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Numerical Investigation about Frequency Behaviour of Conformal FSS

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Additional information is available at the end of the chapter

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Abstract

Frequency selective surfaces (FSSs) are spatial filters widely employed in high-performance applications like hybrid radomes for radars and antennas. While planar geometries are widely studied, less attention has been devoted to conformal ones, where we must consider the influence of both the lattice geometry and the shape and size of the individual elements. In the planar case, periodicity first impacts on the general reflecting properties of the surface, while the shape and the size of the individual element affect its detailed both spatial and frequency filtering behaviour. In particular, the frequency response is dictated mainly by the scattering by the individual element and attains its maximum at resonance conditions. We mean to numerically investigate whether the same also occurs for non-planar surfaces and curved elements, for both cylindrical and conical surfaces. We compare the results of the general frequency behaviour of FSS both made of strips in free space and slots cut in a perfectly conducting material. The effect of the lattice geometrical parameters is also appreciated. The main conclusions are that also for curved elements a frequency selective behaviour can be appreciated and the interaction with the single elements plays an important role, when mutual coupling is not strong.

Keywords: electromagnetic scattering, FSS, conformal surfaces, thin strips, slots, mutual coupling

1. Introduction

Frequency selective surfaces (FSSs) have been studied for the last five decades, and comprehensive books have been also published [1, 2]. They have evolved from simple canonical forms to the complex geometries known today [3]. Moreover, since FSSs are a part of the broad family of artificial materials [4], new research efforts have been dedicated to this topic.

The FSS can be fabricated as planar two-dimensional periodic arrays of metallic elements with special geometric shapes or may be created by periodic openings in a metal screen. The transmission and reflection properties of these surfaces are dependent on the operating frequency and may also depend on the polarization and the incidence angle of the electromagnetic wave impinging the material. While the frequency behaviour of the surface is dictated both by the elements spacing and the shape of the basic element, hereafter we are interested to consider the effect of the latter one. In this chapter, we consider a comparison between the planar and the cylindrical case, in order to verify if the frequency behaviour remains similar when the surface is conformal. In addition, results of the scattering by a conical surface are presented.

While several numerical approaches are available for planar FSS [5] and for complicated structures [6], conformal (or curved) FSSs are more difficult to be analysed since the periodicity and the infinite extent of the surface are lost and a unit cell cannot be recognized. For instance, for a conformal surface made of thin loops, an approach based on the numerical solution of the relevant integral equation by the method of moments is introduced in Ref. [7] leading to the observation that each elements is excited in a different way by an impinging plane wave. In Ref. [8], a spectral domain approach is introduced to try to alleviate the computation burden for the scattering by a spherical FSS.

In Ref. [9], frequency-selective behaviour has been observed for the field scattered by a periodically slotted cylinder compared to a solid cylinder. In Ref. [10], an electromagnetic model for their scattering is introduced, but the numerical analysis cannot provide definitive results.

Therefore, the interest arises to conduct further investigation, by a purely numerical approach, about their frequency behaviour. In particular we focus our attention on the curvature and periodicity effects, due to the conformal geometry (cylinder or cone), to which less interest has been paid in the literature. We start out our analysis by considering first, in Section 2, a surface made of thin perfectly electrical conducting (PEC) periodic strips in free space. For the sake of comparison, first a planar arrangement is reported and next the scattering of a plane wave by a cylindrical one is evaluated. The strips are both aligned along the axis of the cylinder and oriented along its cross section. The longitudinal and transverse (with respect to the cylinder axis) periods are varied. Finally, an example for strips arranged on a finite conical surface is reported.

In Section 3, we move to examine the scattering by slotted PEC surfaces. While for slotted planar geometries, it is possible to use the Babinet's principle so that the results obtained for the strips (complementary structure) can be used to predict its frequency behaviour, for conformal structures the Babinet's principle is not applicable, and it is necessary to use a numerical analysis of the entire structure in order to evaluate the frequency behaviour. In this chapter, we analyse a conformal cylindrical structure, made by a PEC circular cylinder in which thin slots are cut. For the purpose of the numerical simulation, the scattering from a finite slotted strip of the cylinder is used with the appropriate periodic boundary conditions to simulate an infinite cylinder. Again different periods between the slot elements are considered and a comparison with the results of planar structures is performed. At the end of the section, again, an example of a slotted finite cone is reported.

All results are computed by numerical simulation of the electromagnetic scattering by PEC objects through a commercial software based on the Finite Difference Time Domain method,

which is the common choice for broad-band analysis. Since we are not interested in the angular filtering properties of the structures but only in exploring possible frequency filtering about their scattered field, we choose to report the total scattered power vs. frequency.

2. Strip geometry

2.1. Planar strips

In the first scenario, an infinite planar passive FSS, made by metallic straight strips is simulated to verify the frequency behaviour. In particular, we focus our attention on the scattered field vs. frequency, and we run simulations changing the spatial period (horizontal and vertical) to verify the modification of the frequency behaviour. **Figure 1** shows a top view of the geometry where TD and VD denote the transverse and vertical spacings between the elements, respectively.

The strip is 15 mm long and 1 mm wide, and the excitation is provided by a y -polarized incident plane wave, propagating along the z direction (**Figure 1**). **Figure 2** shows the scattered power for different spatial (vertically and transverse with respect to the alignment of the strip) periods.

As expected, when the strips are far away, the maximum interactions occur when their lengths are around $\lambda/2$, that is, at resonance with the isolated strip. On the contrary due to the increased mutual coupling effect, for lower spacings, resonance moves to higher frequencies. In addition, transverse displacement affects more mutual coupling and so also the scattered power.

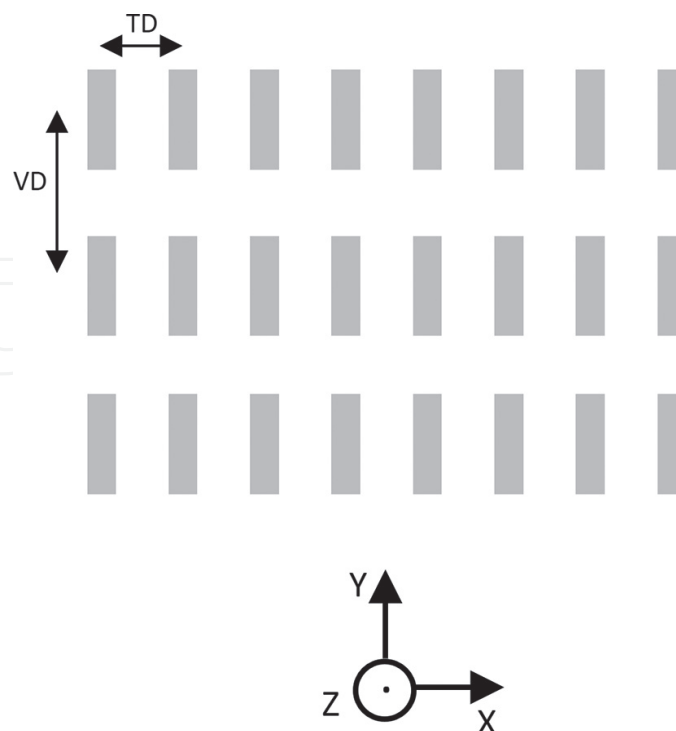


Figure 1. Geometry of a planar passive FSS composed of metallic strips.

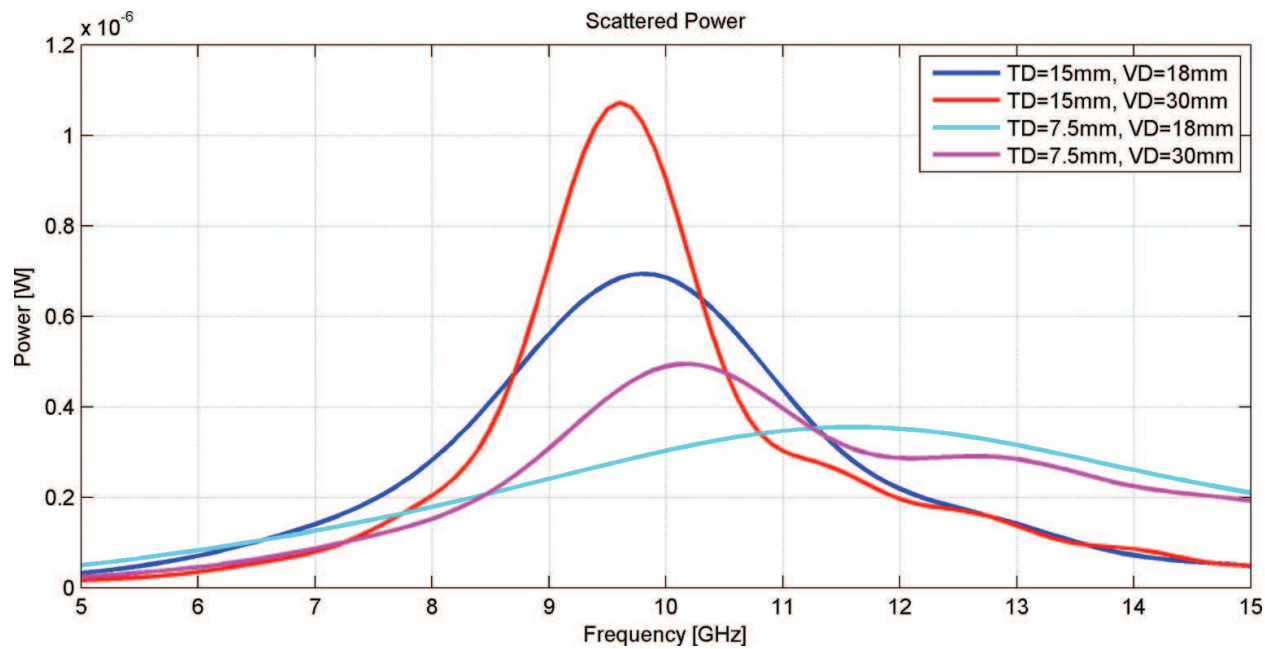


Figure 2. The power scattered by a planar FSS made of strips, for various transverse (TD) and vertical (VD) spacings.

2.2. Planar thin loop

In this scenario, an infinite planar passive FSS is considered, made by circular 1 mm large loop strips with 30 mm circumference (Figure 3). The same plane wave excitation as above is assumed.

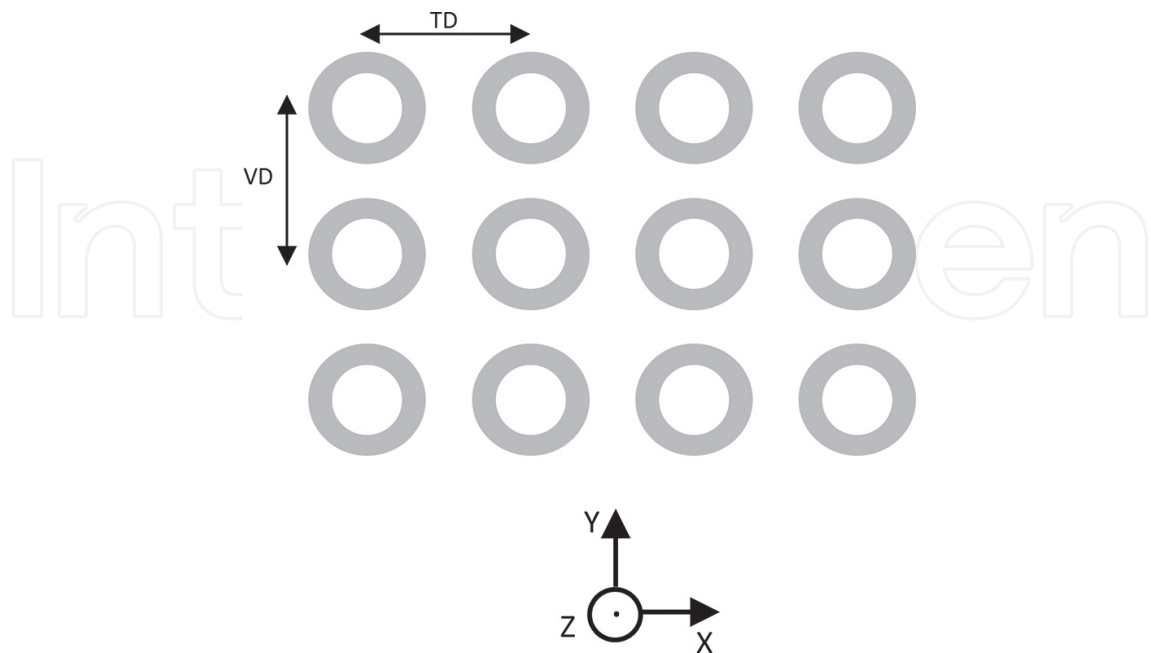


Figure 3. Geometry of planar passive FSS composed of metallic strip loops.

Figure 4 shows the scattered power by an infinite planar FSS made by circular loop strips, for different (equal) spacings between the loops.

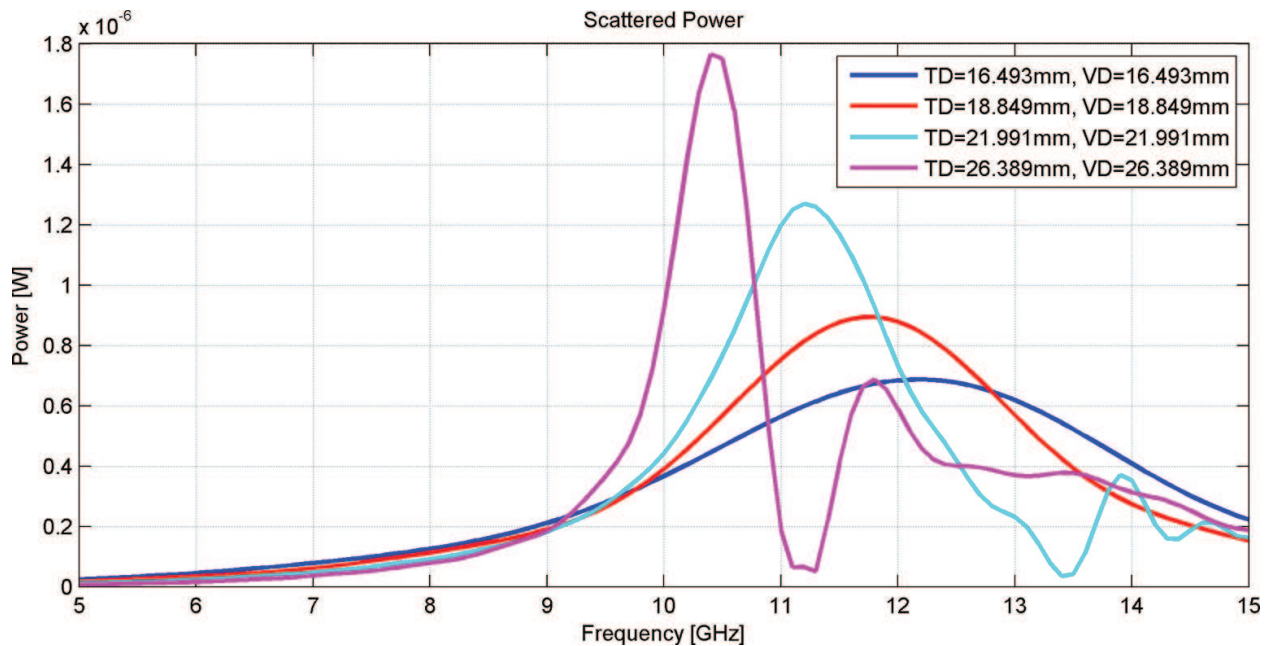


Figure 4. The power scattered by a planar FSS made of loop strips, for various transverse (TD) and vertical (VD) spacings.

As expected, when the loops are far away, the maximum interactions occur when their length is around λ , that is, at resonance with the isolated loop. On the contrary due to the increased mutual coupling effect, for lower spacings, resonance moves to higher frequencies.

2.3. Straight strips on a cylinder

In this scenario, the strips are placed on a conformal cylindrical surface with a radius of 42 mm (**Figure 5**). An infinite structure is considered by imposing periodic boundary conditions in the numerical simulations along the z-axis at various VD spacings. Again, we show the results obtained by changing the transverse spatial period, so implying different number of strips. Again the strips have the same dimensions as in the previous case. The impinging plane wave is polarized along the z-axis and propagates along a direction normal to the cylinder.

From **Figure 6**, a frequency-selective behaviour, though for a rather broad band, can be still appreciated for the non-planar surface case mainly for the largest transverse spacing. Instead, the mutual coupling badly affects this behaviour in a similar way as observed for the planar structures.

2.4. Curved strips on a cylinder

In this scenario, we consider curved, 15 mm long and 1 mm wide strips arranged on a conformal cylindrical surface with a radius of 42 mm (**Figure 7**). In this way, two curvature effects are considered, that is, of both the single scattering element and the surface. An infinite struc-

ture along the z -axis is simulated by resorting to periodic boundary conditions. The incident plane wave is y -polarized and propagates normally to the cylinder.

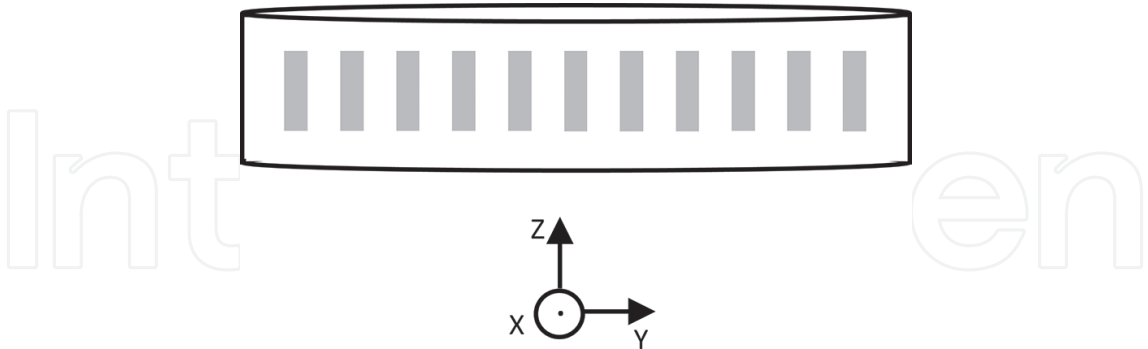


Figure 5. Relevant to the geometry of a conformal cylindrical FSS composed of straight metallic strips.

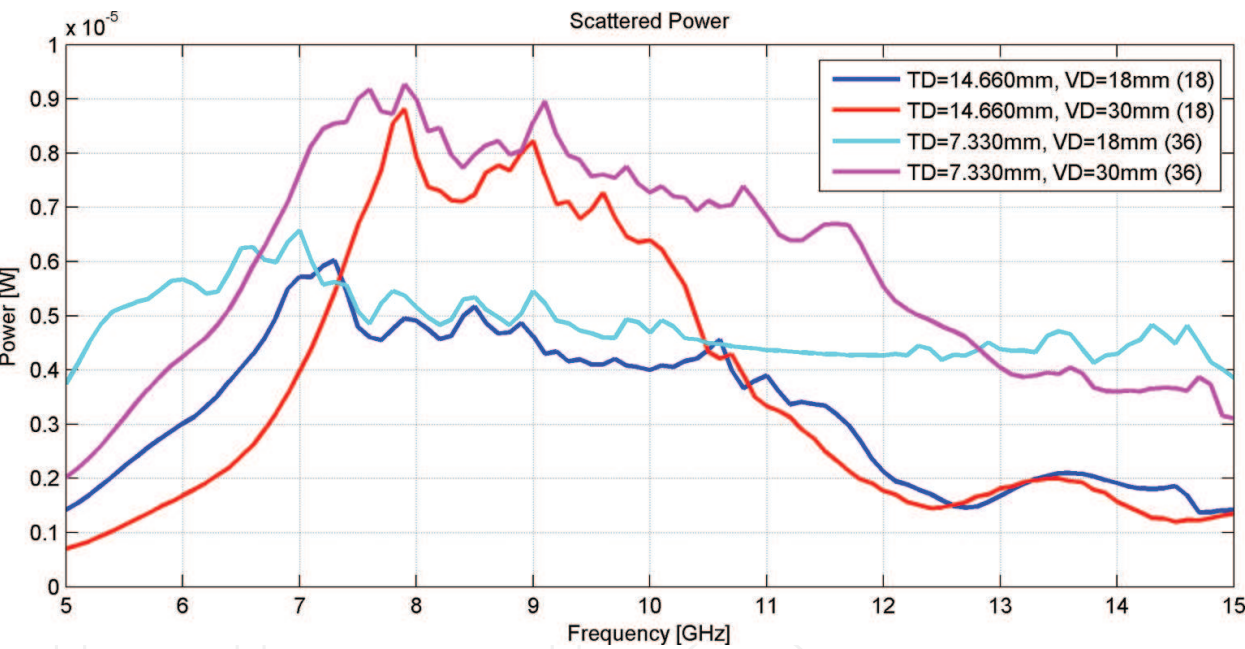


Figure 6. The power scattered by a cylindrical FSS made of straight strips, for various transverse (TD) and vertical (VD) spacings (in brackets, the number of strips is reported).

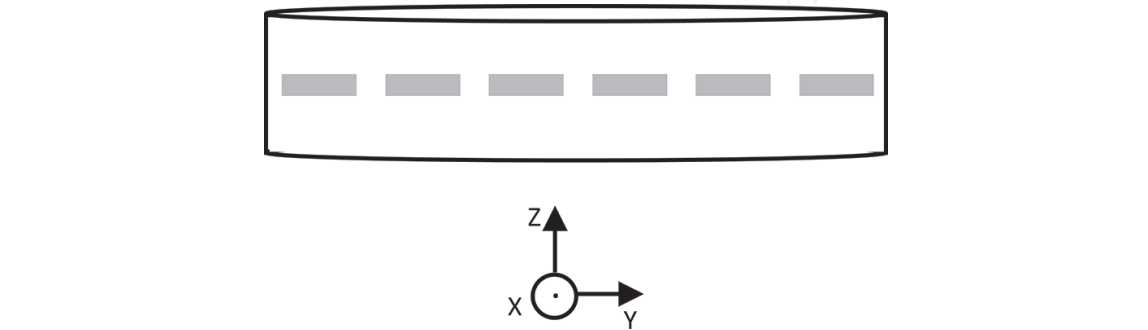


Figure 7. Relevant to the geometry of a conformal cylindrical FSS composed of curved metallic strips.

From **Figure 8**, a frequency-selective behaviour, though for a rather broad band, can be still appreciated for the non-planar surface case and curved strips mainly for the largest transverse spacing. Again, the mutual coupling affects badly this behaviour in a similar way as observed for the planar structures. In fact, as well known, the radiation of wire structures is more affected by similar wire objects when they are approaching each other along the transverse direction, where the induced current is stronger, than along the vertical direction, where the current vanishes.

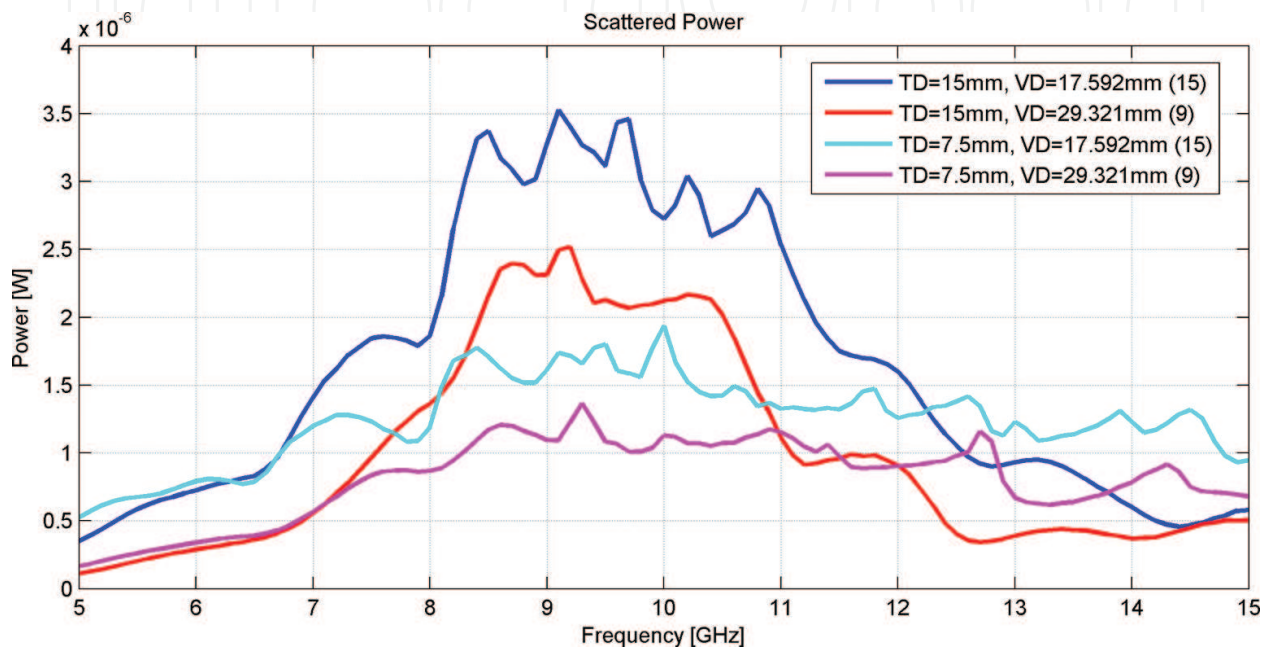


Figure 8. The power scattered by a cylindrical FSS made of curved strips, for various transverse (TD) and vertical (VD) spacings (in brackets, the number of strips is reported).

2.5. Curved loops on a cylinder

Finally, we consider a circular crown, made of curved loop strips, arranged on the same cylindrical surface as above (**Figure 9**). The transverse and vertical spacings are varied for the same amount for different simulations. The incident plane wave is z-polarized and propagates normally to the cylinder.

From the results of **Figure 10**, a frequency-selective behaviour of the scattered power is observed around the same frequency as it occurs in the planar case, that is, when the loop length is about λ . However, when the loops are approaching each other the mutual coupling affects the selectiveness by slightly reducing it.

2.6. Straight strips on a cone

In this scenario, the strips are placed on a conformal conical surface with 30° aperture angle. The cone height (along z) is 268.9 mm and eight rows of strips are distributed along its surface as given in **Figure 11**; the height of the row closest to the vertex is 5.85 mm. The vertical spacing

between the rows is 30 mm, while for all rows, the transverse one is about 15 mm along the arc. Again, the strips have the same dimensions as in the previous cases. The impinging plane waves are linearly polarized.

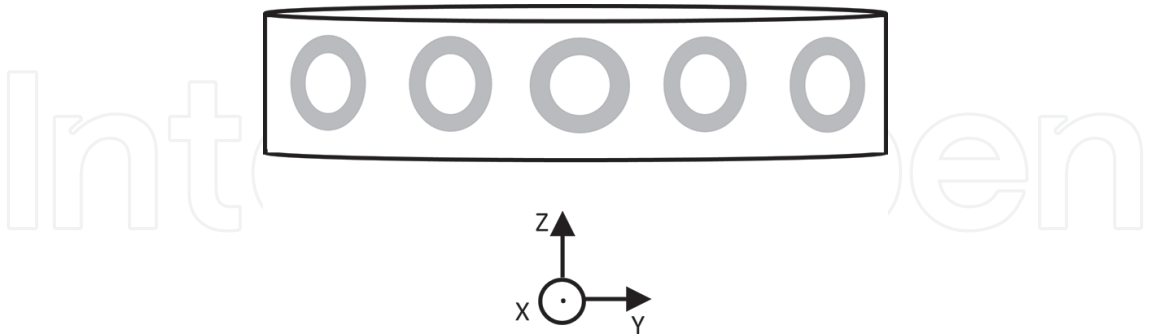


Figure 9. Relevant to the geometry of a conformal cylindrical FSS composed of metallic loop strips.

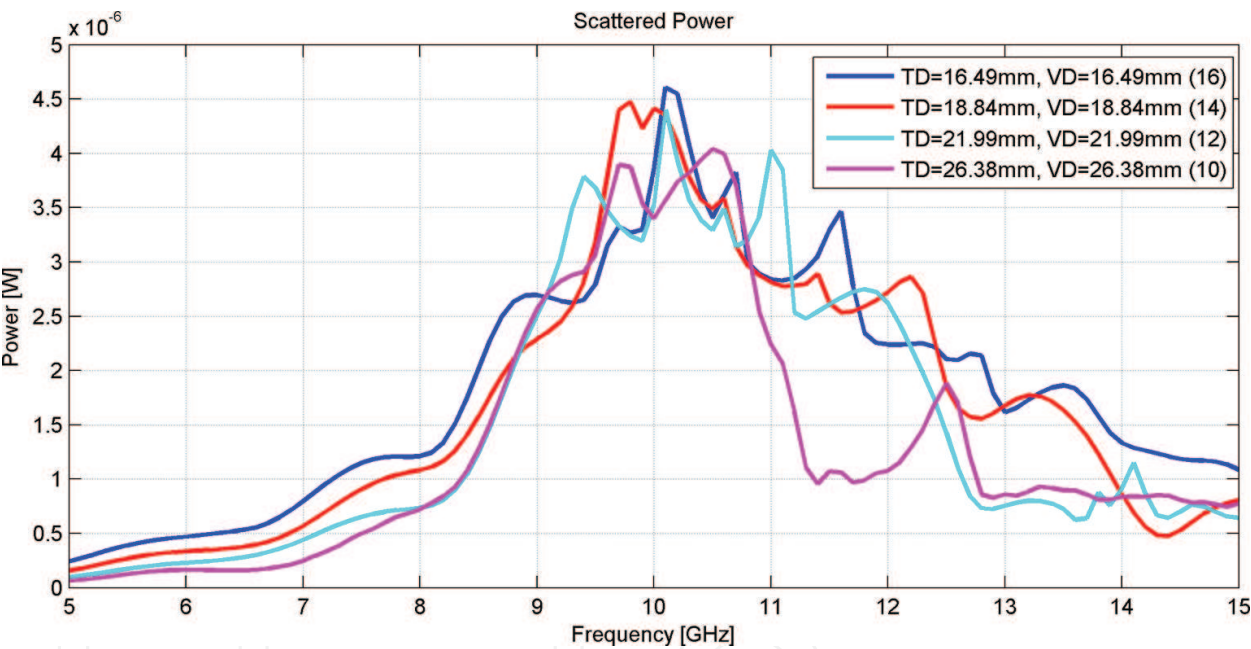


Figure 10. The power scattered by a cylindrical FSS made of curved loops, for various transverse (TD) and vertical (VD) spacings (in brackets, the number of loops is reported).

From **Figure 12**, a frequency-selective behaviour can be appreciated, similar to the planar and cylindrical case of previous sections.

2.7. Curved strips on a cone

In this scenario, the strips are placed on a conformal conical surface with 30° aperture angle. The cone height (along z) is 149.4 mm, and eight rows of strips are distributed along its surface as given in **Figure 13**; the height of the row closest to the vertex is 39 mm. The transverse spacing between the rows is 15 mm, while for all rows, the vertical one is about 30 mm along the arc. Again, the strips have the same dimensions as in the previous cases. The impinging plane waves are linearly polarized.

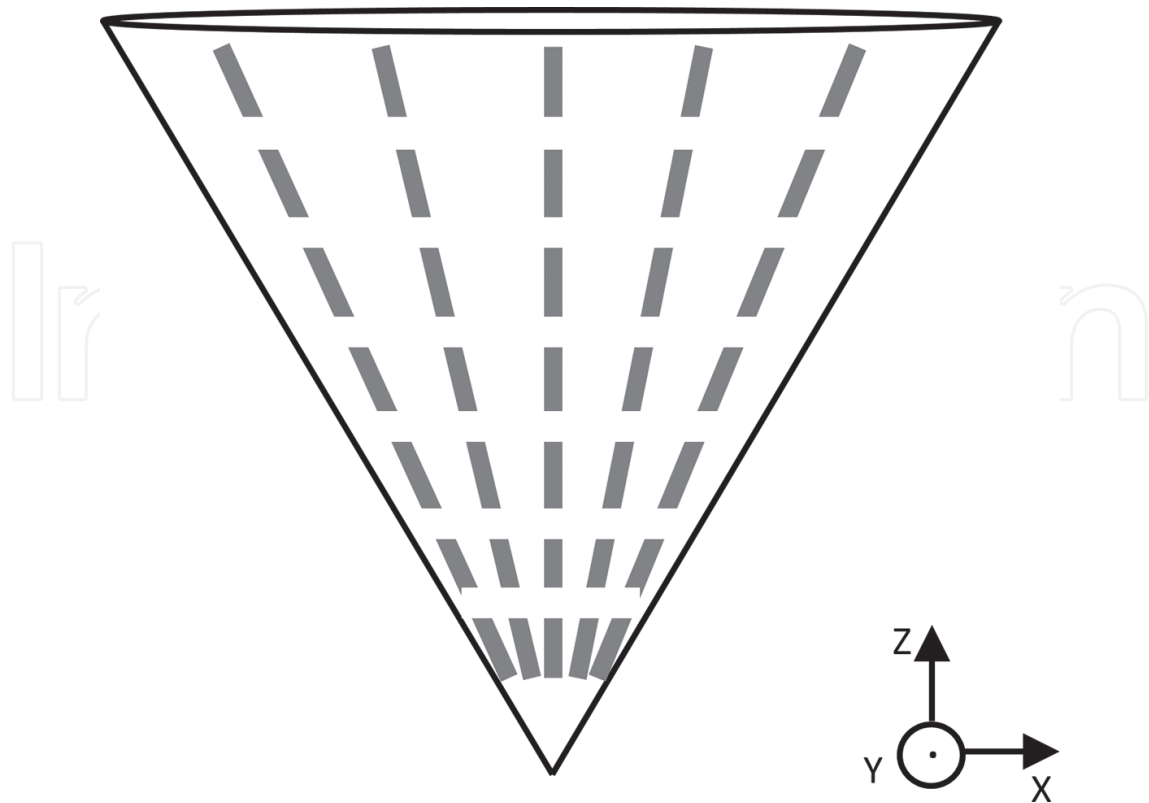


Figure 11. Geometry of a conformal conical FSS composed of straight metallic strips.

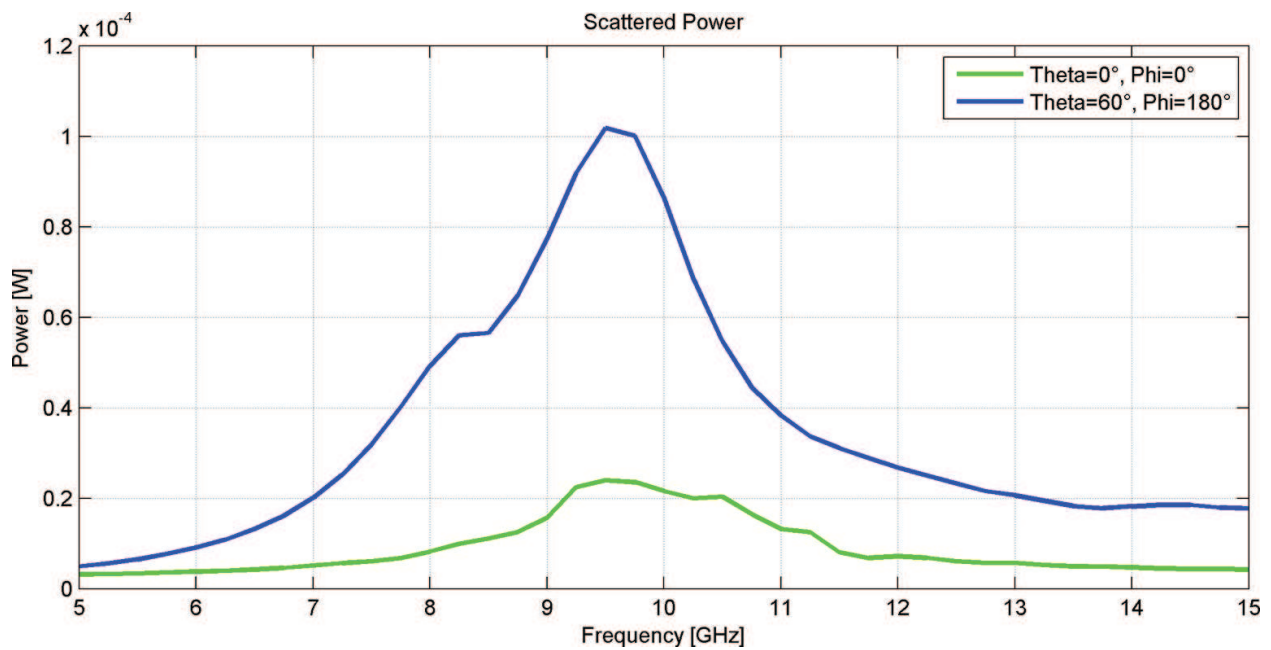


Figure 12. The power scattered by a conical FSS made of straight strips, for various plane wave incidence: $\theta = 60^\circ$, $\varphi = 180^\circ$ (blue line), $\theta = 0^\circ$, $\varphi = 0^\circ$ (green line).

From **Figure 14**, a frequency selective behaviour can be appreciated, similar to the planar and cylindrical case of previous sections.

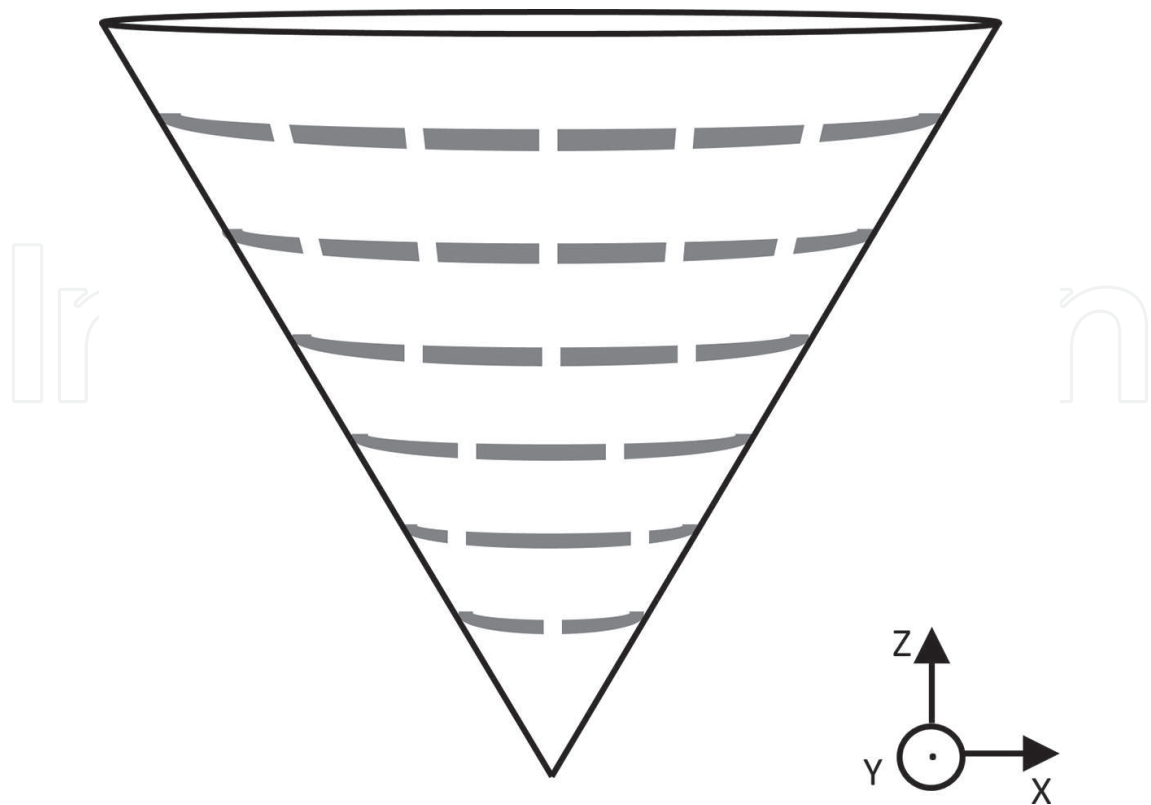


Figure 13. Geometry of a conformal conical FSS composed of curved metallic strips.

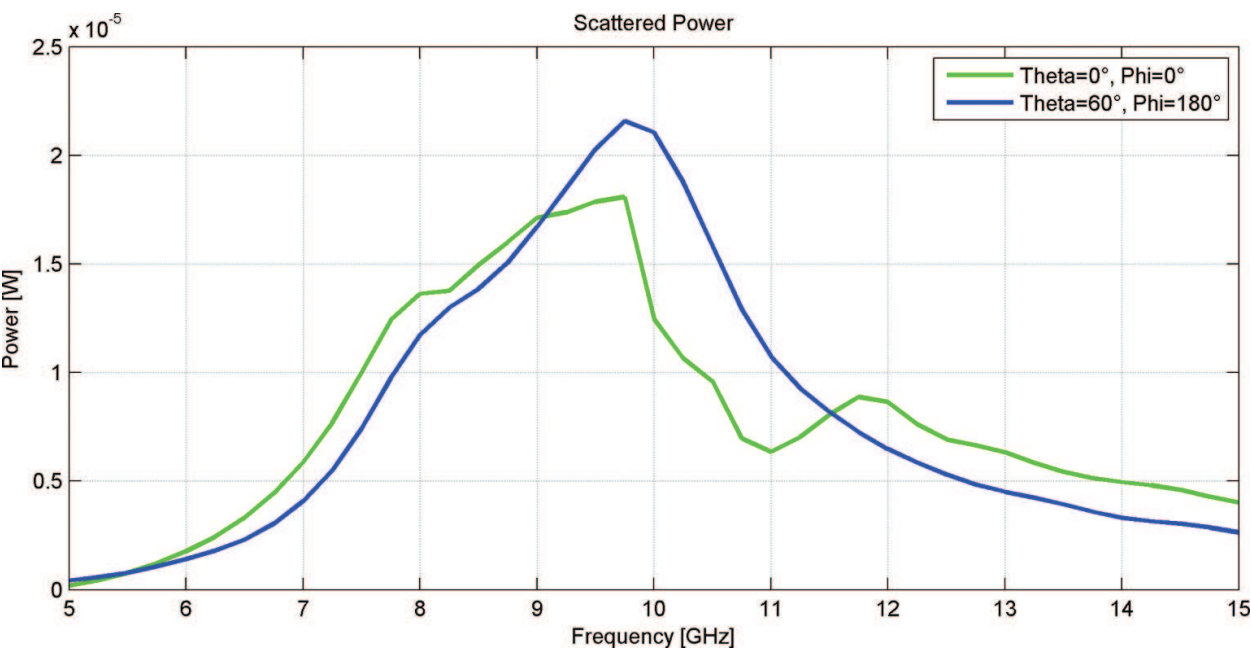


Figure 14. The power scattered by a conical FSS made of curved strips, for various plane wave incidence: $\theta = 60^\circ, \varphi = 180^\circ$ (blue line), $\theta = 0^\circ, \varphi = 0^\circ$ (green line).

3. Slot geometry

3.1. Planar slots

The scattering of plane waves by planar FSS made of slots cut in a PEC surface obeys the Babinet's principle and therefore can be predicted by the results of the complementary strip case. In fact, field transmitted by the slotted surface, and then the transmitted power, is minimum at those frequencies for which the total field scattered by the complementary strip surface achieves its maximum value. Accordingly, the analysis of one of the two structures allows to predict the frequency behaviour of the other one. For non-planar structures, unfortunately, the same investigation must be performed numerically, which can become resource demanding for electrically large structures. For an infinite cylindrical surface, however, application of periodic boundary conditions can reduce this burden.

3.2. Straight slots on a cylinder

In this scenario, slots are placed on a conformal cylindrical surface with a radius of 42 mm (**Figure 15**). We show the results obtained by changing the transverse spatial period, so implying different number of slots. Slots are 15 mm long and 1 mm wide to be complementary to the strips of previous section. The impinging plane wave is polarized along the y -axis and propagates along a direction normal to the cylinder.

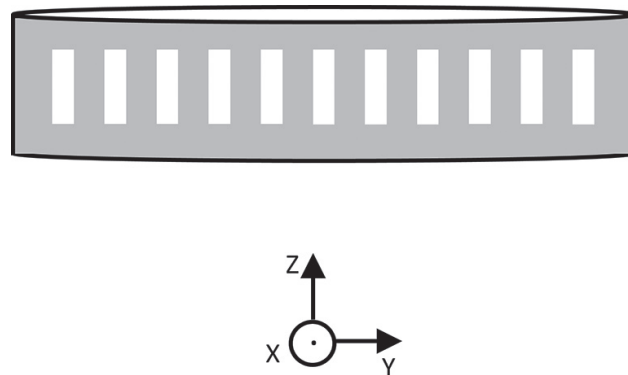


Figure 15. Relevant to the geometry of a conformal metallic cylindrical FSS composed of straight slots.

From **Figure 16**, a frequency-selective behaviour, complementary to the one of the structure of Section 2.4, can be still appreciated for the non-planar surface case mainly for the largest transverse spacing. Instead, the mutual coupling badly affects this behaviour in a similar way as observed for the planar structures, so making the minimum of the scattered power less pronounced.

3.3. Curved slots on a cylinder

In this scenario, we consider curved, 15 mm long and 1 mm wide slots arranged on a conformal cylindrical surface with a radius of 42 mm (**Figure 17**). In this way, two curvature effects are considered, that is, of both the single scattering element and the surface. An infinite structure along the z -axis is simulated by resorting to periodic boundary conditions. The incident plane wave is z -polarized and propagates normally to the cylinder.

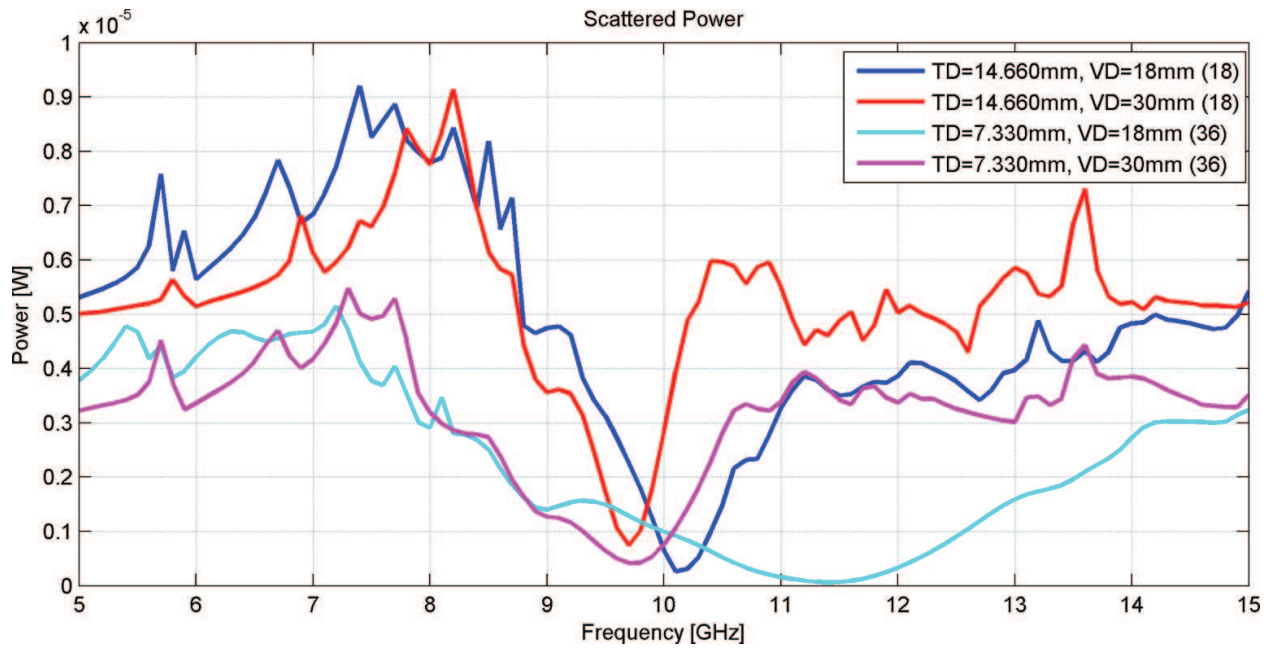


Figure 16. The power scattered by a cylindrical FSS made of straight slots, for various transverse (TD) and vertical (VD) spacings (in brackets, the number of slots is reported).

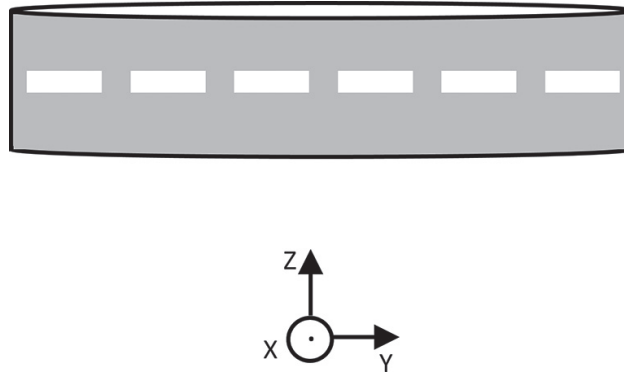


Figure 17. Relevant to the geometry of a conformal metallic cylindrical FSS composed of curved slots.

From **Figure 18**, a frequency-selective behaviour can be still appreciated for the non-planar surface case and curved loops mainly for the largest transverse spacing, along the same line as the case of strips of Section 3.3. Again, the mutual coupling badly affects this behaviour so that for slot closer along the transverse direction no significant frequency-selective behaviour can be appreciated.

3.4. Curved loop slots on a cylinder

Finally, we consider one circular crown, made of curved loop slots, varying the horizontal and vertical deltas at the same time (**Figure 19**). The slots circumference is 30 mm long and 1 mm wide. The incident plane wave is y -polarized and propagates normally to the cylinder.

From the results given in **Figure 20**, a frequency-selective behaviour of the scattered power is observed especially for the largest spacings. However, when the loops are approaching each other, the mutual coupling affects the selectiveness by slightly reducing it.



Figure 18. The power scattered by a cylindrical FSS made of curved slots, for various transverse (TD) and vertical (VD) spacings (in brackets, the number of slots is reported).

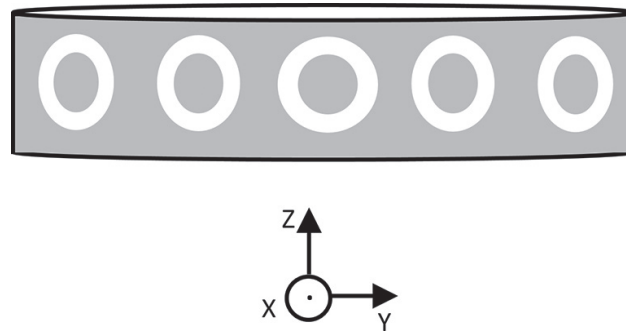


Figure 19. Relevant to the geometry of a conformal metallic cylindrical FSS composed of loop slots.

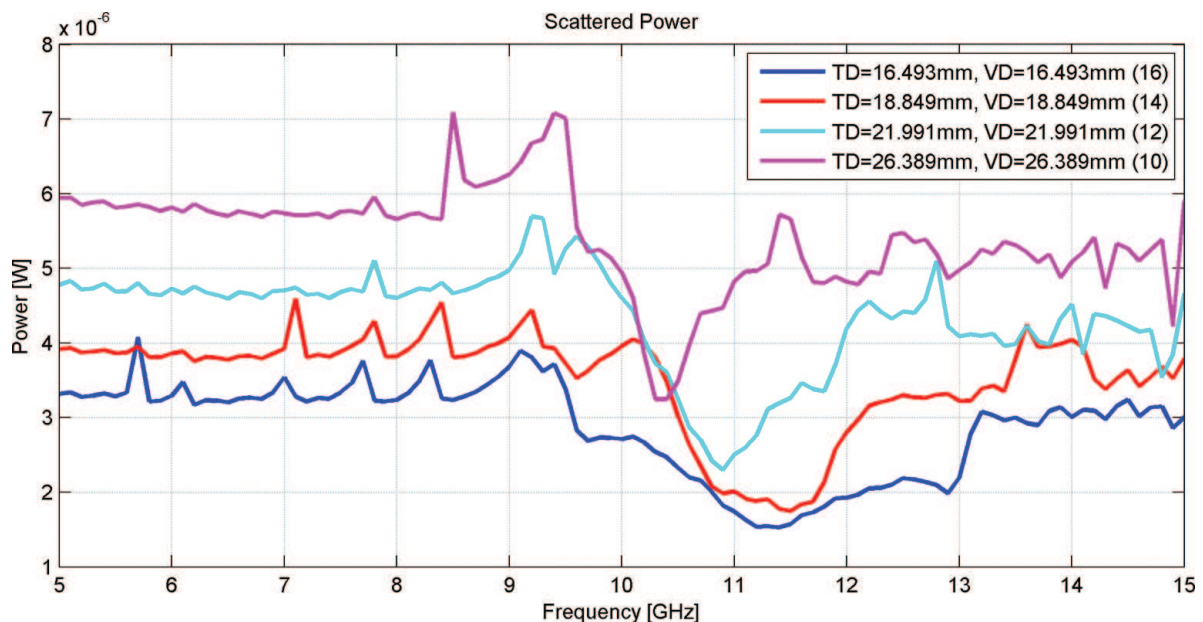


Figure 20. The power scattered by a cylindrical FSS made of loop slots, for various transverse (TD) and vertical (VD) spacings (in brackets, the number of loops is reported).

4. Conclusions

Scattering by conformal FSS cannot be easily investigated by standard techniques as planar periodicity is lost, thus requiring a purely numerical approach. Anyway, it is of interest to explore whether the main features of the planar surfaces behaviour still hold. With reference to a simple wire geometry over a conformal cylindrical surface the power scattered under plane-wave incidence has been evaluated under different scenarios. The main results confirm the possibility to achieve a peaked frequency-selective response under conditions similar to the planar case, that is, for the resonance (open wires) or anti-resonance (closed-loop wires) length. However, when the objects are approaching each other, mutual coupling effects change the induced current appreciably and reduce the frequency selectiveness of the surface. Similar conclusions can be drawn also when the strips are distributed along a conical surface and for FSS made of slots where a complementary stop band behaviour is observed, since the scattered power is reduced within a certain band.

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