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DESIGN OF A RECONFIGURABLE ANTENNA FOR GROUND PENETRATING RADAR APPLICATIONS

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Abstract—This paper deals with the design and numerical analysis of a reconfigurable antenna implemented according to the total geometry morphing approach. The reconfigurable antenna is designed so to resemble a reference bowtie antenna, suitable for a stepped frequency Ground Penetrating Radar (GPR) applications, with geometry variable in order to work in different operative conditions. In particular, the good agreement between the reference antenna and the reconfigurable one is tested within the work frequency band 0.3–1 GHz for both the free-space and half-space geometry. Finally, a trial of the reconfigurability of the proposed solution is shown for operative conditions with antenna in contact with different dielectric media.

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1. INTRODUCTION

The recent advances in the development and the implementation of *RF/microwave switches* have permitted the birth of a new concept of the antenna as a device that can dynamically adapt its behavior to different measurements situations and operational contexts, thanks to the change of its main parameters such as: input impedance, frequency band, radiation pattern [1–12].

In this framework, here we deal with the design of an antenna with a geometry completely reconfigurable and the performances of the antenna, in terms of reconfigurability, are tested against a reference bow-tie antenna, of interest in Ground Penetrating Radar systems [13], within the frequency band 0.3–1 GHz.

The structure is "synthesized" by means of the ***total geometry morphing approach*** [14] that represents the most structurally complicated of the methods exploited to achieve the reconfigurability of an antenna.

Usually, such an approach is implemented by means of a large array of switchable sub-elements whose dimension is small compared to the radiated wavelength (usually of the order or less than 1/20 of the wavelength). By switching adjacent sub-elements via RF switches, an aggregated structure that forms the desired radiator is achieved. Therefore, this sub-element arraying allows a considerable flexibility in forming the radiator by obtaining the desired geometry of the antenna in dependence of the application of interest.

In particular, in the design procedure we exploit as numerical tool the High Frequency Simulator Software (HFSS) of the Ansoft [15] that is a 3D full-wave Finite Element Method (FEM) [16] able to compute the electrical behavior of high-frequency and high-speed components.

Therefore, the paper is organized as follows. Section 2 presents briefly the numerical code and the steps exploited in the antenna design procedure. Section 3 deals with the description of the reference continuous bow-tie antenna and of the performances of the reconfigurable solution in free space; in addition, the case of the inaccuracy in resembling the geometry of the antenna is considered. Section 4 will present the performances of the reconfigurable antenna in presence of a non homogeneous half-space scenario typical of the GPR application; in addition, we will present the possibility offered by the reconfigurability by means of the total geometry morphing approach in terms of the "almost invariance" of the scattering parameter in presence of different GPR scenarios (media with different dielectric permittivity). Finally, conclusions follow.

2. THE FEM CODE

In the design procedure the HFSS based on finite element method is exploited. The software is able to deal fully with the tri-dimensionality of the scenario and to face both scattering and antenna characterization problems [17].

The geometric model is automatically divided into a large number of tetrahedra, where a single tetrahedron is a four-sided pyramid. This collection of tetrahedra is referred to as the finite element mesh. The code exploits an iterative procedure where the mesh is more and more finely discretised in a non uniform way. There is a trade-off among the size of the mesh, the desired level of accuracy, and the necessity to keep the computational cost low.

To generate the optimal mesh, the code uses an iterative process, denoted as "adaptive analysis", in which the mesh is automatically refined in critical regions. First, it generates a solution based on a coarse initial mesh. Then, it refines the mesh in areas of high error density and generates a new solution. When selected parameters converge within a desired limit, the code breaks out of the loop.

In the more general case, the convergence criterion for the stopping of the procedure is based on the change in the scattering matrix coefficients between two consecutive iterations. In particular, if the modulus and phase of all scattering coefficients change by an amount less than a prefixed maximum ΔS from one iteration to the next, the adaptive analysis stops. Otherwise, it continues to refine the mesh. The maximum ΔS is defined as

$$\Delta S = \mathrm{Max}_{ij} \left[\left| S_{ij}^{N} - S_{ij}^{N-1} \right| \right] \tag{1}$$

where i and j cover all scattering matrix entries, and N represents the iteration number.

Standard radiation boundary condition have been exploited for the mesh termination in order to simulate an open problem.

3. THE RECONFIGURABLE ANTENNA

In this paper, the reconfigurability of the proposed structure is first shown by considering as reference a bow-tie antenna, similarly to the case presented in [18]. In addition, reconfigurable bow-tie antennas have been designed and analyzed in [19, 20]. In this paper, we consider a bow-tie antenna that has a metallic element made by copper with a thickness of 36 μm; the metallic element is located on a layer of glass epoxy FR4 with extent 20 cm×20 cm and 3 mm thickness. The bow-tie antenna, shown in Fig. 1, has 64 mm length and flare angle of 30 degree.

In this framework, the reconfigurable antenna design is based on the total geometry morphing approach that exploits a rectangular grid, with 1295 pads and 2141 switches (see Fig. 2); this solution offers the highest degree of reconfigurability. The choice of the size of the sub-elements and interconnections has been made to ensure a dynamic structure easily adaptable to different geometries. In particular, each sub-element is a square with side of 2.5 mm and is driven at the ON state/OFF state by means of a ideal circuital model resembling a typical PIN diode whose resistance is $R = 0.985 * 10^{-3}$ Ohm for the ON state and $R = 4 * 10^{6}$ Ohm for the OFF state. The use of PIN diode of 1 mm size as interconnection element allows an excellent isolation if the sub-elements are not connected and an accurate reconstruction of the distribution of the current on the reference antenna.

Let us turn now to show the effectiveness of the proposed solution first in the case of the antenna in free-space.

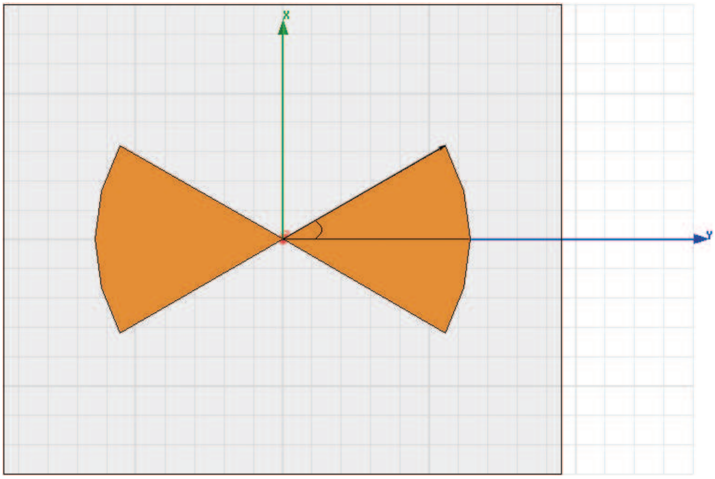

Figure 1. Reference bow-tie antenna: thickness 36 μm, radius 64 mm and flared angle 30 degree, placed on substrate epoxy FR4 with extent 20 cm×20 cm×3 mm.

3.1. Free Space

Here, we tackle the case of the antenna embedded in a free-space scenario. The bow-tie antenna is simulated by the reconfigurable one thanks to the 275 sub-elements at the state ON (i.e., able to radiate) as shown in Fig. 2.

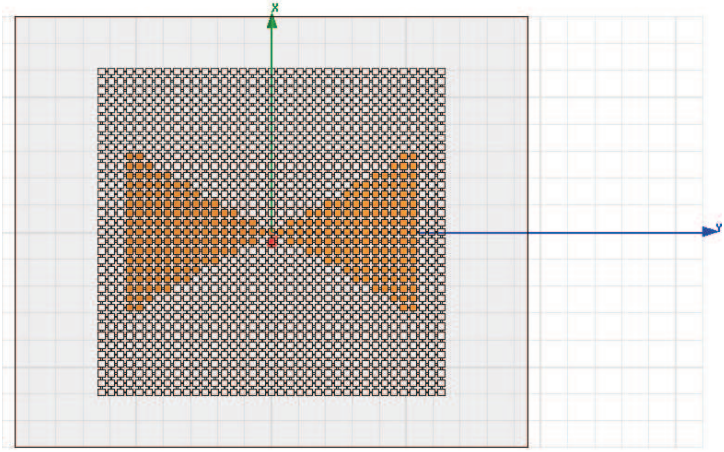

Figure 2. The reconfigurable antenna in the bow-tie geometry.

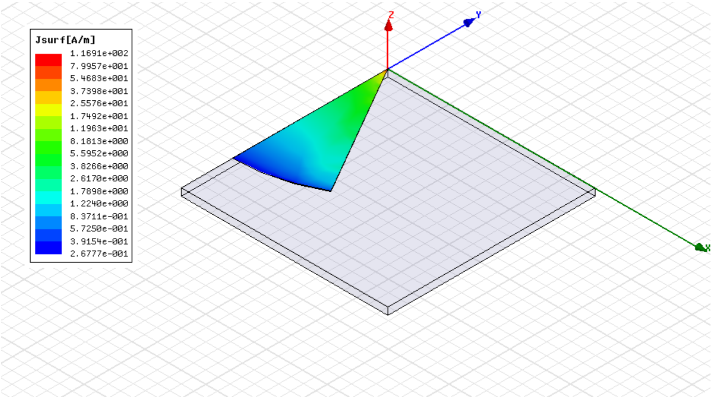

Figure 3. Current distribution computed by HFSS simulation of the reference bow-tie antenna (a quarter of the antenna is shown).

Such a configuration permits us to achieve a good approximation of the behavior of the reference bow-tie antenna. In fact, Figs. 3 and 4 permit to appreciate a good agreement between the current distribution on the radiating element for the reference and reconfigurable antenna, respectively.

The good agreement between the scattering parameter S_{11} of the reconfigurable and of the reference antennas for a free space condition is shown in Fig. 5; both the radiating systems have the same resonance frequency at 700 MHz. Trough the paper, the scattering parameter

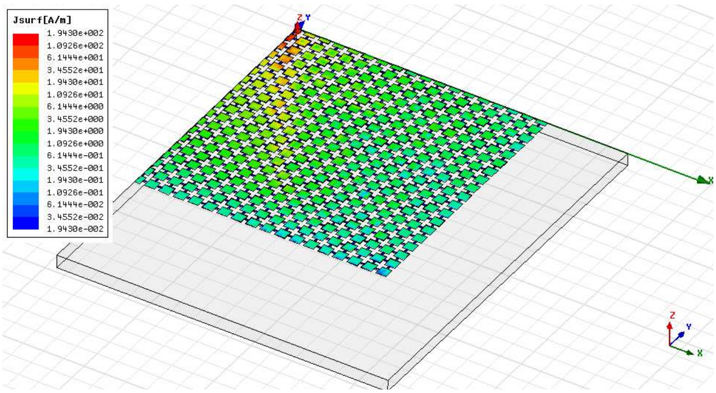

Figure 4. Current distribution computed by HFSS simulation of reconfigurable antenna (a quarter of antenna is shown).

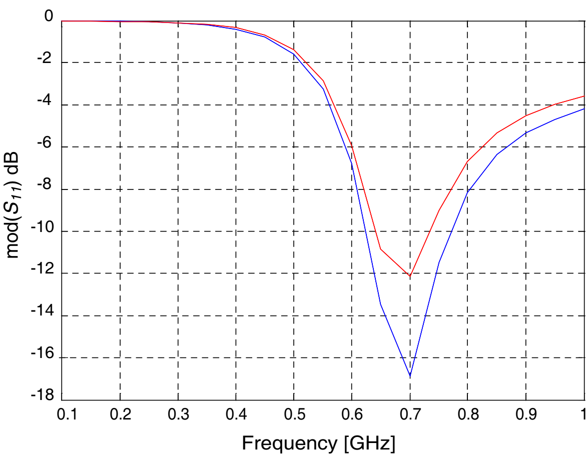

Figure 5. Comparison between the modulus of S_{11} scattering parameter of reference antenna (blue line) and reconfigurable antenna (red line).

S_{11} is evaluated by assuming a 50 Ohm characteristic impedance of the feed-line.

Figures 6 and 7 depict the very good agreement of the input impedance given in terms of real and imaginary part, respectively.

Finally, the effectiveness of the proposed solution can be also appreciated by comparison between the radiation pattern in the E-plane at 650 MHz (almost the center of the work frequency band) in Fig. 8; as can be seen a very accurate agreement is achieved. Finally,

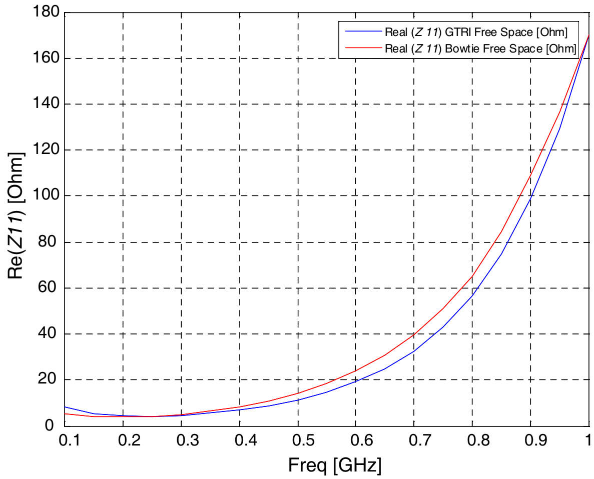

Figure 6. Comparison between the real part of the input impedance: reference antenna (red line) and reconfigurable antenna (blue line).

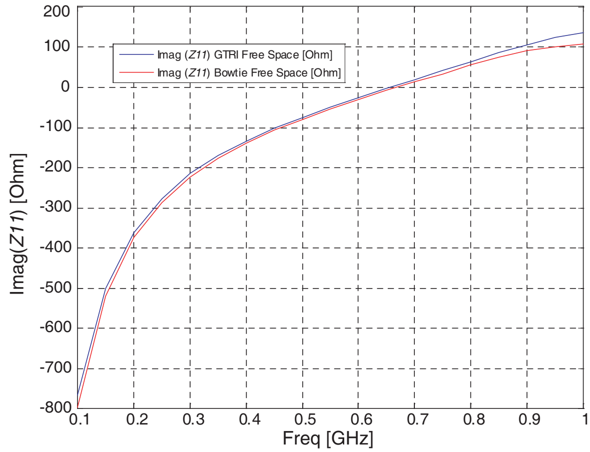

Figure 7. Comparison between the imaginary part of the input impedance: reference antenna (red line) and reconfigurable antenna (blue line).

Fig. 9 depicts the 3D representation of the far field radiated by the reconfigurable antenna.

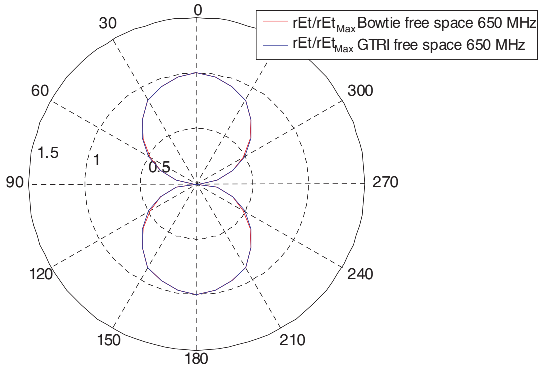

Figure 8. Comparison between the radiation patterns in the E-field at 650 MHz: reference antenna (red line) and reconfigurable antenna (blue line).

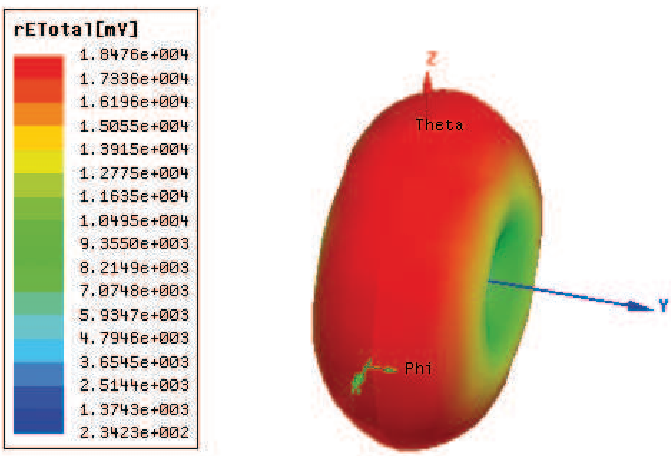

Figure 9. 3D-polar plot of the reconfigurable antenna in free space at 650 MHz.

3.2. The Effect of the Increase in the Pads Extent

Here, we present the effect of the increase of the extent of the pads and of the interconnections on the inaccuracy of the results. In particular, we consider the case of square pads with the side of 5 mm (twice the one presented above); in this case, such an increase in the extent of

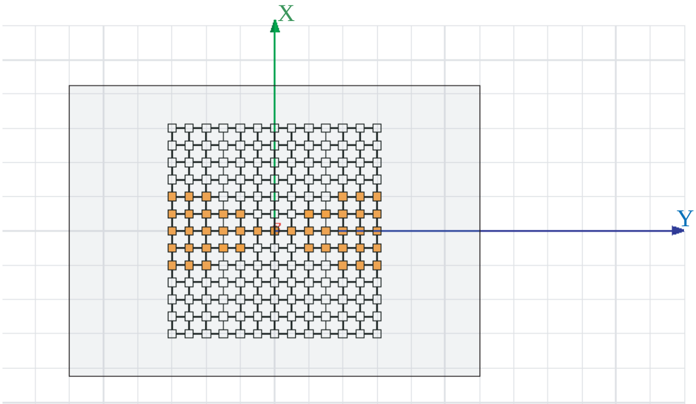

Figure 10. Reconfigurable bow-tie antenna with the 5 mm×5 mm pads.

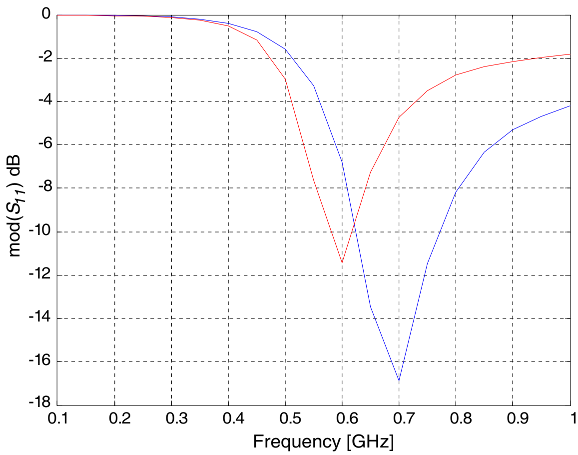

Figure 11. Comparison between the modulus of S_{11} scattering parameter of reference antenna (blue line) and reconfigurable antenna (red line).

the pads does not allow to resemble accurately the reference antenna geometry. Fig. 10 depicts the geometry of the reconfigurable antenna where 45 of the overall 169 pads are in the ON state.

Figure 11 depicts the comparison between the S_{11} scattering parameter of the reference and the reconfigurable antenna. We have that due to the rough discretization, the resonance frequency becomes different for the two antennas. The different behavior between the reference and the reconfigurable antenna is also evident by the comparison between the input impedance (see Figs. 12 and 13); in fact, the agreement gets worse and worse as long as the work frequency increases.

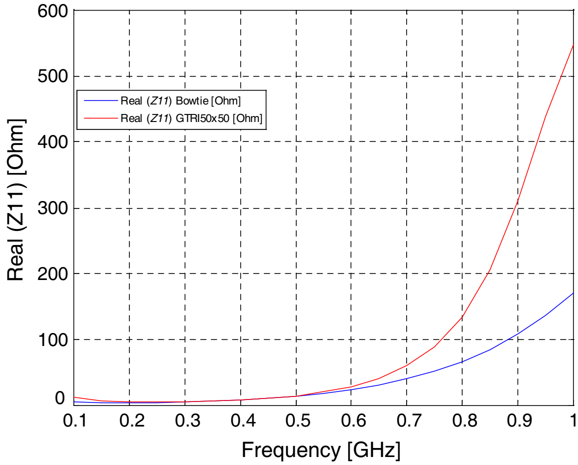

Figure 12. Comparison between the real part of the input impedance: reference antenna (blue line) and reconfigurable antenna (red line).

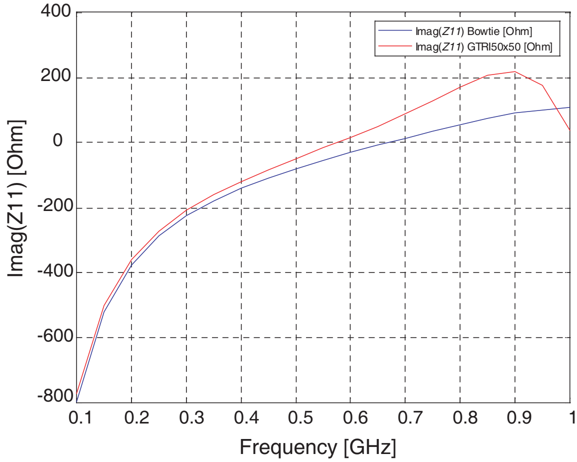

Figure 13. Comparison between the imaginary part of the input impedance: reference antenna (blue line) and reconfigurable antenna (red line).

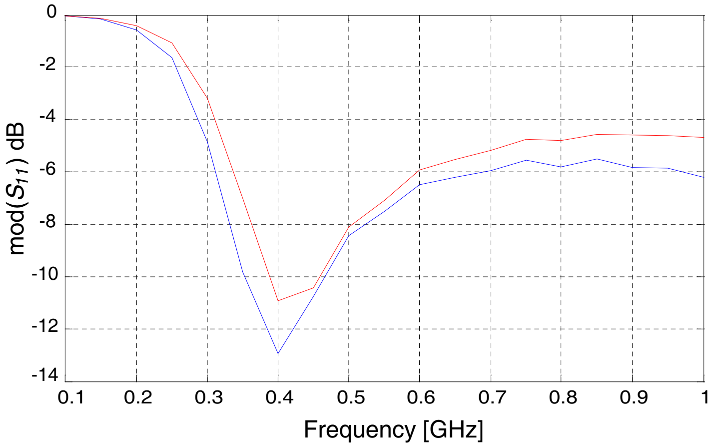

Figure 14. Comparison between the modulus of S_{11} scattering parameter of reference antenna (blue line) and reconfigurable antenna (red line) in the case of the relative dielectric permittivity of the investigated medium equal to 9.

4. THE HALF-SPACE GEOMETRY

The design phase presented in the section above had the aim to preliminarily assess the feasibility of the approach in the conditions of free space.

Anyway, the reference bow-tie antenna was originally designed to work in GPR applications in presence of layered scenarios [17]; therefore, it is important to compare the performances of the reconfigurable and reference antennas in the more realistic case of antenna located at the interface between two different dielectric media (air-investigated medium).

In particular, we will consider two different cases with the relative dielectric permittivity of the investigated medium equal to 9 and 20, respectively. The switches are arranged in contact with the dielectric material in order to simulate the operational condition of the antenna directly in contact with the half-space.

Figures 14 and 15 depict the comparison between the S_{11} scattering parameter of the reconfigurable and reference antennas in the case of relative dielectric permittivity equal to 9 and 20, respectively. As can be noted, the reconfigurable antenna accurately reproduces the characteristics of antenna reference also in the case of the half-space geometry. Now, as expected the resonance frequency of both the antennas is decreased compared to the one in the free space;

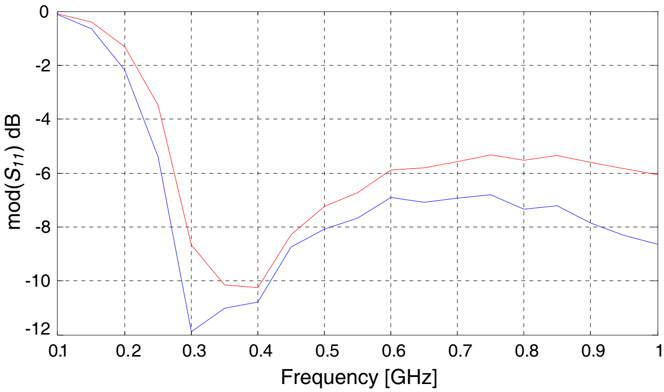

Figure 15. Comparison between the modulus of S_{11} scattering parameter of reference antenna (blue line) and reconfigurable antenna (red line) in the case of the relative dielectric permittivity of the investigated medium equal to 20.

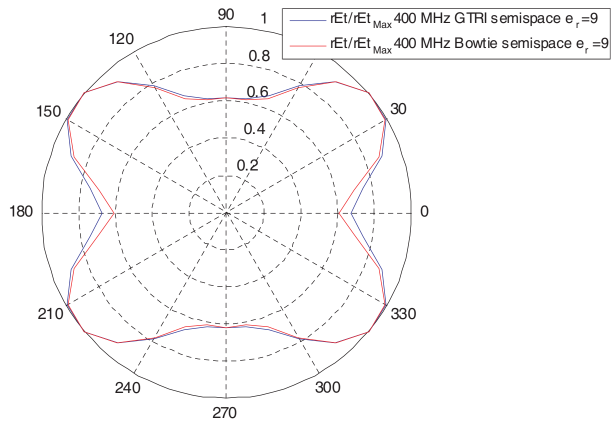

Figure 16. Comparison between the radiation patterns in the E-field at 400 MHz in the case of the relative dielectric permittivity equal to 9: reconfigurable antenna (blue line) and reference antenna (red line).

this arises due to the fact that the antenna are radiating in a denser medium.

Also, the good comparison between the radiation patterns are given for the case of the antennas in presence of the medium with the relative dielectric permittivity equal to 9 and 20. (see Figs. 16 and 17).

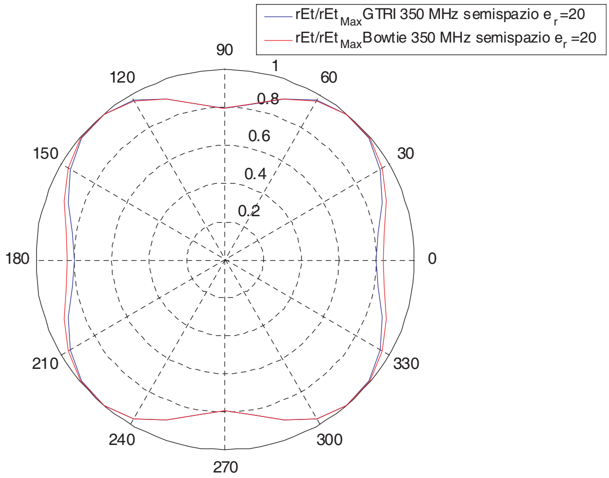

Figure 17. Comparison between the radiation patterns in the E-field at 350 MHz in the case of the relative dielectric permittivity equal to 20: reconfigurable antenna (blue line) and reference antenna (red line).

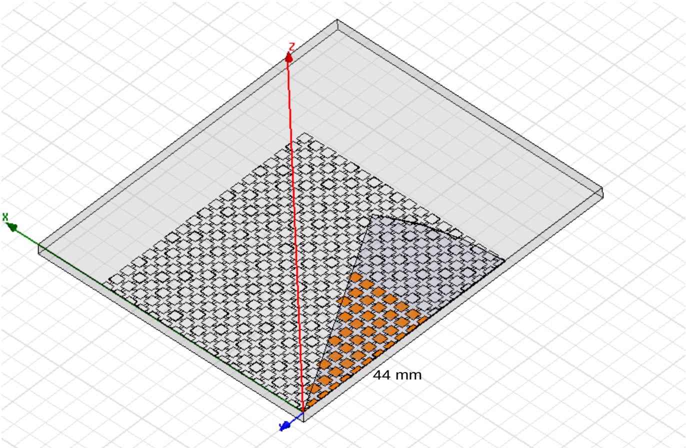

Figure 18. Geometry of the reconfigurable antenna with the dielectric permittivity of the investigated medium equal to 4, the grey zone depicts the geometry of the reference bow-tie antenna.

As final comment, we observe that, in the case of relative dielectric permittivity equal to 20, the capability of the reconfigurable antenna in resembling the properties of the continuous bow-tie are worsened. This is mainly due to the fact that dimensions of the pads and of the

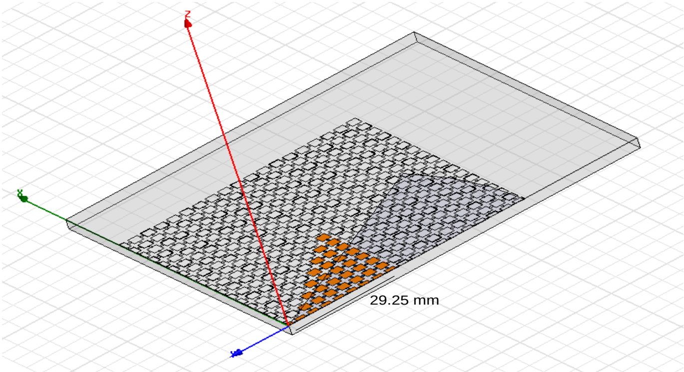

Figure 19. Geometry of the reconfigurable antenna with the dielectric permittivity of the investigated medium equal to 9, the grey zone depicts the geometry of the reference bow-tie antenna.

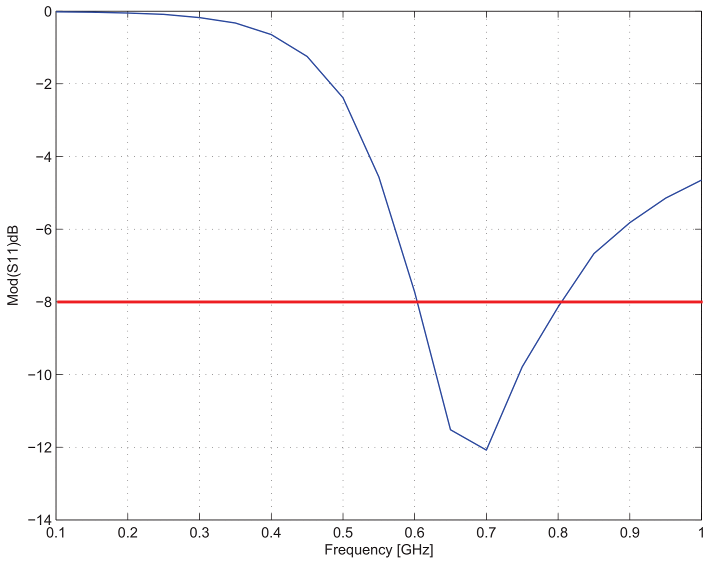

Figure 20. Modulus of S_{11} scattering parameter of reconfigurable antenna in the case of the relative dielectric permittivity equal to 4 and resonance frequency equal to 700 MHz.

interconnections increase in terms of the radiated wavelength in the dielectric medium; this arises an effect similar to the one shown above for the case of the reconfigurable antenna in the free space with the pads of 5 mm side.

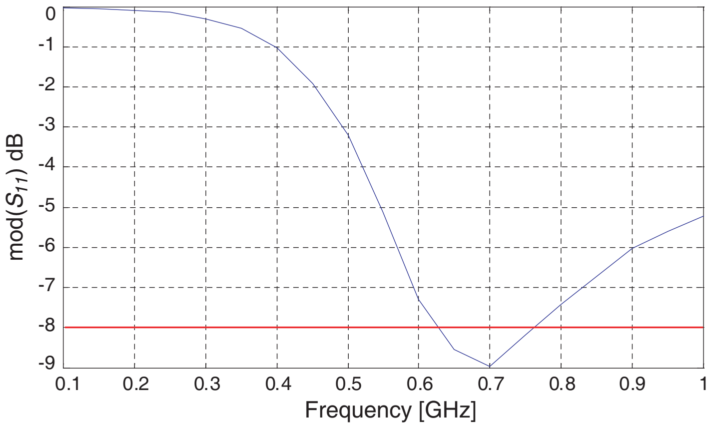

Figure 21. S_{11} scattering parameter of reconfigurable antenna in the case of the relative dielectric permittivity equal to 9 and resonance frequency equal to 700 MHz.

To highlight the reconfigurable properties of the proposed antenna, we present a case where the change of the geometry, by redefining the combination of the switches, is in order to guarantee the modulus of the scattering parameter S_{11} at least less than -8 dB in a frequency band of about 100 MHz around the frequency of resonance. This behavior has been ensured for two cases of the structure in contact with a medium with relative dielectric permittivity equal to 4 and 9, respectively. In particular, the antenna was designed so to have as resonance frequency the same as in the free-space case (700 MHz).

Figures 18 and 19 depict the geometry of the reconfigurable antenna in the two cases. As expected, since the antenna radiates in presence of a denser medium, its extent has to be decreased.

The scattering parameter S_{11} parameter is shown in Figs. 20 and 21 for the two values of the dielectric permittivity; we can appreciate the reconfigurabiliy of the structure that is able to achieve the desired performances in terms of resonance frequency (700 MHz) and the allowable bandwidth (where the modulus of S_{11} is less than -8 dB).

5. CONCLUSION

In this work, we proposed the preliminary design of a reconfigurable antenna based on the total geometry morphing approach with the aim of resembling the 0.3–1 GHz bow-tie antenna behavior in GPR applications. First we have presented the design of the antenna first in free space and then for the half-space scenario. Also, we have presented some preliminary result about the possibility offered by the reconfigurable structure in achieving an invariance of the S_{11} scattering parameter against different values of the dielectric permittivity of the investigated medium.

As future developments, we will address: the impact of the switches and of the corresponding DC network on the radiation characteristics of the reconfigurable antenna [21]; the complete implementation of the antenna thanks to the design of the feed-line and of the absorbing case; the numerical characterization of the behavior of the antenna in presence of the other one; the hardware realization of the proposed solution.

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