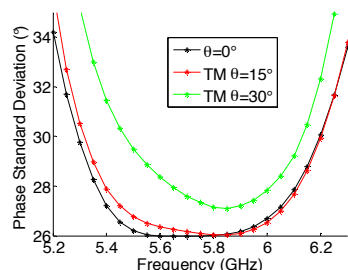


Fig. 12. Phase standard deviation versus frequency, of the cell of size  $m=28\text{mm}$ , for different angle of incidence in TM polarization