TLM Modelling of a Microstrip Circular Antenna in a Cylindrical Grid

Tijana Dimitrijević, Jugoslav Joković, Nebojša Dončov, Bratislav Milovanović

Abstract – **This paper explores applicability of the integral TLM method in a cylindrical grid for the purpose of modelling of coax-fed microstrip antennas in configurations of the circular patch antenna and cavity-backed inverted microstrip antenna. Obtained results representing S_{11} parameter are compared with corresponding results reached by the rectangular grid based TLM method for different mesh resolutions as well as with referenced measured results. Also, a feed position has been considered to provide best matching of the antennas.**

Keywords – **Circular microstrip antenna, coaxial feed, TLM method, wire node, cylindrical mesh**

I. Introduction

Microstrip patch antennas have profound applications in the field of medical, military, mobile and satellite communications due to their well-known efficient features such as compatibility with monolithic microwave integrated circuits (MMIC), light weight, less fragile, low profile, low cost, mass production, dual-frequency operation possibilities etc. These applications of the microstrip patch antenna are evolving new motivations for further research and development of the patch antennas [1, 2].

The microstrip antenna basically consists of a radiating patch on one side of a dielectric substrate, which has a ground plane on the other side. For an electrically thick substrate patch antenna, coaxial feed is typically used. The patch is generally made of conducting material such as copper and gold, it is very thin and is placed a small fraction of a wavelength above the ground plane. The radiating patch may be square, rectangle, thin strip (dipole), circular, elliptical, triangle or any other configuration. While the rectangular patch antenna is perhaps the most commonly implemented microstrip antenna, the circular patch antenna can offer pattern options that are generally much more flexible in a single element [1, 2, 3].

Besides fully planar antennas development much effort has been involved to make these antennas suitable for emerging technologies, whether they are used as stand alone or in arrays. One of the suitable choices is to place the patch antenna into a metallic cavity. For the last two decades, cavity enclosed microstrip patch antennas have gained considerable interest from antenna designers due to their miniature configuration, isolation from surroundings, reduced backward radiation, and suppression of surface waves, considerably reducing the efficiency of conventional patch antennas. The resonant fields in the cavity help reducing the size of the antenna without greatly affecting the antenna performance [4,5]. The inverted microstrip circular patch (IMCP) in a cavity enclosed geometry has been employed in designing several active antenna modules in the last decade [6,7,8]. The air dielectric below the patch in the inverted microstrips is advantageous from various aspects [6] and hence should be an attractive candidate in exploring new integrated antennas [9].

One of the numerical, differential methods that can be successfully used for modelling and analyses of patch antennas is the TLM (Transmission-Line Matrix) method [10]. It is a full-wave method that uses the mesh of transmission lines interconnected at nodes to represent the propagation space. An enhancement of the TLM method in form of the compact wire model, has allowed accurate modelling of wires of smaller diameter than the TLM node size [11]. In practice, it enables modelling of a coaxial feed while including the influence of the real excitation in the analysed model.

There are several commercial software packages that use the TLM method for analysis of microwave structures. Besides they are not allowed to be changed like self-written codes, they are generally based on a rectangular coordinate system, meaning that a cuboid-shaped node is used for modelling of both rectangular and cylindrical structures. However, if a cylindrical boundary needs to be described in a rectangular TLM mesh of finite spatial resolution, it is inevitable to use a stepwise approximation. A numerical error arises because when using a standard node, it is only possible to accurately describe features that are placed at integer multiples of the nodal spacing. To obtain correct results the rectangular TLM mesh of higher resolution needs to be applied. As consequence, duration of a simulation is increased, requiring more computer resources. On the other hand, due to implementation of the compact wire model an account must be taken of the ratio between the wire radius and size of nodes through which the wire propagates, which should ensure convergence of the results. As a result of these two opposite demands, a maximum probe radius that could be modelled using the rectangular grid based TLM method is limited. Thus, we find more convenient to use the TLM method developed in a cylindrical grid, since it enables precise modelling of boundaries irrespective of the mesh resolution that can be defined only according to the probe radius. For that reason, we have developed and implemented the compact wire model in the TLM method based on the cylindrical coordinate system, resulting in the non-commercial code *3DTLMcyl_cw* [12].

The goal of this paper is to investigate advantages and possibilities of the presented integral cylindrical TLM method for modelling of microstrip antennas of circular geometry.

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Two configurations of a coax-fed circular patch antenna have been considered, and resonance values obtained using the integral TLM cylindrical mesh have been compared with those reached by the rectangular mesh as well as with referenced measured ones.

II. TLM MODEL OF A MICROSTRIP ANTENNA

The TLM method is a time-domain numerical method for solving field problems using the equivalence between Maxwell's equations and the equations for voltages and currents on a mesh of transmission lines, the latter representing the propagation space. EM properties of a medium of the considered structure are modelled by using a network of link lines interconnected at nodes. A typical structure of the node is the symmetrical condensed node (SCN), but to operate at a higher time step the hybrid symmetrical condensed node (HSCN) is rather used. In a TLM cylindrical mesh (Fig. 1), each node describes a portion of a medium as it is shown in Fig. 2, with all ports designations.

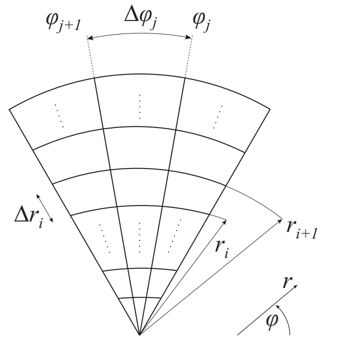

Fig.1. TLM cylindrical mesh in r-φ plane

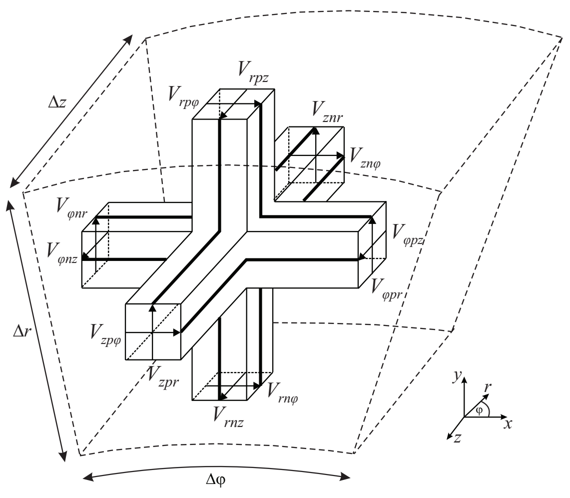

Fig. 2. The cylindrical SCN

The basic computational procedure in a SCN mesh that provides the solution to the problem consists of the initial problem definition and imposing initial conditions, followed by the calculation of voltages and currents, scattering and connection. An efficient computational algorithm of scattering properties, based on enforcing continuity of the electric and magnetic fields and conservation of charge and magnetic flux, is implemented to speed up the simulation process. To excite a particular field component incident voltage pulses have to be injected into the appropriate ports at the beginning of the simulation. As regards to the output from the simulation, the electric and magnetic field or the electric current flowing on conducting bodies are available at any stage. They are generated directly in the time-domain, but they may be transformed to frequency-domain data using Fourier transform. An algorithm in the cylindrical TLM mesh requires modification that involves calculation of link and stub lines parameters where account must be taken of the details of the different geometry.

For the cylindrical mesh based on the HSCN node of type I, characteristic admittances of link lines are calculated as:

$$Y_{ij} = Y_{ji} = Y_0 \frac{2c\Delta t\Delta k}{\mu_{rk}\Delta i\Delta j}\,, \tag{1}$$

and characteristic admittances of open stubs are as follows:

$$Y_{ok} = Y_0\left[\frac{2\varepsilon_{rk}\Delta i\Delta j}{c\Delta t\Delta k} - \frac{4c\Delta t}{\Delta k}\left(\frac{\Delta i}{\mu_{ri}\Delta j} + \frac{\Delta j}{\mu_{rj}\Delta i}\right)\right], \tag{2}$$

where $(\Delta i, \Delta j, \Delta k) = (r\Delta\varphi, \Delta r, \Delta z)$.

In regards to microstrip antennas that represent an open-boundary problems, the modelling procedure requests extension of the space all around the antenna, with external boundaries presented as absorbing walls. Further, the radiating patch and the ground plane, considered as perfectly conducted materials, have to be modelled as internal metallic boundaries representing electric walls. The boundaries of arbitrary reflection coefficient ρ_w are modelled by terminating the link lines at the edge of the problem space with an appropriate load [10, 11]. If the characteristic impedance of a link line differs from the intrinsic impedance of a medium, the equivalent link line reflection coefficient, ρ_{ij}, will be different from ρ_w. The link line reflection coefficient, ρ_{ij}, can be found by terminating the link line, of characteristic impedance Z_{ij}, with the same resistance:

$$\rho_{ij} = \frac{R - Z_{ij}}{R + Z_{ij}} = \frac{(1+\rho_w) - \hat{Z}_{ij}(1-\rho_w)}{(1+\rho_w) + \hat{Z}_{ij}(1-\rho_w)} \tag{3}$$

where a $\hat{Z}_{ij} = Z_{ij} / Z_{ij}^{s}$ is normalized characteristic impedance. If the external boundary represents an electric or magnetic wall then $\rho_w = \rho_{ij}$. Otherwise, ρ_{ij} will depend on Z_{ij}.

Due to presence of a dielectric in the patch antenna, an account must be taken of the modelling of an inhomogeneous media and losses. When different materials are being modelled, characteristic impedances between two link lines are different, making the velocity of propagation also different. This causes pulses to arrive at different times at nodes of the system, and consequently, it is impossible to combine pulses. Thus, it is of significant importance to maintain time-step so the voltage pulses could be synchronized with each other. In that context, the TLM solver described here demands that inhomogeneous media is modelled by a network where the node size used for describing the dielectric is $\sqrt{\varepsilon_r}$ (ε_r is dielectric constant of the substrate) times less compared to the node size used for describing an air-filled area. When losses are concerned, they are incorporated in the TLM model by introducing the stubs with losses in the nodes where scattering is going on [13]. The stubs with losses may be considered as infinitely long transmission lines or, equivalently, as lines terminated by theirs characteristic impedance. Thus, both electric and magnetic losses may be introduced. In the HSCN, these 'lossy' stubs are directly implemented in the scattering matrix, including coupling with the corresponding EM field component.

If σ_{ek} and σ_{mk} represent effective specific electric and magnetic conductivity, respectively, along *k* direction, where $k \in (\varphi, r, z)$, elements in 3-D TLM nodes used for modelling of losses are defined as:

$$G_{ek} = \sigma_{ek} \frac{\Delta i \Delta j}{\Delta k}, \; R_{mk} = \sigma_{mk} \frac{\Delta i \Delta j}{\Delta k}, \qquad (4)$$

where $(\Delta i, \Delta j, \Delta k) = (r\Delta\varphi, \Delta r, \Delta z)$.

Starting from equations $\varepsilon_k^* = \varepsilon_o \varepsilon_{rk} - j\frac{\sigma_{ek}}{\omega}$, $\mu_k^* = \mu_{rk} - j\frac{\sigma_{mk}}{\omega}$ [14], loss tangent can be defined at the appropriate frequency as follows:

$$\tan\delta_{ek} = \frac{\sigma_{ek}}{2\pi f \varepsilon_0 \varepsilon_{rk}}, \; \tan\delta_{mk} = \frac{\sigma_{mk}}{2\pi f \mu_0 \mu_{rk}}. \qquad (5)$$

Thus, in case of modelling of mediums with losses, after defining a loss tangent, corresponding equations for total voltages and currents in the corresponding direction have to be modified [10].

A special TLM technique that should be employed in microstrip antenna numerical solver is the modelling of wires. The wire presence might affect modes behaviour, making knowledge of model behaviour under feed conditions a task of paramount importance. For that purpose, the compact wire model has been developed and implemented into the TLM solver based on the cylindrical grid [12]. The signal propagation along the wire and interaction with EM field is simulated through the wire network formed of additional link and stub lines interposed over the existing network to account for increase of the capacitance and the inductance of the medium caused by the wire presence (Fig.3).

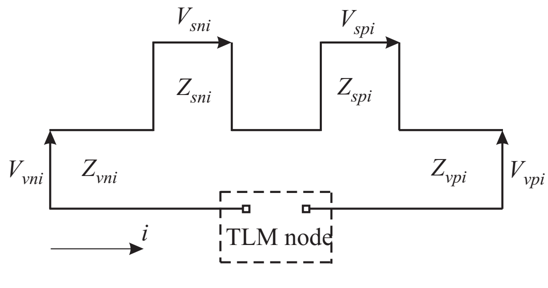

Fig. 3. Wire network configuration for wire segment along i direction

The single column of TLM nodes, through which a wire conductor passes, can be used to approximately form the fictitious cylinder which represents capacitance and inductance of a wire per unit length. An equivalent radius of the fictive cylinder in a cylindrical grid for calculating the capacitance and inductance, r_{Cz} and r_{Lz}, respectively, for a wire segment running along *z* direction are $r_{Cz} = k_{Cz}\Delta z_c$ and $r_{Lz} = k_{Lz}\Delta z_c$, where Δz_c represents a mean dimension of the node cross-section in *z* direction ($\Delta z_c = \left(\frac{(r_i + r_{i+1})}{2}\Delta\varphi + \Delta r\right)/2$, where k_{Cz} and k_{Lz} are factors empirically obtained by using known characteristics of the TLM network. Distributed capacitance and inductance per unit length, needed for modelling of wire segments, may be expressed as:

$$C_{wz} = \frac{2\pi\varepsilon}{\ln(r_{Cz}/r_w)}, \; L_{wz} = \frac{\mu}{2\pi}\ln(r_{Lz}/r_w) \qquad (6)$$

where r_w is a wire radius.

III. Numerical Results

An accurate prediction of the S_{11} parameter of a coax-fed circular patch antenna is very important for the attempts to improve the antenna performance. Two types of patch antenna configurations have been analysed using *3DTLMcyl_cw* software in order to investigate possibilities and accuracy of the proposed method for modelling of patch antennas with excitation in the form of a wire conductor.

Due to approximate modelling of the circular patch in a rectangular grid, the mesh resolution might have a significant influence on simulated results related to resonant frequency and reflection coefficient values. Here, an investigation has been conducted for variable resolutions of both meshes in order to compare possibilities and accuracy of both approaches. When the rectangular grid based TLM method was applied, resolution has being changed simultaneously in both *x* and *y* direction, whereas dimension of nodes in the radial direction has being varied in a cylindrical TLM mesh.

The first example of an application of the integral cylindrical TLM method is related to the model of a circular microstrip antenna [15]. A circular-shaped antenna, shown in Fig. 4, is built on a substrate with relative dielectric constant ε_r = 2.32, loss tangent *tan δ* = 0.001 and with the thickness *h* = 1.59 mm, while the radius of the circular patch is *a* = 50 mm. As an excitation, wire conductor loaded in the substrate with diameter d_0 = 1.27 mm is used.

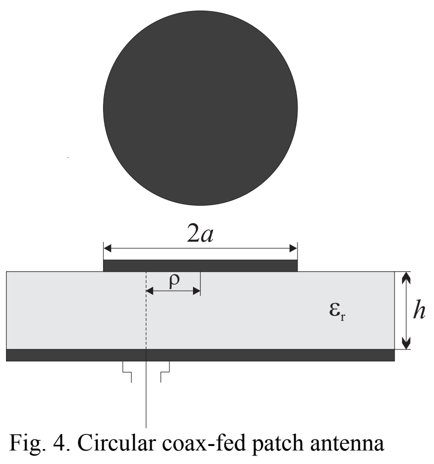

Fig. 4. Circular coax-fed patch antenna

According to the reference [15] operating frequency of this antenna is f_r = 1.13GHz. As an illustration, Fig. 5. shows E_z field component of the circular patch antenna without any feed attached when the TLM method with an impulse excitation was applied. The resonant frequency f_r = 1.118GHz can be observed.

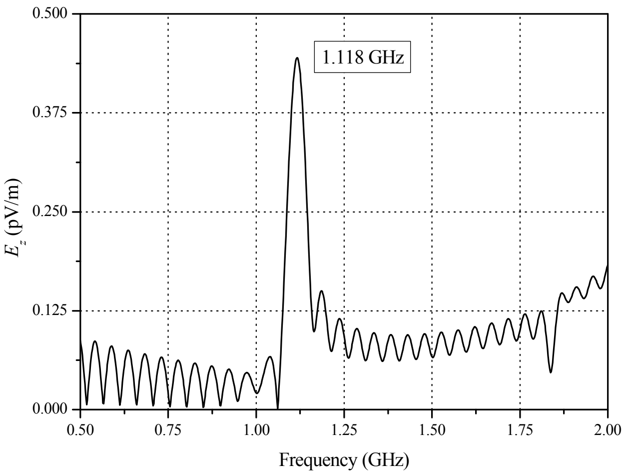

Fig. 5. E_z field component of circular coax-fed patch antenna

First, we approached to examination of the mesh resolution effects on the resonant frequency values in both grids. For that purpose several simulations have been carried out for different mesh resolutions in both coordinate systems. Simulated resonant frequency values versus mesh resolution are illustrated in Fig. 6. As can be seen, in both approaches, resonant frequency value is approaching the referent value, f_r = 1.13GHz, as mesh is becoming finer.

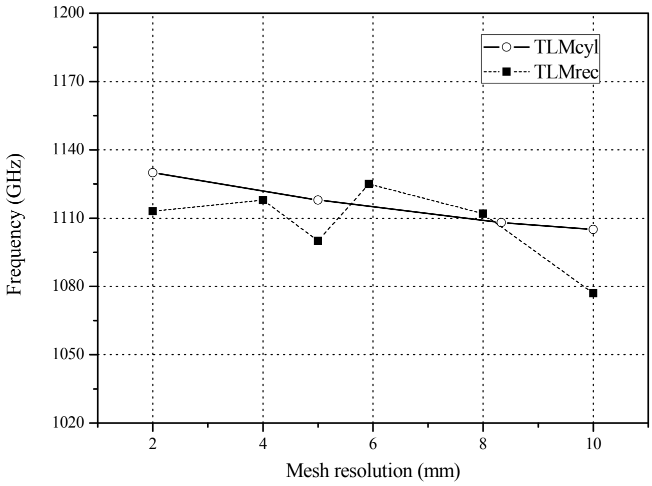

Fig. 6. Resonant frequency value of the circular microstrip antenna versus the mesh resolution for both cylindrical and rectangular TLM grids

Comparing two graphs, one can observe that, when the rectangular TLM mesh is used, changes in the resolution cause considerable variations of the resonant frequency value. This is the consequence of changing the radiating surface due to approximate modelling of the circular patch. Thus, even small changes in resolution might result in abrupt changes of a radiating patch surface being modelled. On the other hand, the patch surface is constant in the cylindrical grid, and thus even coarse mesh causes much smaller frequency deviation than the corresponding rectangular mesh.

To compare accuracy of the resonant frequency prediction achieved by cylindrical and rectangular grid TLM methods, the circular antenna with the position of the feed ρ = 17.5 mm has been analysed in both ways. Graphs corresponding to the simulated S_{11} parameter in the narrow frequency range are plotted in Fig. 7. The solid graph is related to the case when the cylindrical mesh of node size along r and φ direction $\Delta r = a/10 = 5$mm, $\Delta\varphi = 2\pi/36$, respectively, was applied. The other two graphs were obtained by two resolutions of the rectangular mesh which node sizes along x and y direction were $\Delta x = \Delta y = a/10 = 5$mm and $\Delta x = \Delta y = a/25 = 2$mm.

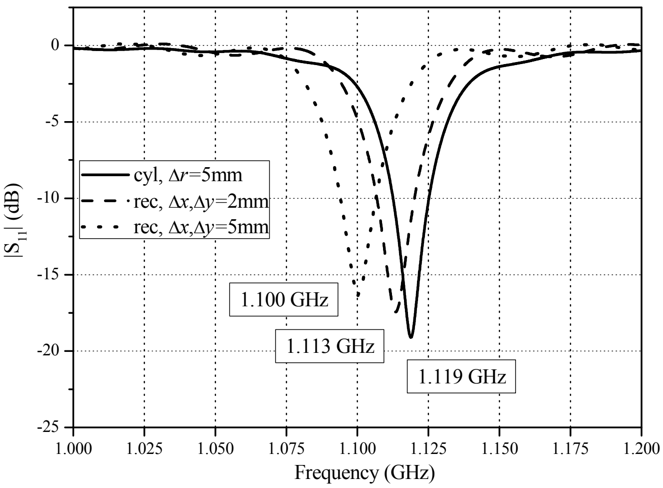

Fig. 7. S_{11} parameter of circular microstrip antenna

Besides mutual concurrence between these results, there is a slightly better agreement of the resonant frequency value obtained by the integral cylindrical TLM method with the referenced one (f_r=1.13 GHz) [16]. Note that cylindrical mesh of smaller resolution and greater node dimension has provided better results in terms of accurate resonance prediction than the rectangular mesh of smaller node dimension.

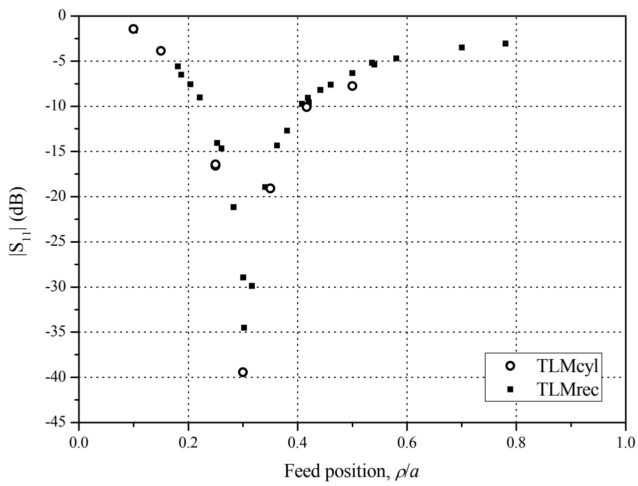

Fig. 8. S_{11} parameter of circular microstrip antenna versus feed position

Further simulations have been carried out in both grids for different TLM mesh resolutions and a variable feed position in order to determine an optimal feed position. Results of S_{11} parameter at the operating frequency generated from all these simulations are illustrated in Fig. 8, showing an agreement between results by both approaches. Generally, reaching the precise optimal feed position is determined by the mesh resolution in either case.

Another antenna model that has been the subject of the TLM modelling is a cavity-backed inverted microstrip circular patch (IMCP) antenna [16]. The antenna layout is presented in Fig. 9.

The relative dielectric constant of a substrate is ε_r = 2.3, radius r = 30mm, radius of a radiated patch a = 20mm, whereas heights of the areas filled with air and substrate are h_1 = 1.43mm and h_2 = 1.57mm, respectively. As an excitation, the wire conductor of diameter d_0 = 0.5 mm is used.

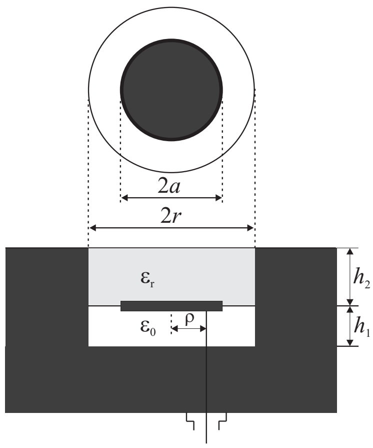

Fig. 9. Cavity-backed inverted microstrip circular patch antenna

In references [9, 16] can be found the operating frequency of this antenna equal to f_r = 3.9GHz. The corresponding numerical model of the antenna without any feed attached has been simulated by the TLM method with an impulse excitation. Fig. 10. shows simulated E_z field component of the cavity-backed inverted microstrip circular patch antenna, where the resonant frequency f_r = 3.783GHz can be observed.

Fig. 11. illustrates S_{11} parameter showing the resonant frequency of a considered antenna for optimal feed position ρ = 7 mm obtained by both cylindrical and rectangular TLM meshes. Presented results were obtained for cylindrical node size $\Delta r=a/10$=2mm, $\Delta\varphi=2\pi/36$ along r and φ direction, respectively, and for rectangular node sizes along x and y axes $\Delta x=\Delta y=a/10$=2mm and $\Delta x=\Delta y=a/20$=1mm. Comparing simulated values of the resonant frequency obtained by both TLM approaches with the measured one (f_r=3.9 GHz) [16], it can be seen that a better agreement with the referenced result is achieved when the integral cylindrical TLM method is used.

To examine the mesh resolution impact on the resonant frequency value, simulations have been carried out for different mesh resolutions in both coordinate systems. Fig. 12. shows the resonant frequency value as a function of the normalized feed position for different mesh resolutions. It can be found from Fig. 12. that results converging to the measured resonant frequency can be obtained for smaller cylindrical mesh resolution in r direction (Δr) compared to the rectangular mesh (Δx, Δy).

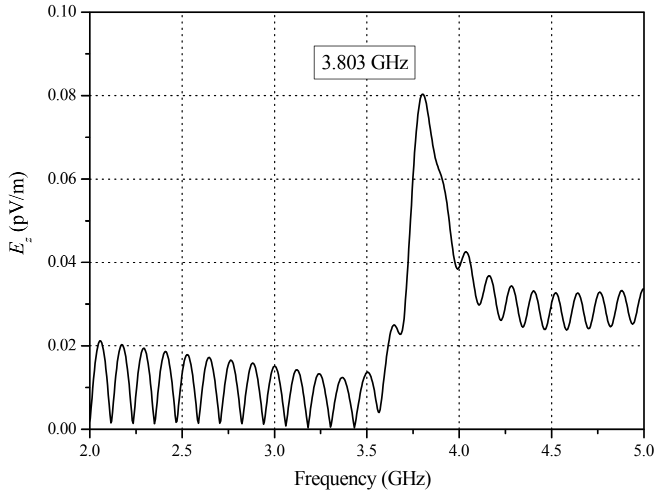

Fig. 10. E_z field component of the cavity-backed inverted circular patch antenna

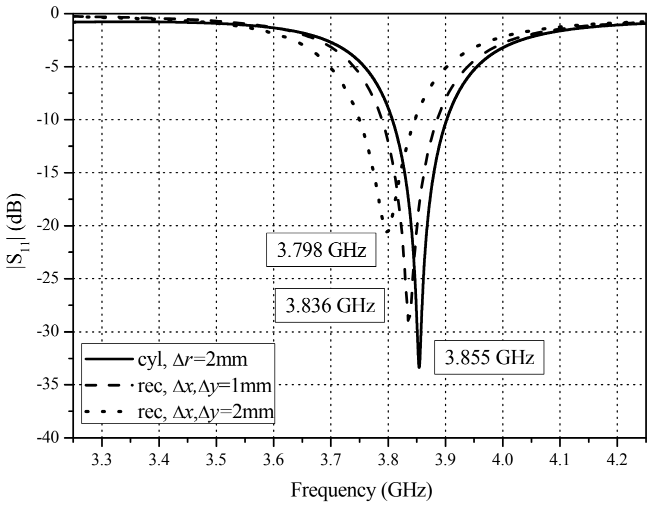

Fig. 11. S_{11} of the cavity-backed IMCP antenna

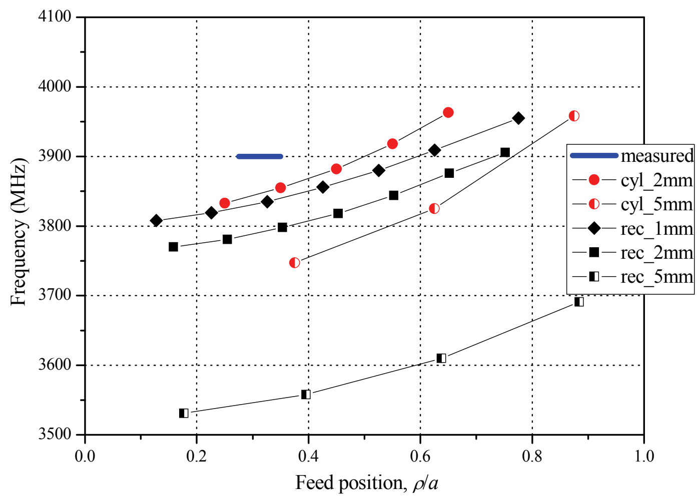

Fig. 12. The cavity-backed IMCP antenna operating frequency versus the normalized feed position

IV. CONCLUSION

In this paper, coax-fed patch antenna configurations have been the subject of modelling using 3D TLM approach based on the cylindrical grid and enhanced with the compact wire model. Two different examples of patch antennas were examined: circular microstrip antenna and cavity-backed inverted microstrip circular patch (IMCP) antenna.

Verification of the presented method is based on a good agreement achieved between results obtained by using the integral cylindrical TLM method and those obtained by measurements, whereas advantages of the method have been considered in regards to the corresponding rectangular grid based TLM method in terms of the mesh resolution. In order to consider an impact of the mesh resolution on the accuracy of obtained resonant frequency and S_{11} parameter, simulations have been carried out for different TLM mesh resolutions in both cylindrical and rectangular grid. Also, antennas with different coaxial feed offsets have been analysed in order to determine the best position providing matching of the antennas.

It has been shown that approximate modelling of a circular-shaped antenna in the rectangular TLM method might generate results with a numerical error, which is dependent on the mesh resolution applied. Because of that, even small changes in a resolution might result in great deviations of resonant frequency and level of the S_{11} parameter. On the other hand, the integral cylindrical TLM method gives better results with the mesh that is coarser than the corresponding TLM rectangular mesh. Thus, the numerical error is avoided and additionally gives more possibilities regarding the probe radius and position.

In overall, the integral cylindrical TLM method is more convenient for antennas with circular geometry, allowing precise modelling of radiating patch as well as structures such as ring resonators or patch antennas with radial slots.

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