Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Electromagnetic Field

Ing. David Vrba

Electrically Miniaturized Antennas Based on Zeroth-Order Resonance

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Candidate: **Ing. David Vrba**
Department of Electromagnetic Field, CTU in Prague, FEE
Faculty of Electrical Engineering of the CTU in Prague
Technická 2, 166 27 Prague 6

Supervisor: **Ing. Milan Polívka Ph.D.**
Department of Electromagnetic Field, CTU in Prague, FEE
Faculty of Electrical Engineering of the CTU in Prague
Technická 2, 166 27 Prague 6

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Chairman of the Board for the Defence of the Doctoral Thesis
in the branch of study Radioelectronics
Faculty of Electrical Engineering of the CTU in Prague
Technická 2, 166 27 Prague 6.

Abstract

Purpose:

Purpose of this dissertation thesis is to introduce several new arrangements of electrically miniaturized antennas, above all those working on a principle of zeroth order mode resonators (ZOR). And further to verify (both theoretically and experimentally) theirs working principles and to develop new ideas allowing to improve technical parameters of the discussed antennas, mainly its radiation and antenna efficiency.

Methods:

At the beginning of our work several presumptions (hypothesis) dealing with ideas how to achieve an improvement of the electrically miniaturized antennas behaviour were identified by aid of analytical methods. Consequently these presumptions were verified by aid of a method of moment based EM field simulator. After that these hypothesis were verified experimentally as well, i.e. parameters of several proposed and realized antennas were measured and compared with the results of the EM simulations. Basically important hypothesis in this thesis deals with a distribution of currents along the studied structures and the new ideas for improvement of discussed type antennas implied from that. Some of other hypothesis deals with the new technologies for the antennas working on the principle of the zeroth order mode resonator. One another hypothesis deals with an improvement of an equivalent circuit model of the ZOR antennas. Based on it a circuit analysis of the ZOR antenna input impedance was made and its result was compared with a measurement.

Results and Conclusions:

This doctoral thesis was written with motivation firstly to summarize state of the art in the field of ZOR antennas and then, based on this knowledge, to bring new ideas, information and experiences to this scientifically and technologically very interesting and very important area. We identified the ZOR antennas as very prospective technology for further development of electrically small antennas, therefore significant part of this work deals with them. Main achievements of my dissertation thesis can be shortly summarized as follows:

1) Proposal of the several novel ZOR antennas with improved radiation efficiency.
2) Study and identification of dominantly radiating parts of the studied ZOR antennas.
3) Identification of new ideas for design of the ZOR antennas.
4) Proposal of a novel Radiation Equivalent Circuit Model of the ZOR antenna.
5) Comparison of the ZOR antennas with several other common antenna structures.

Keywords: Zeroth order resonator mode antenna, electrically small antenna, equivalent circuit model, radiation and antenna efficiency, composite right/left-handed structures.

State of the Art

In all areas of electrical engineering, especially in electronic devices and systems, the attention has been shifted towards miniaturization. Electromagnetism, microwave components and antennas technique and technology in particular are of no exception. There are fundamental limits as to how small the antenna elements can be made [1].

One of the latest technologically available mechanisms how to miniaturize antennas is to use metamaterials structures, more exactly so called Zeroth-Order mode Resonator (ZOR), where the operating wave is a standing wave exhibiting constant-phase field distribution along all the structure. Due to the unique nature of this zeroth-order mode, the size of the resonator does not depend on its physical length but only on the amount of reactance provided by its unit cells. The size of the ZOR is thus limited just by the minimal size of the cells forming the ZOR.

The concept of metamaterial structures has been first comprehensively introduced by Veselago in 1968 [2]. In the aforementioned publication, he speculated on the existence of materials with a simultaneously negative permittivity (ε) and permeability (μ). He named these materials as left-handed (LH) because **E**, **H,** and **k** vectors of electromagnetic wave form a left-handed triad in case the wave propagates through such environment. He predicted unique electromagnetic properties of such materials as e.g. the reversal of Snell's law and the Doppler effect.

Although a possible implementation of composite right/left-handed transmission line [3] appeared even before the Veselago work was published, it remained hidden for the electromagnetic community for three further decades. The first experimental verification of LH material phenomena was performed by a research group at University of California, San Diego only in 2001 [4]. The left-handed material used in the above mentioned verification consisted of metal split ring resonators and a mesh of thin metal wires. Later on, the concept of left handed materials was implemented in the planar transmission line technology [5], [6] via lumped capacitors and inductors periodically incorporated into the transmission line. This approach is considered more practical for series realizations.

Main Aims of this Dissertation Thesis

This doctoral thesis is focused mainly on general studies of basic technical properties and technological limits of the so called ZOR antennas, methods of its development and optimization. In conclusion to description of the state of the art in research of electrically small antennas I would like to identify the main aims of my doctoral thesis – i.e. what I consider to be my own "dissertable" contributions to the area of electrically small antennas. In general it is to present perspective technological possibilities of antennas based on the principle of zeroth-order mode resonator and its applications in communications, industry, medicine, etc. on one side and consequently to identify its limitations on the other side. And further to propose technical and technological solutions to some of the identified limitations. Main aims of my dissertation thesis thus can be summarized as follows:

1) <u>Identification of dominantly radiating parts of ZOR antenna</u>
   We would like to demonstrate in this thesis, that in general the identification of dominantly radiating parts of ZOR antenna is of essential importance when new types of such antennas are being studied. We would like to demonstrate this basic rule with the case of ZOR antenna realized on microstrip transmission line which was divided into several sections and then studied by the aid of microwave simulator IE3D, where the comparison of radiation diagram of selected part and the whole structure is possible (see chapter 2).

2) Improvement of radiation and antenna efficiencies

Our motivation for this research activity was to answer the question whether the MTM antenna could be an effective radiator. Radiation and antenna efficiency of these antennas has not often been studied or relatively low values between approx. 5 to 50 % are reported. Extremely low efficiency values do not enable this structure to work efficiently as an antenna. Therefore radiation as well as antenna efficiency of zeroth-order mode resonator antenna, implemented in composite right/left-handed microstrip transmission line structure will be studied here (in our case by the method of moment by aid of EM field simulator IE3D). The main aim of this activity will be to find the way how to improve both radiation and antenna efficiency of zeroth-order mode resonator antenna. The radiation will be investigated with focus to individual parts of the ZOR antenna which show significant values of the surface current density. The new solutions for increasing both radiation and antenna efficiencies will be presented and proposed.

3) Improvement of radiation equivalent circuit model (RECM)

Both in the analysis and in synthesis of electronic circuits and systems equivalent models of studied structures may play a very important role. Generally it is a very important tool helping us to understand well the behavior of studied structures. Therefore a radiation equivalent circuit model (RECM) of a zeroth-order mode resonator antenna implemented in a microstrip line technology comprising radiation resistance and mutual inductance of shunt inductors in each element cell will be investigated. The antenna input impedance acquired from RECM will be compared with measured data at vector network analyzer and it is found that the presented model provides a good first-order approximation for the initial design of presented ZOR type antenna (see chapter 6).

4) Experimental verification of studied zeroth-order mode resonator antenna

To verify all theoretical hypothesis discussed in this thesis we will do experimental verification of EM simulation of each antenna presented in this dissertation thesis. We fabricated them, we made measurements and we compared these measurements with corresponding simulations.

5) Critical comparison of zeroth-order mode resonator antenna with common antenna structures

To be able to identify and to evaluate major advantages of metamaterial antenna technology the performance of the studied ZOR antenna is subject to critical evaluation based on the comparison with the reference Quarter-Wavelength Patch Antenna (QWPA) that has the same dimensions. In chapter 5 there is a comparison of the aforementioned ZOR antenna and the new developed multiloop antenna with the same size.

6) Proposal of new type of zeroth-order resonator antenna

One of the major results of this dissertation thesis is the proposal of a new type of zeroth-order mode resonator antenna. In chapters 2 and 3 there are proposed new types of suitable structure for the creation of zeroth-order mode resonator antenna structures with different radiation pattern. Chapters 4 and 7 propose antenna structures with similar working principles as already known structures of ZOR antenna are presented.

7) Consideration of folded monopole techniques for bigger distances between single mopoles.

One of new principles suitable for comparison with ZOR antenna technology is based on the theorem of folded monopole techniques. In chapter 7 of dissertation thesis the analysis of radiation resistance as a function of number of monopoles will be performed based on EM simulation as well as by method of electromotoric forces. It will be investigated if factor N^2 appropriately takes into account the increase of input resistance by mutual coupling of short monopoles with uniform current distribution even for their spacing up to $\lambda_0/10$.

Chapter 1

Improvement of Radiation Efficiency of the Zeroth-Order Mode Resonator Antenna

The zeroth-order mode resonator implemented in a composite right/left-handed transmission line, has been developed by several researchers and used to design electrically small antennas. The radiation and antenna efficiency have been, so far, rarely under investigation [13], [14], [15]. Relatively low values (ranging up to approx. 50 %) are reported [16]. In ref [17] only the antenna gain without a corresponding value of directivity and/or efficiency is reported.

Extremely low values of radiation efficiency do not enable the ZOR structures to work efficiently as an antenna. Therefore the question is whether this structure behaves rather as a lossy transmission line or as the antenna. As a result, the methods and techniques enabling the investigation of the antenna and radiation efficiency of the studied antenna should be subjects of interest.

This chapter presents the investigation of antenna and radiation efficiency of ZOR antenna implemented in a very thin composite right/left-handed microstrip transmission line. In this chapter, the software for numerical simulation based on method of moment IE3D [18] was used. We investigated radiation from all individual parts of the studied antenna structure. Dominantly radiating parts have been identified and consequently geometrically emphasized by means of the increase of its dimension, namely we increased the height of the structure over the ground plane. The antenna efficiency of the improved (thick-substrate) ZOR antenna has been measured and compared with those of the original antenna (i.e. very thin-substrate antenna).

1.1 Zeroth Order Mode Resonator Antenna

The efficient operation of a ZOR antenna is viable only in the case that such antenna is impedance-matched and provides sufficient radiation efficiency. The latter requirement depends on the antenna physical size and on the particular distribution of the current density on the antenna structure. In this chapter, studied antenna efficiency is investigated from all the individual parts of the ZOR antenna structure which is implemented on a thin substrate ($h = 0.5$ mm) by aid of composite right/left-handed transmission line technology. In the literature, in the case of the described ZOR antenna [17] a meander line forming shunt inductance L_L is used. The mirror current on the ground plane (i.e. below horizontal strips of this structure) has opposite orientation (phase) with respect to the strip currents. In such a case, the contribution to resultant magnetic field from the currents flowing in the opposed direction is mutually eliminated. Consequently, the significant drop in the radiation can be supposed for a very thin-substrate antenna. So the increase in the strip distance over the ground plane together with the use of the straight inductive stubs is supposed to enhance the radiation from such structure. We consider this idea to be a very significant contribution not only to the theory of ZOR antennas, but also to many other types of antennas implemented in general microwave planar technologies. Therefore we decided to verify the above mentioned hypothesis both by EM simulation and by experimental verification.

Owing to that three prototypes of ZOR antenna have been designed. To have the possibility to compare their antenna efficiencies, the first of them was implemented on a very thin dielectric substrate ($h = 0.5$ mm, $\varepsilon_r = 3.05$, $\tan\delta = 0.003$, ~ $1/105\ \lambda_0$), while the second and third were designed using the increased height ($h = 6.9$ mm, ~ $1/8\ \lambda_0$). While the second one uses the same dielectric substrate as the first one, the third one was set up from dielectric substrate (0.5 mm) and air layer (6.4 mm).

1.2 Radiation from selected parts of antenna

From the simulation it was found out, that magnitude of the surface current density flowing on the horizontal strips of shunt inductors exceeds by its values level of surface currents existing on the rest of the structure by at least 10 dB. The above-mentioned strips thus form source areas that radiate significantly.

For the investigation of the radiation of the ZOR antenna the current distribution of the whole antenna and also selected antenna regions (denoted in Fig. 1.1 by dashed red rectangles) is used. The relative drop-off of the radiation of selected regions to the radiation of the whole antenna structure can be observed in four cases, see Fig. 1.2 and 1.3 The aforementioned drop-off is evaluated and the dominantly radiating parts are identified. In the improved version of ZOR antenna, these parts (namely horizontal strips and vertical pins) are then geometrically emphasized by a rise in the antenna height above the ground plane.
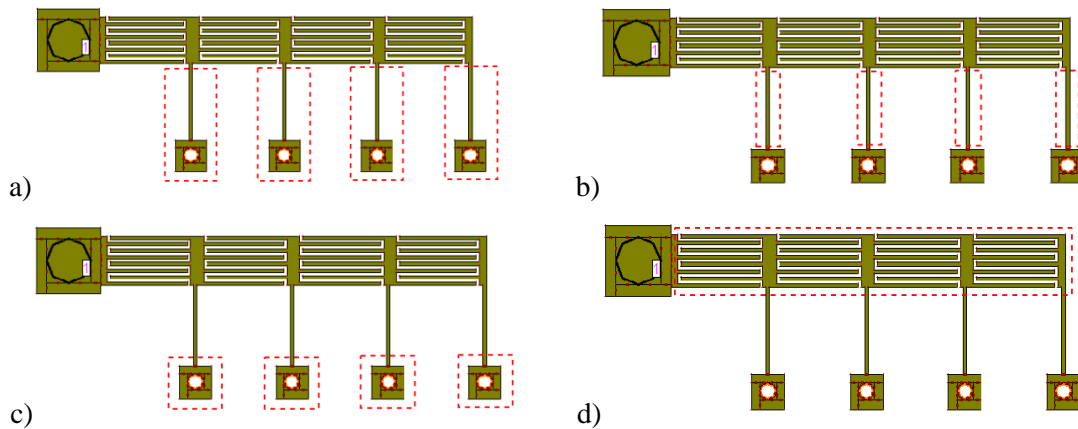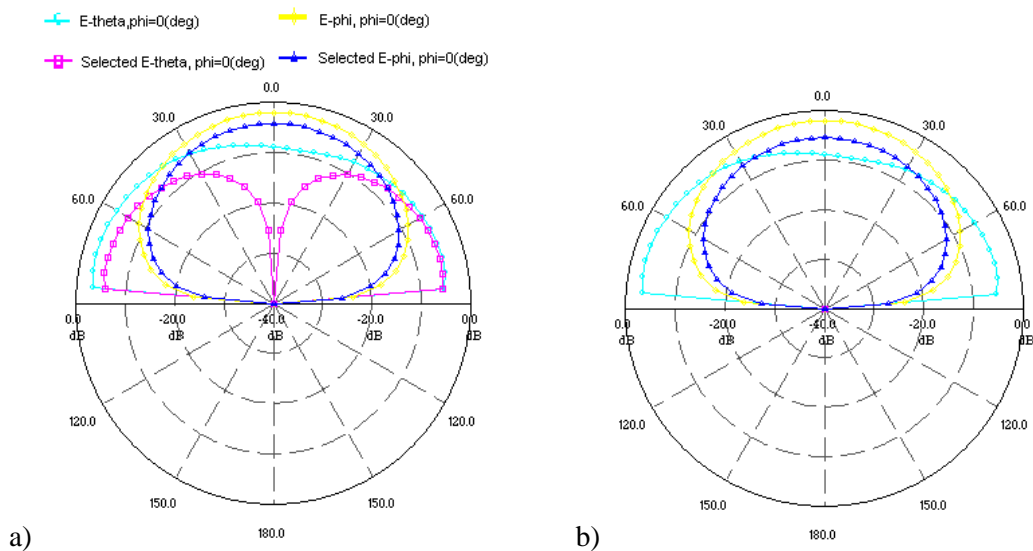

Fig. 1.1: Picture of antenna footprint with selected regions: a) horizontal strips and vertical vias of shunt inductors, b) horizontal strips solely of shunt inductors, c) vertical vias solely of shunt inductors, d) series capacitors
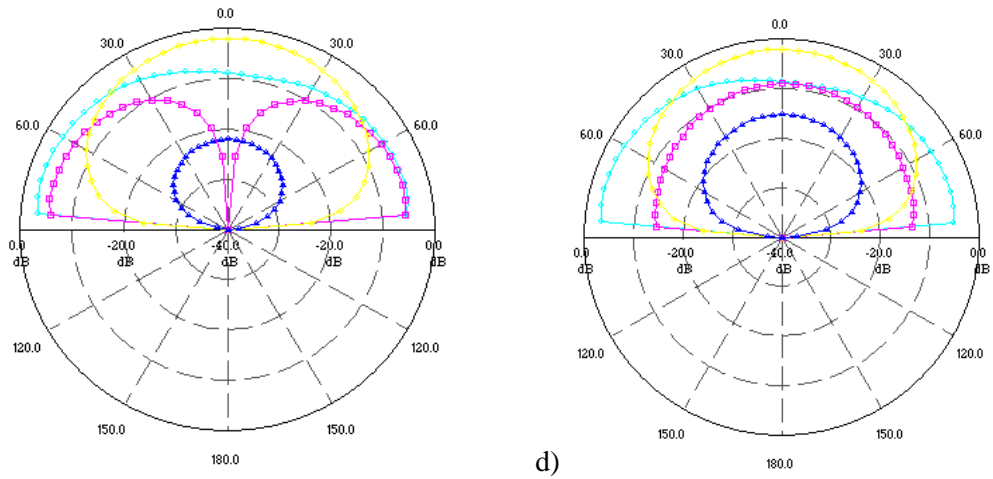

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c)   d)

Fig. 1.2: Radiation pattern from both, total structure and selected regions of <u>original</u> ZOR antenna design ($h = 0.5$ mm) in $\varphi = 0°$ plane: a) horizontal strips and vertical vias of shunt inductors, b) horizontal strips solely of shunt inductors, c) vertical vias solely of shunt inductors d) series capacitors
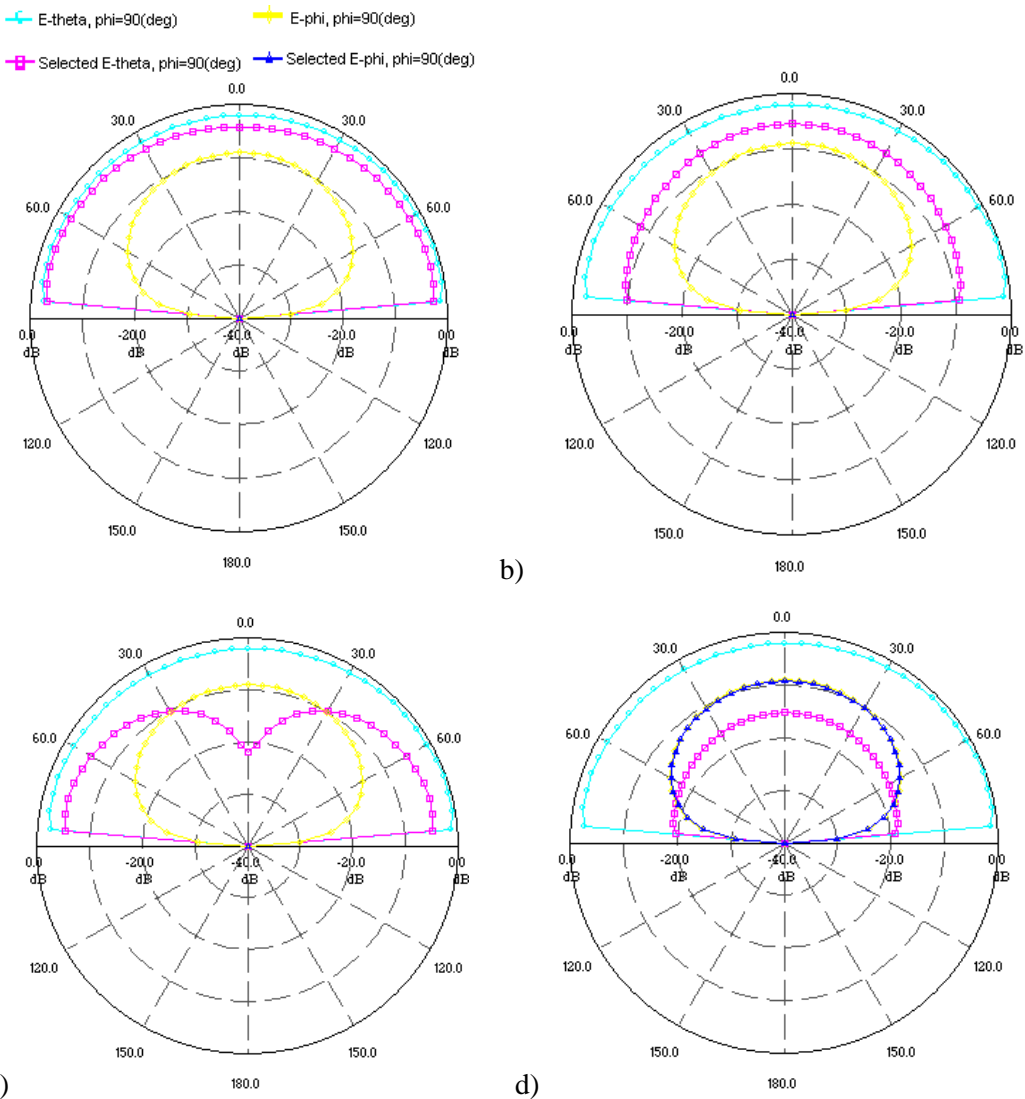

a)   b)

c)   d)

Fig. 1.3: Radiation pattern from both total structure and selected regions of <u>original</u> ZOR antenna design ($h = 0.5$ mm) in $\varphi = 90°$ plane: a) horizontal strips and vertical vias of shunt inductors, b) horizontal strips solely of shunt inductors, c) vertical vias solely of shunt inductors d) series capacitors

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First, let us comment on the radiation pattern components in the $\varphi = 0°$ plane (xz plane) and then in the $\varphi = 90°$ (yz plane) plane. We always compare the magnitudes of the E-field components from the whole structure (e.g. E_θ ($\varphi = 0°$) or E_φ ($\varphi = 0°$)) and from the selected regions (e.g. selected E_θ ($\varphi = 0°$) or selected E_φ ($\varphi = 0°$)). As it is evident from the comparison of E_φ ($\varphi = 0°$) (yellow line) and selected E_φ ($\varphi = 0°$) (dark blue line) components in Fig. 2.7b, the horizontal strips of the shunt inductors significantly contribute to the radiation in the whole upper hemisphere. From the comparison of E_θ ($\varphi = 0°$) (light blue line) and selected E_θ ($\varphi = 0°$) (violet line) components in Fig. 2.7c, it is obvious that the significant radiation contribution into the directions out of normal comes from the vertical vias of the shut inductors, whereas in case of the direction of normal, it comes from the series capacitors (see Fig. 2.7d). The comparison of E_θ ($\varphi = 90°$) (light blue line) and selected E_θ ($\varphi = 90°$) (violet line) components in Figs. 2.8b and 2.8c shows similar results as the previous comparison of E_φ ($\varphi = 0°$) and selected E_φ ($\varphi = 0°$) components in $\varphi = 0°$ plane.

The supposed way how to improve the radiation efficiency is to increase the height of the composite right/left-handed transmission line over the ground plane. This measure is taken in order to increase the distance of the currents flowing on the horizontal strips of inductive stubs over their mirror out-phase currents that are induced on the ground plane. The antenna improved according to this hypothesis thus has an additional air layer between the ground plane and the thin dielectric substrate carrying the antenna motif. The height of the air layer is, due to the available foam spacers, chosen as h_{air} = 6.4 mm ($\sim 1/9\,\lambda_0$), so that the total height equals to $h = h_{diel} + h_{air} = 0.5 + 6.4 = 6.9$ mm. The frequency dependence of the efficiencies of the improved antenna is depicted in Figs. 1.4. To properly take into account for the presence of dielectric substrate between the antenna layer and the ground plane the simulated value of efficiencies for an antenna designed on a thick ($h = 6.9$ mm) substrate was about 30 %. Further improvement of radiation efficiency up to more than 80 % can be reached by decreasing the relative permittivity below the antenna motif − removing the dielectric which is substituted by an air of thickness 6.4 mm, (see Fig. 1.4 b).
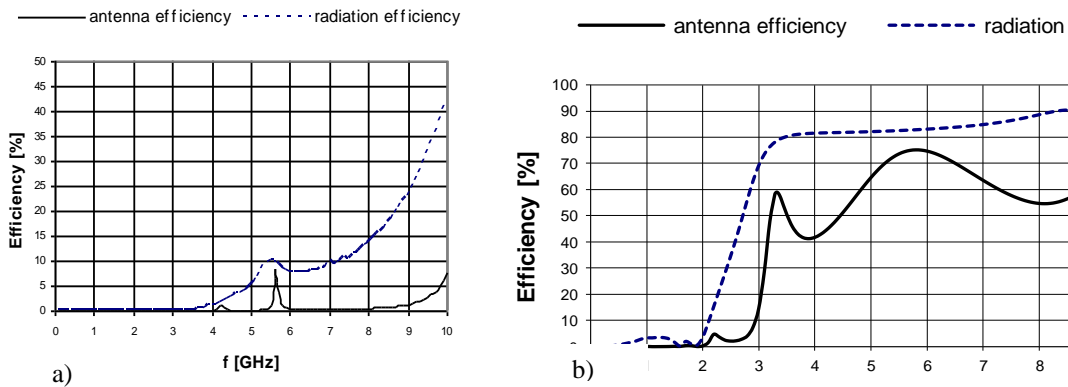

Fig. 1.4: Simulated radiation and antenna efficiency of a) original thin antenna ($h = 0.5$ mm) and b) improved antenna ($h = 6.9$ mm with air layer of thickness 6.4 mm)

1.3 Results

Given the measured and simulated frequency behavior of the reflection coefficient $S_{11,}$ it is apparent that for the original (first type) thin-substrate antenna, the shapes and minima of the above-mentioned curves are almost identical (see Fig. 1.5 a). On the contrary, for the improved antenna (third type) the measured reflection coefficient exhibit two sharp minima around the simulated zeroth order mode resonance. This effect can be caused by several reasons, e.g. by the fabrication tolerance (see the photograph of the manufactured prototype in Fig. 1.5 b) or resonance of finite sized ground plane. Simulation of the original and improved antennas has also been performed with finite ground

plane to make the comparison of directivity and gain of simulated and measured antennas more precise.
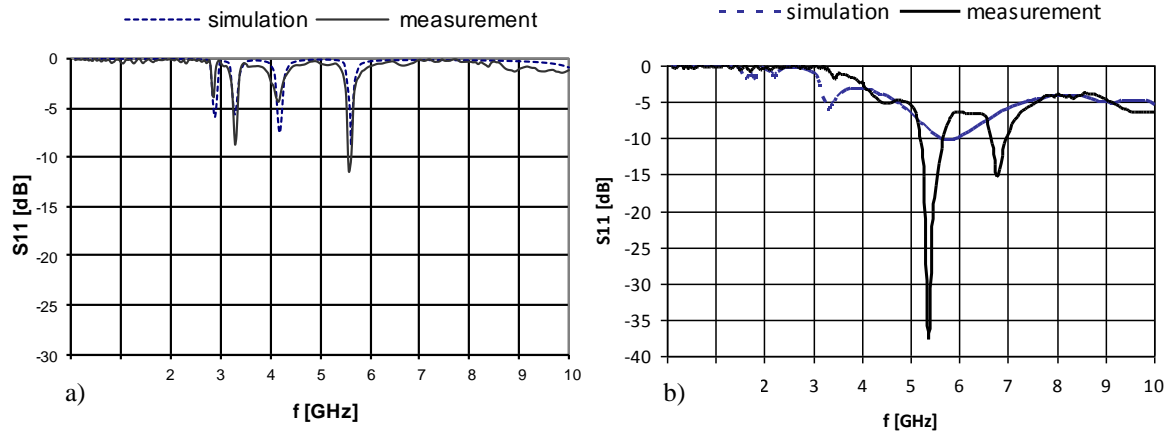

Fig. 1.5: Measured and simulated reflection coefficient of realized prototype of a) original antenna
b) improved antenna

Simulated and measured parameters of both, the original and the improved antennas now with finite ground plane are presented in Table 1.1.

Antenna (finite ground plane)	Original		Improved	
	Sim.	Meas.	Sim.	Meas.
f_0 [GHz]	5.60	5.64	5.80	7.79
G [dBi]	- 3.0	- 4.5	4.0	5.0
D [dBi]	5.8	5.7	4.5	5.1
η [%]	13.2	9.5	89.1	97.7

Tab.1.1: Measured gain G, calculated directivity D, and calculated efficiency η of original and improved antennas at f_0 realized with finite ground plane.

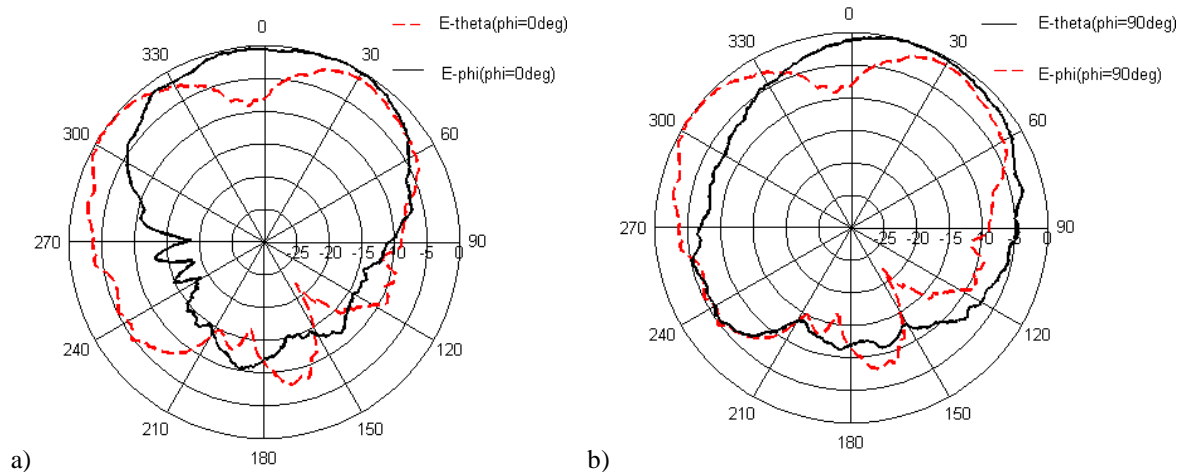Measured radiation patterns of both antennas with finite ground plane are presented in Fig. 1.6 and Fig. 1.7.

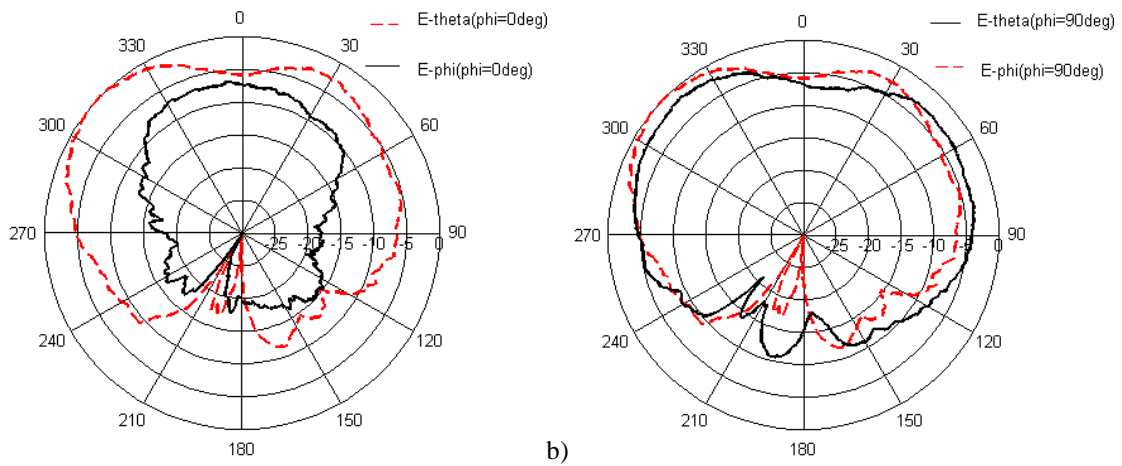Fig. 1.6: Radiation patterns of original (thin profile) antenna a) phi = 0° (*xz* plane), b) phi = 90° (*yz* plane)

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Fig. 1.7: Radiation patterns of improved (increased profile) antenna a) phi = 0° (*xz* plane), b) phi = 90° (*yz* plane)

1.4 Summary of important results in Chapter 1

The radiation of the very thin profile ZOR antenna implemented in composite right/left-handed transmission line has been investigated from selected regions of the antenna. The objective was to find the dominantly radiating source areas. It has been found that these areas are formed by the horizontal strips and vertical vias of left handed inductors. Given these findings, an efficiency of improved ZOR antenna with air substrate and increased vertical height from 0.5 mm to 6.9 mm, which represent relative increase of height from $1/105\ \lambda_0$ to $1/8\ \lambda_0$ has been designed and measured. The simulated 6.9 mm thick full dielectric substrate antenna provides just partial improvement of radiation efficiency from about 10 up to 30 % at f_0. Further improvement, maintaining the antenna height, up to more than 80 % can be reached by decreasing the relative permittivity of substrate layers bellow the antenna motif. The simulated antenna efficiency of finite ground plane air substrate antenna has been in this way increased from 13.2 to 89.1 %, while the measured one has been increased from 9.5 to 97.7 %. The measured gain has been enhanced from – 4.5 to 5.0 dBi. The increased height of vertical vias of improved antenna change a shape of the radiation pattern which is more similar to a case of the monopole antenna, see Fig. 1.6 and Fig. 1.7 where component values denoted by the red dashed curve dominates.

In summary, it can be stated that the radiation efficiency (and consequently also the antenna efficiency) depends predominantly on the vertical dimension of the antenna structure (according to our experiences improvement of antenna and radiation efficiency increases up to the height of third type of the presented antenna, further increase in height has no more any positive effect) and on the value of relative permittivity (to obtain high efficiency we need the value of relative permittivity as low as possible – from this fact comes out our recommendation to use dielectric substrate as thin as possible and combine it with air layer).

Chapter 2

Shielded Micro-Coplanar CRLH TL Zeroth-Order Mode Resonator Antenna

In this chapter, our attention is paid to a proposal of a novel ZOR antenna structure which we firstly introduced in [20]. It is implemented in the technology of composite right/left-handed shielded micro-coplanar transmission line (CRLH SM-CP TL). We will demonstrate by aid of EM simulation and by aid of measurement that this antenna exhibits a broadside radiation pattern, which is typical for patch-type antennas. This phenomenon arises from the predominantly horizontal position of shunt inductances of micro-coplanar transmission line that form air bridges between signal and ground conductors.

2.1 Composite Right/Left-Handed Shielded Micro-Coplanar Transmission Line ZOR Antenna

The announced novel ZOR antenna structure - the four unit cell composite right/left-handed shielded micro-coplanar transmission line ZOR antenna (CRLH SM-CP TL ZORA) has been implemented on the dielectric substrate (GIL GML 1000) of thickness $h_1 = 1.5$ mm. Its model created in the MoM simulator IE3D is depicted in Fig. 2.1.
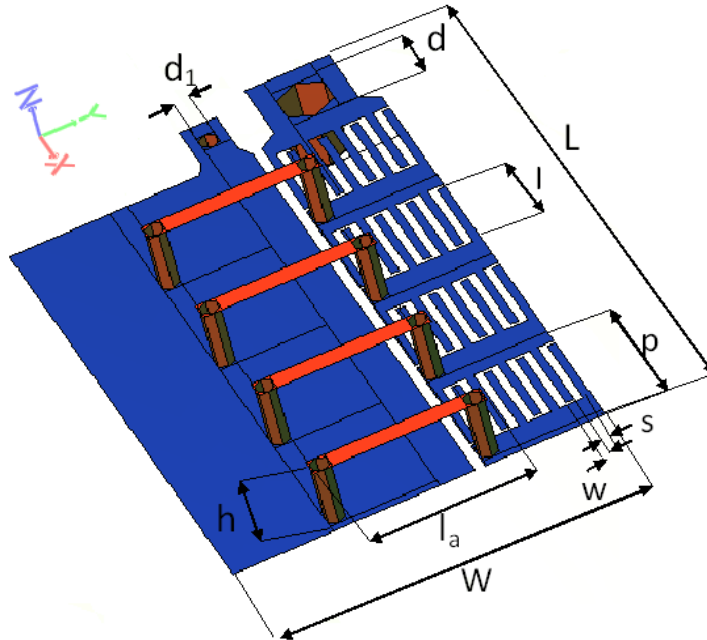

Fig. 2.1: Schematic view of four-element CRLH SM-CP TL ZORA carried out on GML 1000 substrate ($\varepsilon_r = 3.05$, $\tan\delta = 0.003$) of height $h_1 = 1.5$ mm with air bridges forming shunt inductors of height $h_2 = 1.6$ mm.

The height of discussed ZOR antenna consists of further $h_2 = 1.6$ mm of wire air bridges forming shunt inductances. As a result, its total height equals $h = 3.1$ mm. The footprint dimensions of one unit cell are $p \times W = 3.3 \times 9.35$ mm, the total dimensions of the antenna with feeder follow: $L \times W \times h = 15.6 \times 9.35 \times 3.1$ mm ($0.27 \times 0.16 \times 0.05 \lambda_0$ at measured zeroth-order mode resonant frequency $f_0 = 5.14$ GHz). The antenna model was excited with a vertical pin of a coaxial feeder of the diameter $d = 1.25$ mm. The series capacity of the equivalent circuit of a unit cell was implemented as an inter-digital capacitor. The size of the shielded plane is 60.0×40.0 mm, which is approx. $1.0 \times 0.7 \lambda_0$ at f_0.

The length of fingers of the inter-digital capacitors equals $l = 2.2$ mm and the width of finger w is the same as the width of the gap s, i.e. $w = s = 0.2$ mm. The length of wire air bridges corresponds to $l_a = 4.4$ mm and its width $w_a = 0.5$ mm. The value of its equivalent elements was found by fitting the S-parameters in the electromagnetic and circuit simulators Zeland IE3D and AWR MWO.

It accounts for $C_R = 0.90$ pF, $L_R = 1.15$ nH, $C_L = 0.6$ pF, $L_L = 1.5$ nH, thus, in conformity with the relation for ω_0 presented in [5], $f_0 = 4.95$ GHz.

As it can be seen in Fig. 2.2a, due to in phase current distribution, the inductive stubs contribute significantly to the radiation. The magnitude of the surface current exceeds its values existing on the rest of the structure. The simulated reflection coefficient of the zeroth order mode resonator reaches at resonant frequency $f_0 = 4.95$ GHz value of reflection coefficient $|S_{11}| = -9.3$ dB, while the measured one equals to $|S_{11}| = -7.3$ dB at frequency $f_0 = 5.14$ GHz. Thus there is a relative frequency shift of 3.8 % between simulation and measurement. This effect can be caused by several reasons; for instance by the fabrication tolerance (see the photograph of the manufactured prototype in Fig. 2.2b).
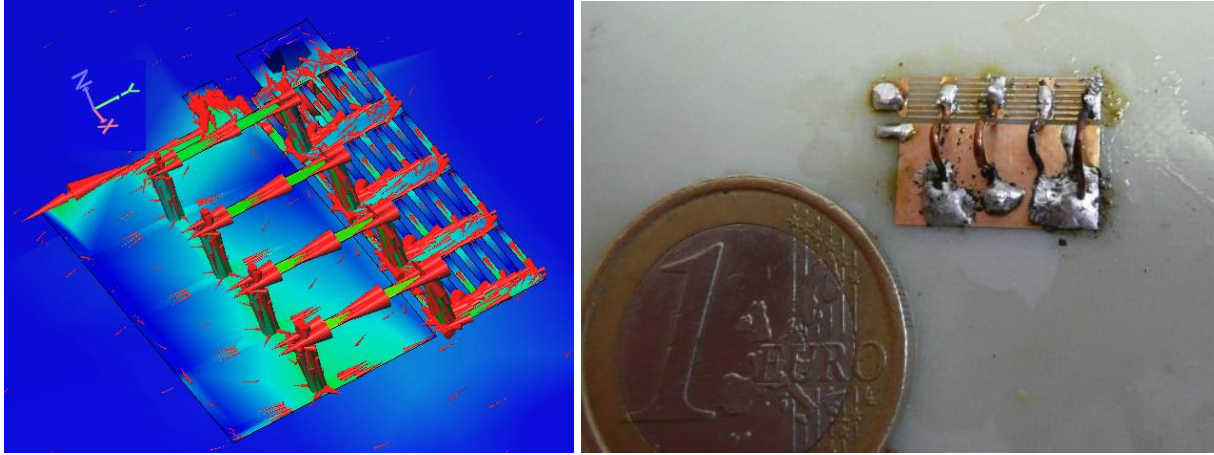

Fig. 2.2: a) Vector current density distribution of ZOR antenna at zeroth-order mode resonant frequency $f_0 = 4.95$ GHz and b) photograph of proposed ZOR antenna.

The comparison of the here simulated and measured parameters of the studied ZOR antenna can be seen in Tab. 2.1.

$m = 0$	simulation	Measurement			
		$\varphi = 0°$	$\varphi = 45°$	$\varphi = 90°$	$\varphi = 135°$
f_0 [GHz]	4.95	5.12			
G [dBi]	4.9	3.3 [1]	4.6 [1]	-1.3 [1]	-13.8 [1]
D [dBi]	7.0	7,2 [2]	7,8 [2]	7,4 [2]	7,4 [2]
η [%]	61.6	41.0	47.9	13.5	0.7

Tab.2.1: Simulated and measured parameters of ZOR antenna for $m = 0$ mode. [1] Gain measured in corresponding φ-plane, [2] directivity calculated from measured radiation patterns.

Since the components of the vectors of current distribution are situated in both, the x- and y-axis directions, our measurements involved the radiation patterns, gain and directivity in directions corresponding to $\varphi = 0°$, 45°, 90°, 135°; where φ stands for the angle counted in spherical coordinates from the x-axis.
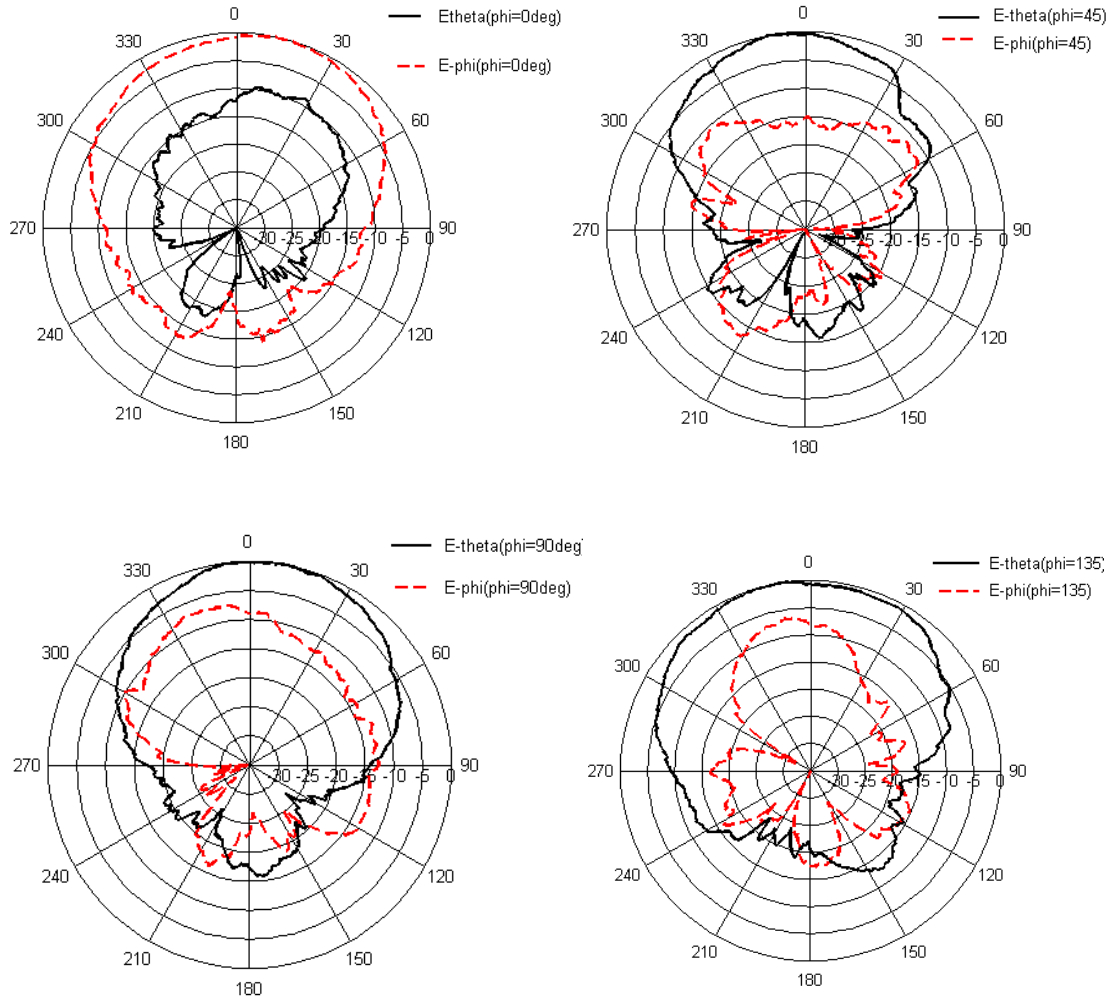
Fig. 2.3: Measured radiation patterns of antenna in planes: a) φ = 0° (*xz* plane), b) φ = 45°, c) φ = 90° (*yz* plane) and d) φ = 135°.

2.2   Summary of important results in Chapter 2

A novel small broadside radiating ZOR antenna with the relative dimensions of $0.27 \times 0.16 \times 0.05 \, \lambda_0$, implemented in the composite right/left-handed shielded micro-coplanar transmission line was designed, optimized by aid of EM simulator and measured. In comparison to the previously published designs of ZOR antennas, the type of its radiation characteristic is considered to be novel. Its measured radiation efficiency and gain reach values of 48 % and 4.6 dBi, respectively, which might be considered as acceptable values for various wireless technologies.

Chapter 3

Comparison of micro-coplanar ZOR antenna and small 3D multi-loop antenna

The motivation for this chapter was to compare a new multi-loop antenna developed in the frame of this dissertation thesis for the purpose of having an antenna with a similar current distribution and dimensions as ZOR antenna, implemented on a micro-coplanar waveguide. The principle of folded monopole is used to develop a novel loop antenna which can be specified as a 3D four-loop antenna (3D-LA). It represents another space arrangement of an antenna with a very similar current distribution to that of ZOR antenna. The space arrangement of the 3D-LA enables antenna module realization which can be integrated in the printed circuit board.

As it was presented in chapter 2 the dominant radiating components of there described ZOR antenna are the parallel air bridges which form together with their images current loops [19-21], see Fig. 3.1a.
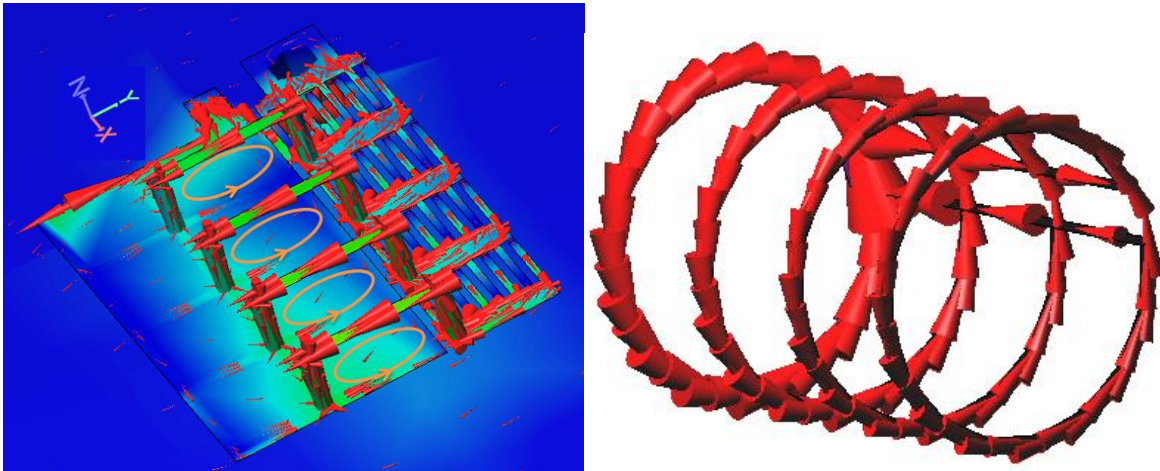

Fig. 3.1: a) Current density distribution of ZOR antenna implemented on micro-coplanar waveguide and b) current density distribution of the whole four-loop antenna.

This phenomenon offers the realization of an interesting alternative to the ZOR antenna in the form of a 3D multi-loop antenna. Basic parameters of this 3D multi-loop antenna were designed and optimized by aid of an EM simulator IE3D. Values of these basic parameters are as follows: radius of each loop is $r = 2$ mm and distance between two adjacent loops is $l = 8$ mm, see Fig. 3.1b. From the current density distribution of the whole four-loop antenna it can be seen that currents on all loops are in phase. Orientation of current vectors on dominantly radiating parts of both antennas has similar shape, see Fig. 3.1a and 3.1b.

Fig. 3.2: Photograph of realized 4 loop antenna

Radiation efficiency of the discussed antenna is studied for several cases (from one to four loops). It can be concluded that the increase of the number of loops enhances radiation efficiency. This corresponds to the concept of folded dipole, where the same behaviour can be observed. Results of our simulations are given in Fig. 3.3. The values of radiation efficiency of both of the compared antennas are almost the same. At the working frequency $f = 5.14$ GHz the efficiency of ZOR antenna is 70 %.
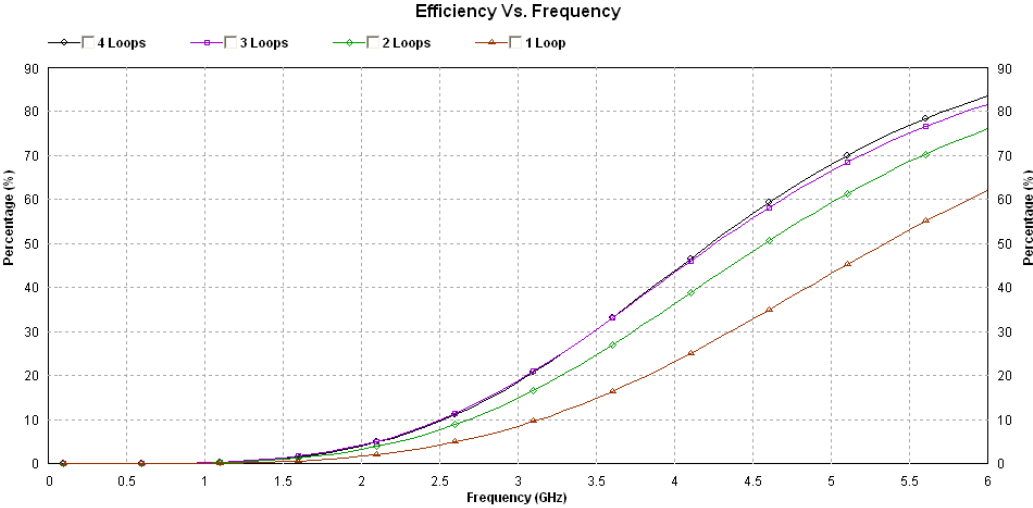

Fig. 3.3: Dependence of radiation efficiency on number of loops.

The working frequency of 3D multi loop antennas can be easily tuned by adding capacity between two adjacent loops, for example by transmission line stub. The additional capacity can also further decrease the overall antenna dimensions. Such method is relatively difficult to implement and therefore the working frequency of the here realized antenna was tuned by adjusting the distance between the loops. The equivalent circuit models of the ZOR antenna implemented in shielded micro-coplanar transmission line and the 3D multi loop antennas have to be similar because of the similar working principle. In comparison with the conventional transmission line the additional serial capacitance in the equivalent circuit model, represents the capacity between the loops (in the ZOR antenna the capacity is created by interdigital capacitors) and additional inductance represents loops between the two wire transmission line (in ZOR antenna the inductance represents the air bridge). In Fig. 3.4 the radiation pattern of the 3D multi loop antenna at the resonant frequency is given. Corresponding radiation pattern compared ZOR antenna was displayed in Fig. 2.3.
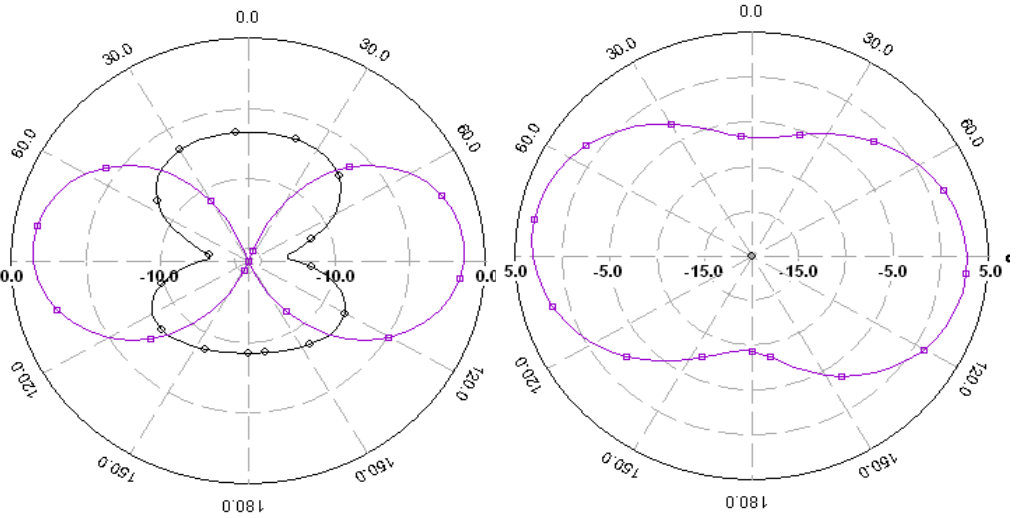

Fig. 3.4: Radiation pattern of 3D multi loop antenna at its resonant frequency: a) *E*-theta (0°) ◊ black line and *E*-phi(0°) □ magenta line b)*E*-theta (90°) ◊ black line and *E*-phi(90°) □ magenta line.

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	ZORA, $m = 0$	3D loop antenna
f_0 [GHz]	4.95	8
η [%]	61.6	87.8

Tab.3.1: Efficiency of compared antennas.

3.2 Summary of important results in Chapter 3

In this chapter we made a comparison of a new multi-loop antenna developed in the frame of this dissertation thesis for purpose to have an antenna with a similar current distribution and dimensions as the ZOR antenna, implemented on micro-coplanar waveguide.

In this comparison of measured efficiencies for the ZOR antenna and the 3D loop antenna we found that the loop antenna can reach a higher radiation efficiency, in this case almost 90%. On the other hand we found that the ZOR antenna can work at a lower frequency in the case of the same size of loops, see Tab 3.1. Efficiency was verified by measurement using the method of wheeler cap by aid of the microwave network analyzer.

Chapter 4

Radiation Equivalent Circuit Model of Zeroth-Order Mode Resonator Antenna

In this chapter we would like to describe our significant improvement of in literature generally used lossless equivalent circuit model (ECM) for ZOR antenna.

Our new approach to describe the real behaviour of ZOR antenna led us to insert lossy elements in the ZOR antenna equivalent model. According to our experience and both theoretical and experimental results the most important role plays radiation resistance. Therefore we propose to call our new equivalent model of ZOR antenna as radiation equivalent circuit model (RECM).

By our proposed radiation equivalent circuit model of the ZOR antenna is in comparison with that in the literature usually presented (ECM) extended by implementation of three new elements: radiation resistance, loss resistance and mutual coupling among all inductive posts and the feeding pin. As we will demonstrate in this chapter implementation of these new elements into ZOR antenna model resulted in much better agreement between simulated and measured values of real and imaginary part of input impedance of the ZOR antenna realized in microstrip line technology (see ZOR antenna described in chapter 2).

A few authors also presented equivalent circuit models for the ZOR antenna input impedance considering radiation resistance which models radiation loss of the studied ZOR antenna [16,17]. However, none of them did not include into his consideration loss resistance and mutual inductance of shunt inductors and feeding pin which is a substantial factor for achievement of a good agreement between simulated and measured results.

4.1 Reactance elements of the unit cell

Our proposed novel radiation equivalent circuit model of the ZOR antenna with included radiation resistance ($R_{\text{rad\_mon}}$), loss resistance ($R_{\text{loss\_mon}}$) and mutual coupling (in RECM denoted by a dot) among all inductive posts and feeding pin is presented in Fig. 4.1.
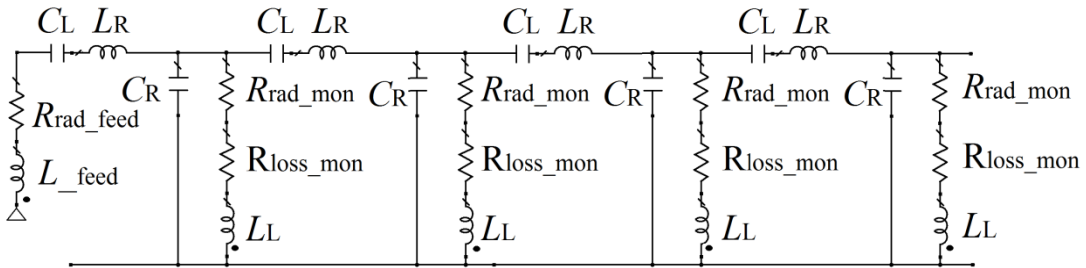

Fig. 4.1: Novel radiation equivalent circuit model of ZOR antenna with included radiation resistance, loss resistance and mutual coupling among all vertical posts and feed pin.

In this first part of chapter 4 we will focus on way how to determine elements of equivalent circuit model (ECM) usually used in literature. Above mentioned new elements in by us proposed radiation equivalent circuit model (RECM) will be studied in following parts of this chapter.

Each unit cell consists of an artificially inserted series interdigital capacitor C_L and parallel shunt inductor L_L (subscript L denotes here left-handed properties) which are evaluated according to empirical approximate equations. The value of C_L (pF) is calculated according to [22] by following equations

$$C_L = \frac{\varepsilon_r + 1}{w_p} l\big[(n-3)A_1 + A_2\big] \tag{4.1}$$

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$$A_1 = \frac{1}{25.4}\left[0.3349057 - 0.15287116\left(\frac{h}{x}\right)^{-1}\right]^2$$

$$A_2 = \frac{1}{25.4}\left[0.50133101 - 0.22820444\left(\frac{h}{x}\right)^{-1}\right]^2 \quad x = w_p = s$$

where n is a number of interdigital arms, l is the length of fingers, w_p is width of finger, and s is width of the gap between fingers. Inductance of a vertical post is taken as inductance of a via L_{via} according to [23] by equation

$$L_L = L_{via} = \frac{\mu_0}{2\pi}\left[h.\ln\left(\frac{h + \sqrt{r^2 + h^2}}{r}\right) + \frac{3}{2}\left(r - \sqrt{r^2 + h^2}\right)\right] \tag{4.2}$$

where $h = h_{sub} + h_{air}$ is height of post and r is its radius. The value of inherently presented parallel capacitor C_R is approximated as a capacitance of a parallel plate capacitor formed by the area of interdigital fingers

$$C_R = e_0 e_r \frac{S}{h} \tag{4.3}$$

where S is the total area of fingers of interdigital capacitor, h is the distance of fingers over the ground plane.

The value of discussed equivalent elements at resonant frequency of studied ZOR antenna $f_{ZOR} = 5.64$ GHz has been determined by the aid of previous equations as: $L_R = 0.50$ nH, $C_R = 0.086$ pF, $C_L = 0.14$ pF, $L_L = 3.98$ nH.

4.2 Radiation and loss resistances of the unit cell

Radiation resistance of the unit cell is above all given by radiation resistance of its vertical post, which according to our opinion can be considered as an electrically short monopole antenna situated over the ground plane. Under such situation we can calculate radiation resistance of the unit cell $R_{rad,monopole}$ according to [24] by following equation

$$R_{rad,monopole} = 160\left(\frac{\pi l}{\lambda}\right)^2 \tag{4.4}$$

where l is the total length of significantly radiating conductor (it consist of two sections: vertical pin h and horizontal section l_{ind}) which in the case of the discussed ZOR antenna is 11.8 mm. From the last equation we can obtain at the ZOR antenna resonant frequency $f_{ZOR} = 5.64$ GHz that the value of R_{rad} is 7.73 Ω.

Our opinion is loss resistance is given above all by conductor losses. Conductor losses have been modelled as well. They can be expressed according to [24] as

$$R_{loss} = \frac{d}{2\delta}R_S\frac{l}{3} \tag{4.5}$$

where d is the diameter of conductor, δ is penetration depth, R_s is resistivity of conductor and l is length of the conductor.

According to our results, i.e. EM simulation and measurement of realized ZOR antenna [37], it seems that impact of the loss resistance (R_{loss}) on input impedance of studied ZOR antenna is negligible.

4.3   Mutual coupling

Mutual coupling M of all shunt inductive posts and feed pin, considered as closely spaced wires, can be according to our opinion taken into account by calculation according to following formula [25, 26]

$$M = 2 \left[l \log \frac{l + \sqrt{l^2 + d^2}}{d} - \sqrt{l^2 + d^2} + d \right] \tag{4.6}$$

where l is the length of a conductor and d is distance between two wires. Corresponding coupling coefficient k for two quite the same wires with the same inductance L can be calculated as

$$k = M \Big/ \sqrt{L\,L} = M/L \tag{4.7}$$

The values of mutual coupling coefficients k_{fn} among feeding pin and n-th unit cell via and horizontal strip of the length l_{ind} were calculated from equations (4.2), (4.6), and (4.7) with following result: $k_{f1} = 0.478$, $k_{f2} = 0.27$, $k_{f3} = 0.08$, $k_{f4} = 0.035$.

Coefficients of mutual coupling among neighbouring inductive stubs in case of discussed ZOR antenna are:

$$k_{12} = k_{23} = k_{34} = 0.32,$$
$$k_{13} = k_{24} = 0.14,$$
$$k_{14} = 0.07.$$

The simulations of input impedance of studied ZOR antenna were performed in AWR Microwave Office. In Fig. 4.2 we can see results of calculation and comparison of real and imaginary parts of input impedance, and the module of reflection coefficient for RECM with and without mutual coupling.
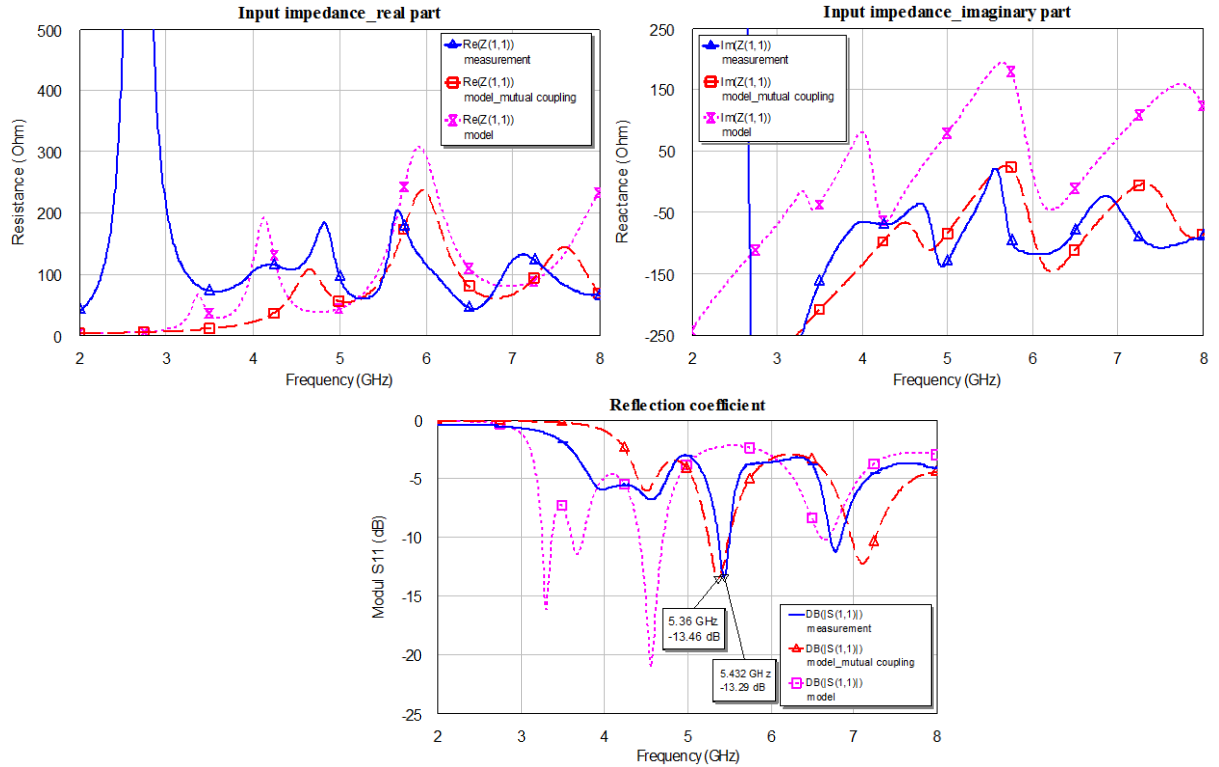

Fig. 4.2: Measured and calculated real (a) and imaginary (b) parts of input impedance, and module of reflection coefficient of ZOR antenna (c).

As can be seen from discussed figures agreement between measured and simulated curves is much better for the case of simulations which are taking into account the mutual coupling *M* of all shunt inductive posts and feed pin.

4.4   Summary of important results in Chapter 4

In this chapter we proposed to improve standard equivalent circuit model (ECM) of ZOR antenna by three new elements (radiation resistance, loss resistance and mutual coupling of inductive parts of ZOR antenna) and to call this improved model as radiation equivalent circuit model (RECM).

We evaluated the impact of these three new elements on ZOR antenna input impedance and we found that the radiation equivalent circuit model of ZOR antenna for input impedance calculation should contain elements for the modeling of radiation losses to achieve a reasonable agreement of simulated and measured input impedance values.

On the other hand, loss resistance (i.e conductor loss), does not act as a significant role and so can be practically neglected in the radiation equivalent circuit model of the discussed ZOR antenna.

Further we found, that for better agreement of simulated and measured values of input impedance the radiation equivalent circuit model should take into account mutual coupling of inductive parts of ZOR antenna (the length of the radiation conductor should comprise from the vertical part and the horizontal part). Mutual inductance is necessary to compute not only between feeding and vias, but also between each two vias.

Chapter 5

## Electrically Small Spiral Transmission Line-Fed Triple-Arm Folded Monopole Antenna

In this chapter we would like to propose a novel type of folded monopole antenna, which can be described as a self-resonant spiral transmission line fed triple-arm folded monopole antenna with in-phase current distribution.

Multiple-arm folded wire technique is favourite and very efficient way how to increase radiation resistance of closely spaced dipoles or monopoles especially in the case of design of electrically small antennas. This technique requires in-phase current distribution on all radiation elements which is simple to achieve in the case of a half-wave folded dipole [27]. However in the case of electrically miniaturized elements special circuit elements such as e.g metamaterial-based (MTM) transmission line cells [10,28,29] need to be used to ensure an appropriate phase shift between short closely spaced wire elements. Such MTM based designs however require the insertion of additional *LC* elements either in the form of chips or planar components to form zeroth order mode resonator type MTM antennas.

As mentioned before, here we would like to propose self-resonant spiral transmission line fed triple-arm folded monopole antenna with in-phase current distribution. Our design is motivated by the simplicity of such antenna structure which is limited to one metal layer etched on thin dielectric substrate which is suspended in the air over the ground plane. Important role is playing here linear performance of vertical vias which are simple to produce by photo-etching technology. Here presented configurations thus differ from that presented by Best [30] which uses variously shaped vertical parts of wire arms to incorporate inductance for compensation of inherent capacitance of electrically small dipole type antenna. Further we will derive in this chapter an analytical expression for the input resistance of an array of closely spaced short monopoles with uniform current distribution based on a method of induced electromotoric forces (EMF) and the integral relation for mutual impedances.

5.1 Self-resonant spiral triple-arm folded monopole antenna

The here discussed self-resonant **s**piral triple-arm **f**olded **m**onopole (SFM) antenna is derived from the idea of a relatively simple configuration of several monopoles with larger distance between them. It consists of three spiral shaped transmission line-fed vertical posts which are supposed to operate as electrically short vertical monopoles, see Fig. 5.1. The height of each vertical post is $h = \lambda_0/20$ and the diameter of the entire described antenna is $d = \lambda_0/10$ at operating frequency $f = 3.0$ GHz. The extended length of transmission line between each two monopoles is $2/5\lambda_0$ so that the total length of the two monopoles and connecting transmission line is $\sim \lambda_0/2$ which means, that the condition for in-phase current distribution on vertical monopoles is fulfilled.

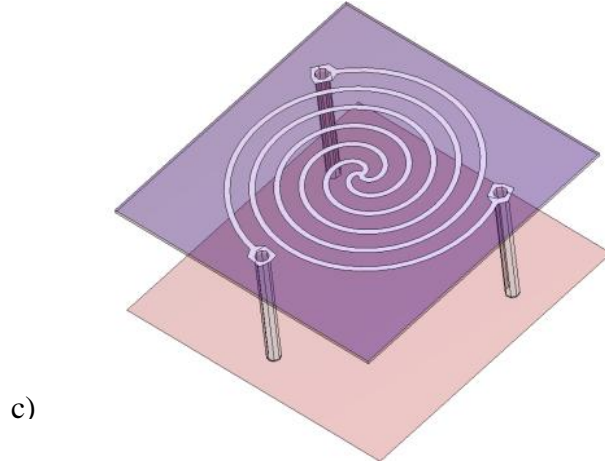a)   b)

c)
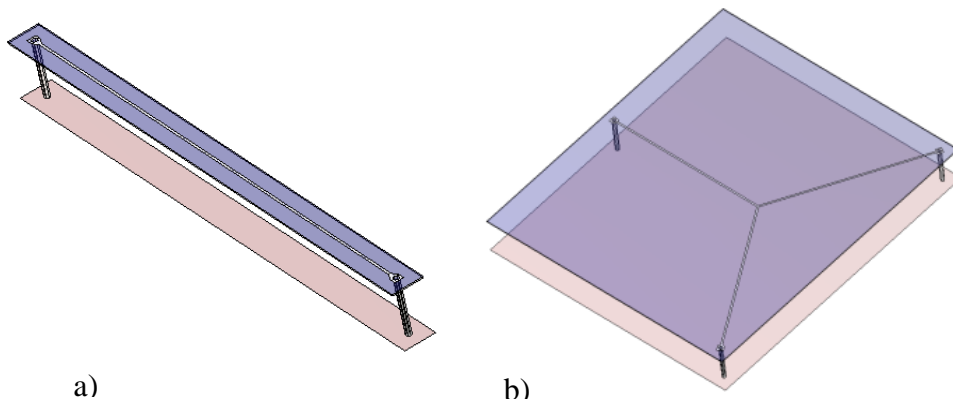
Fig. 5.1: Schematic view of spiral transmission line-feed triple-arm folded monopole antenna and its extended configurations: 2 arms unrolled (a), 3 arms unrolled (b) and 3 arms curled into spiral (c).

5.2 Radiation Resistance versus Number of Monopoles

As it is well-known the input resistance of closely spaced monopoles ($s \ll \lambda_0$) with in-phase current distribution is proportional to the factor N^2, where N is the number of monopoles [27]. However, practically this quadratic approximation is valid in case if wire spacing $s < 0.05\,\lambda_0$, i.e. if self-resistance term R_{11} has nearly the same value as mutual-resistance term R_{1N} [27]. In case of by us here proposed SFM antenna we use slightly larger spacing $s = 0.087\,\lambda_0$ (for $N = 3$) and thus we may expect N^x dependence, where exponent x will be in the range $1 < x < 2$. Simplified analytical expression for input impedance of discussed antenna can be then derived supposing the radiation only from vertical monopoles. Using the equivalent circuit for case of N-element folded dipoles we can create by method of electromotoric force (EMF) [27] following equation

$$\frac{V}{N} = \sum_{N} I_N Z_{1N} = I_1 Z_{11} + I_2 Z_{12} + I_3 Z_{13}$$

(5.1)

For the case when we can suppose that $I_1 \approx I_2 \approx I_3 \approx I$ this formula can be simplified to following equation

$$Z_{in} = \frac{V}{I} \approx N(Z_{11} + Z_{12} + Z_{13})$$

(5.2)

where mutual impedances Z_{1N} need to be evaluated for actual spacing s and uniform current distribution from general formula for mutual coupling of two dipoles p, q with the height h (for monopoles we consider half of this value)

$$Z_{pq} = \frac{j\eta}{4\pi k} \int_{-h/2}^{h/2} \int_{-h/2}^{h/2} \frac{I_p(z)I_q(z')}{I_p I_q} \left(\partial_z^2 + k^2\right) G_{pq}(z-z')\,dz\,dz'$$

(5.3)

The Green's function for the dipole distance s_{pq} is

$$G_{pq}(z-z') = \frac{e^{-jkR_{pq}}}{R_{pq}}, \quad R_{pq} = \sqrt{(z-z')^2 + s_{pq}^2}$$

(5.4)

Supposing that $I_p(z) = I_q(z) = \text{const.}$ then the equation (5) is reduced to

$$Z_{pq} = \frac{j\eta}{4\pi k} \int_{-h/2}^{h/2} \int_{-h/2}^{h/2} \left(\partial_z^2 + k^2\right) G_{pq}(z-z')\,dz\,dz'$$

(5.5)

The derivative term in the kernel of the integral is given by following equation

$$\partial_z^2 G_{pq}(z-z') = \frac{(1+jkR)(3(z-z')-R^2)-k^2R^2(z-z')^2}{R^5} e^{-jkR}$$

(5.6)

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Consequently the whole approximation of the discussed kernel can be written as

$$\left(\partial_z^2 + k^2\right)G_{pq}\left(z - z'\right) = \frac{(1+jkR)(3(z-z')-R^2)-k^2R^2(z-z')^2+k^2R^4}{R^5}e^{-jkR}$$
(5.7)

Futher we may indentify real and imaginary parts of the mutual impedance considering Euler relation

$$e^{-jkR} = \cos(kR) - j\sin(kR)$$

$$R_{pq} = \frac{\eta}{4\pi k}\iint\left\{\sin(kR)\left(\frac{3(z-z')^2}{R^5} - \frac{1+k^2(z-z')^2}{R^3} + \frac{k^2}{R}\right) - \cos(kR)\left(\frac{3k(z-z')^2}{R^4} - \frac{k}{R^2}\right)\right\}dzdz'$$

$$X_{pq} = \frac{\eta}{4\pi k}\iint\left\{\cos(kR)\left(\frac{3(z-z')^2}{R^5} - \frac{1+k^2(z-z')^2}{R^3} + \frac{k^2}{R}\right) + \sin(kR)\left(\frac{3k(z-z')^2}{R^4} - \frac{k}{R^2}\right)\right\}dzdz'$$
(5.8 a,b)

These expressions may be integrated either numerically or analytically considering Taylor series expansion of the sinus and cosinus functions. Due to the symmetry of the monopole placement in the vertices of the equilateral triangle (for $N = 3$) or square ($N = 4$) we may put $Z_{12} = Z_{13}$ or $Z_{12} = Z_{14} \neq Z_{13}$, respectively and Z_{in} in (4) is simplified to

$$Z_{in}(N = 2) \approx N(Z_{11} + Z_{12})$$
$$Z_{in}(N = 3) \approx N(Z_{11} + (N-1)Z_{12})$$
$$Z_{in}(N = 4) \approx N(Z_{11} + (N-2)Z_{12} + Z_{13})$$
(5.9)

In equations (7.11) we present simulated dependence of input resistance on the number N of monopoles for appropriate spacing of monopoles

$N = 2$: $s_{12} = 0.1\,\lambda_0$
$N = 3$: $s_{12} = s_{13} = \sqrt{3}\lambda_0/20 = 0.087\lambda_0$
$N = 4$: $s_{12} = s_{14} = \sqrt{2}\lambda_0/20 = 0.071\lambda_0$, $s_{13} = 0.1\lambda_0$

Self-resistance value can be acquired from well-known analytical relation for uniform current distribution of monopole as

$$R_{11} = 40(kh)^2$$
(5.10)

Self and mutual resistance terms for the above considered monopole spacing with uniform current distribution are then $R_{11} = 3.95\ \Omega$, and $R_{12} = 3.62\ \Omega$ for $N = 2$, $R_{12} = R_{13} = 3.69\ \Omega$ for $N = 3$, and $R_{12} = R_{14} = 3.77\ \Omega$, $R_{13} = 3.62\ \Omega$ for $N = 4$. Further we evaluated dependence of exponent $x(N)$ on the number of monopole arms for $N = \{2, 3, 4\}$ both from EM simulated and EMF method results as can be seen in Tab. 5.1

N	f_{res} (GHz	$R_{rN,sim}$ (Ω)	$R_{rN, EMF}$ (Ω)	$eff_{r, sim}$ (%)	$R_{rN,sim}/R_{11}$	$R_{rN,EMF}/R_{11}$	x_{sim}	x_{EMF}
2	2.86	16.6	15.1	86.6	4.2	3.8	2.07	1.93
3	3.00	42.7	34.0	88.1	10.8	8.6	2.17	1.96
4	3.05	69.9	60.4	89.7	17.74	15.3	2.07	1.97

Tab.5.1: Radiation Resistance, and exponencial factor x as a function of number of monopoles for Multiple-arm folded antenna from Fig. 5.1 (for $N = 3, 4$ feeding transmission line is spiral)

As can be seen from Tab. 5.1, the values from EM simulation x_{sim} are slightly larger then 2. That indicates that the spiral transmission line contributes a little bit to the power radiated by the whole antenna. While EMF method value x_{EMF} are slightly lower than 2 that indicates expected decrease of mutual coupling factor N_x for monopole spacing larger then $s > 0.05\ \lambda_0$. The EMF method, of course, does not take into account residual radiation of either spiral transmission line or eventual ground plane excitation. Satisfactory input resistance values not so far from 50 Ω can be achieved for number of monopoles either $N = 3$ or $N = 4$.

Average deviation of value x_{sim} from $x = 2$ for three simulated models with $N = \{2, 3, 4\}$ is $\Delta x_{sim} = 5.1\%$. Average deviation of value x_{EMF} from $x = 2$ for three EMF models with $N = \{2, 3, 4\}$ is $\Delta x_{EMF} = -2.5\%$.

After evaluation of the results we decided to continue our work for the case of $N = 3$. The description of the antenna developed for further considerations, simulations and measurements is in following parts of this chapter.

5.3 Design of discussed antenna and it measurement

A prototype of the discussed antenna has been designed and implemented on 0.13 mm thin low permittivity substrate Taconic TLP 3-0050-c1/c1 ($\varepsilon_r = 2.33$, $\tan\delta = 0.0009$) suspended at the height of 5 mm above ground plane of the size 140 ×140 mm ($1.4 \times 1.4\ \lambda_0$ at 3 GHz), see Fig. 5.2. The width of strip forming transmission line is 0.2 mm and the resulting gap between two strips is 0.5 to 0.7 mm depending on the actual value of φ. The diameter of feed pin is 1.25 mm (SMA inner conductor) and the other two shorting pins have 0.5 mm.
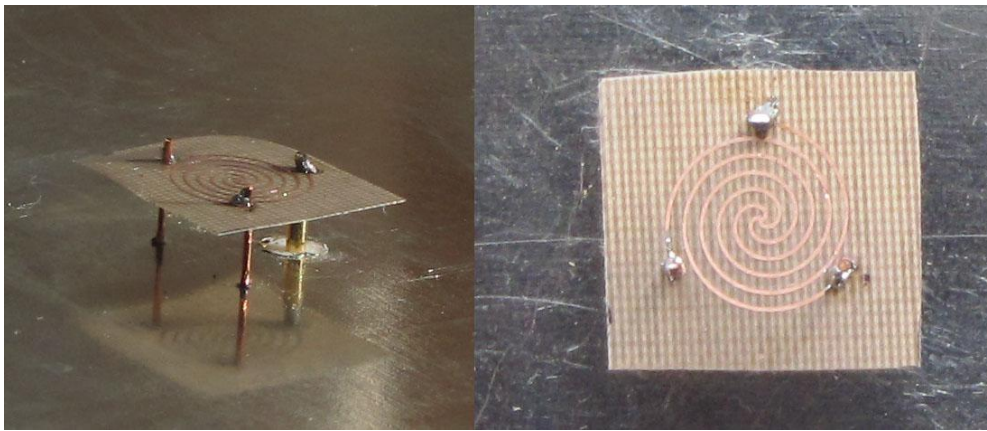

Fig. 5.2: Photograph of spiral transmission line -feed triple-arm folded monopole antenna.

From the simulated current distribution it can be seen that the vectors of current distribution along vertical pins are mutually in phase (i.e. we can observe the same orientation of this vector).

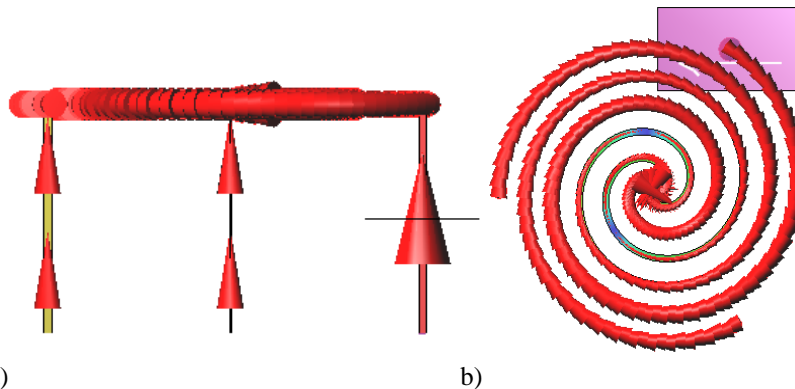a)   b)

Fig. 5.3: Current distribution along the structure at $f = 3.0$ GHz : side view (a), top view (b).

Comparison of simulated and measured reflection coefficient is depicted in Fig. 5.4. The relative frequency shift is 1.3 %. The measured impedance bandwidth is 0.83 % and radiation efficiency evaluated by Wheeler cap method is 81.7 %.
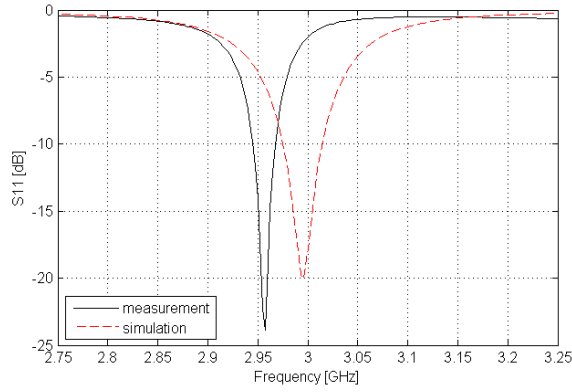
Fig. 5.4: Reflection coefficient of the triple-arm folded monopole antenna

Comparison of radiation resistance and radiation efficiency at design frequency can be seen in Tab. 5.2. The measured value of resistance is approx. about 50 % and even 100 % higher than simulated and analytical values, respectively. This may be explained by the contribution of spiral shaped feeding transmission line to radiation. We may also consider the radiation of the standing wave excited on the ground plane which had the dimension $1.4 \times 1.4\,\lambda_0$ which is close to triple-half of the wavelength.

	f_{res} (GHz)	R_{rad} (Ω)	eff_{rad} (%)
simulated	3.00	42.7	88.1
analytical	3.00	34	-
measured	2.96	60.0	81.7

Tab.5.2: Comparison of simulated and measured values of spiral transmission line feed triple-arm folded monopole antenna

To consider how close is the proposed antenna to the fundamental bounds expressed in terms of quality factor Q which is proportional to impedance bandwidth we compared its quality factor Q to three different definitions of these limits:
- the absolute Chu-McLean limit [31],[32] (derived for spherical geometries),
- Thal [33] limit to appropriately consider the interior fields and the use of non-magnetic materials (derived for spherical geometries),
- Gustafsson limit [34] to appropriately consider the cylindrical shape and vertical polarization of the proposed antenna.

Quality factor Q is also computed at design frequency f = 3 GHz. (based on definition derived from frequency bandwidth VSWR=2) and then depicted into Fig.5.5
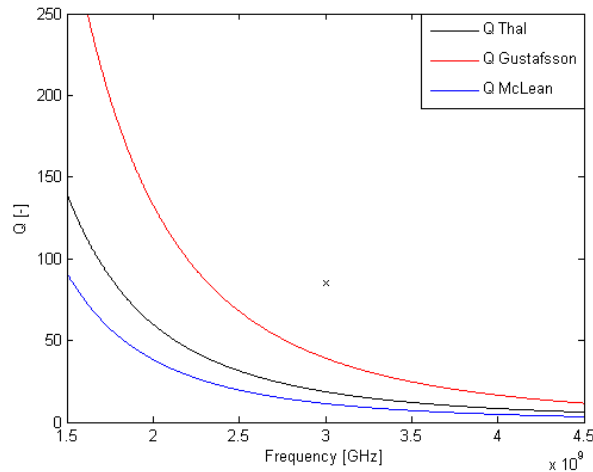

Fig. 5.5: Comparison of quality factor Q of proposed antenna with respect to frequency and to fundamental bounds done according to definitions of Chu-McLean, Thal, and Gustafsson.

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Radiation patterns measured at frequency 2.96 GHz are shown in Fig. 5.6. They exhibit the expected monopolar shape with back lobes of the -10 dB level.
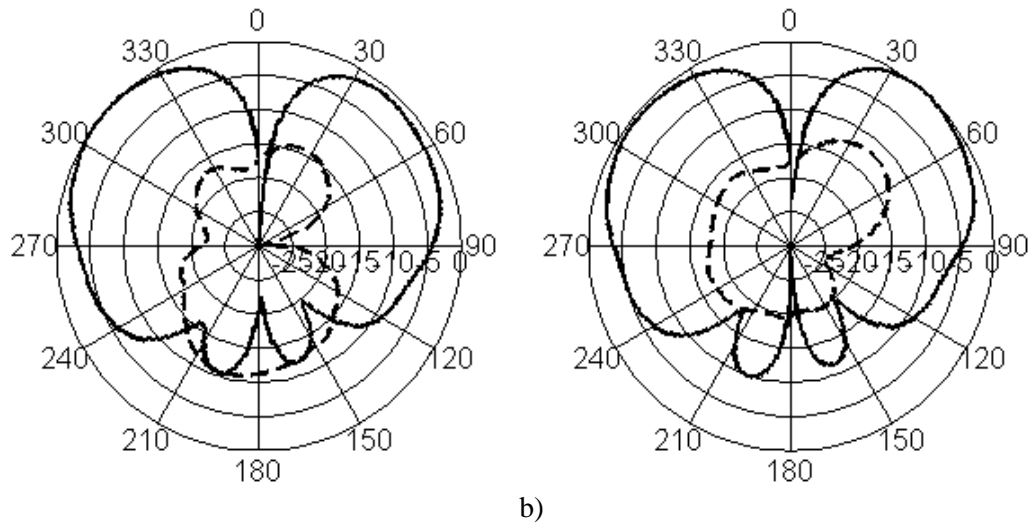

a)   b)

Fig. 5.6: Radiation pattern of the 3-arm folded monopole antenna at 2.96 GHz: a) *xz*-plane, b) *yz*-plane. Solid line: co-pol, dashed line: cross-pol.

5.4   Summary of important results in Chapter 5

Electrically small triple-arm low profile ($\lambda_0/20$) monopole antenna with small footprint ($\lambda_0/10$) was proposed and realized. Both EM simulation and method of induced EMF shows that the rule telling, that increase of input resistance for N closely spaced monopoles should be proportional to N^2, is also valid even for distance of monopoles increasing up to $\lambda_0/10$. The measured radiation efficiency of the described novel antenna is 81.7 % and the bandwidth corresponding to *VSWR* = 2 is 0.83 %. The proposed structure is simple, and might be completely produced in a single layer microstrip technology with linear vertical vias, potentially with an additional air substrate layer to improve bandwidth. Quality factor Q calculated from bandwidth is equal to 85, which is 7.5 times higher value then Chu-McLean limit. However if we consider the more realistic bound done by Thal it is just 4.5 times, and considering the cylindrical geometry it is just only 2.2 times the Gustafsson bound (Q_Gustafsson is equal to 39.4).

Conclusion

This doctoral thesis was written with motivation firstly to summarize state of the art in the field of ZOR antennas and then, based of this knowledge, to bring new ideas, information and experiences to this scientifically and technologically very interesting and very important area. We identified above all the ZOR antennas as very prospective technology for further development of electrically small antennas, therefore significant part of our work deals with them. Main achievements of my dissertation thesis can be shortly summarized as follows:

1) Proposal of several novel types of ZOR antennas with improved radiation efficiency and also verification of basic behavior of these ZOR antennas.

2) Study and identification of dominantly radiating parts of studied ZOR antennas (i.e. identification of current distribution on the antenna structure).

3) Identification of a new principle for design of ZOR antennas, which helps to achieve significant improvement of theirs radiation and antenna efficiency.

4) Proposal of a novel Radiation Equivalent Circuit Model (RECM) of ZOR antenna, which helps to achieve much better results of calculation of ZOR antenna input impedance than in literature usually given Equivalent Circuit Model (ECM).

5) Critical comparison of ZOR antenna with several other common antenna structures (e.g. with quarter wavelength patch antenna, 3D – multiloop antenna and spiral folded monopole antenna).

In more details, this thesis was focused on general studies of basic technical properties and basic technological implementations of ZOR antennas, on methods of its development and its optimization with respect to its main technical parameters, like e.g. its radiation and antenna efficiency.

We would like to describe and underline now the main achievements of my doctoral thesis, i.e. to give an overview of its main results which I consider to be my own "dissertable" contributions to area of antennas using ZOR. Above all to those based on principle of zeroth-order mode resonator, but several novel electrically small antennas based on different principles are described in this thesis as well. Above mentioned main kind of results of this dissertation thesis can be in more details described as follows:

1) <u>Proposal of several novel types of ZOR antenna with improved radiation efficiency and also verification of basic behavior of these ZOR antennas.</u>

In the frame of research activities of this dissertation thesis several novel types of ZOR antenna with improved radiation efficiency were proposed and verified by EM simulations and measurements:

a) <u>Microstrip four unit cell ZOR antenna:</u>
The physical dimensions of the original antenna prototype are $12.0 \times 4.9 \times 6.9$ mm which represents a relative size $1/5 \times 1/11 \times 1/8 \, \lambda_0$. The antenna has an additional air layer between the ground plane and the thin dielectric substrate carrying the antenna motif. The height of the air layer is, due to the available foam spacers, chosen $h_{air} = 6.4$ mm ($\sim 1/9 \, \lambda_0$), so that the total height equals to $h = h_{diel} + h_{air} = 0.5 + 6.4 = 6.9$ mm. The measured efficiency and measured gain are 97.7 % and 5.0 dBi, respectively.

b) <u>Shielded microcoplanar four unit cell ZOR antenna:</u>
A novel small broadside radiating ZOR antenna with the relative dimensions of $0.27 \times 0.16 \times 0.05 \, \lambda_0$, implemented in the composite right left handed shielded micro-coplanar

transmission line was designed, optimized by aid of EM simulator and measured. In comparison to the previously published designs of ZOR antennas, the type of its radiation characteristic is considered to be novel. Its measured radiation efficiency and gain reach values of 48 % and 4.6 dBi, respectively, which might be considered as acceptable values for various wireless technologies.

c)   Unshielded microcoplanar four unit cell ZOR antenna:

A novel electrically small low-profile (~ 0.18 x 0.18 x 0.065 λ_0) ZOR antenna implemented in the composite right left handed unshielded micro-coplanar transmission line with both-side broadside radiation pattern has been developed. Its measured radiation efficiency and gain as one the main antenna parameters are 54 % and 2.1 dBi, respectively. Compared to the same sized simple patch antenna the ZOR antenna exhibit decrease of resonant frequency by the factor of 2.21.

2) Study and identification of dominantly radiating parts of studied ZOR antennas (i.e. identification of current distribution on the antenna structure).

The radiation behavior of the each of studied ZOR antennas implemented in several different composite right left handed transmission lines were investigated. Objective of these activities was to find theirs dominantly radiating parts (i.e. so called "source areas"). It has been found that dominantly radiating areas are mostly formed by the horizontal strips and by vertical vias of the left handed inductors.

3) Identification of new principle for design of ZOR antennas, which helps to achieve significant improvement of theirs radiation and antenna efficiency.

As written before, the dominantly radiating parts have been identified in case of each of studied antennas with a motivation to find new way – i.e. new principle – how to increase radiation and antenna efficiency of ZOR antennas in general. We proposed and verified that in general this can be achieved by the increase in the antenna height over the ground plane. This proposed new principle for design of ZOR antennas was experimentally verified by comparison of several ZOR antennas with theirs heights ranging from 1/105 λ_0 to 1/8 λ_0. The measured parameters of in this way improved antenna prototype have been enhanced so they reached the following values (compared to original ones): gain 5.0 dBi (-3.0 dBi), antenna efficiency 97.7 % (9.5 %).

4) Proposal of novel Radiation Equivalent Circuit Model (RECM) of ZOR antenna, which helps to achieve much better simulation results than in literature usually used Equivalent Circuit Model (ECM).

In this thesis we proposed to improve standard equivalent circuit model (ECM) of ZOR antenna by three new elements (radiation resistance, loss resistance and mutual coupling of inductive parts of ZOR antenna) and to call this improved model as Radiation Equivalent Circuit Model (RECM).

We evaluated impact of these three new elements on ZOR antenna input impedance and we found that radiation equivalent circuit model of ZOR antenna for input impedance calculation should contain elements for modeling of radiation losses to achieve a reasonable agreement of simulated and measured input impedance values.

On the other hand, loss resistance (i.e conductor loss), does not act a significant role and so can be practically neglected in the radiation equivalent circuit model of the discussed ZOR antenna.

Further we found, that for better agreement of simulated and measured values of input impedance the radiation equivalent circuit model should take into account mutual coupling of inductive parts of ZOR antenna (the length of the radiation conductor should comprise from vertical part and horizontal part). Mutual inductance is necessary to compute not only between feeding and vias, but also between each two vias.

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5) <u>Comparison of ZOR antenna with several other common antenna structures (quarter wavelength patch antenna, 3D – multiloop antenna and spiral folded monopole antenna)</u>

The performance of the proposed ZOR antenna is subject to critical evaluation based on the comparison with several reference antennas:

a) Quarter-wavelength patch antenna (QWPA) that has the same dimensions. It has been found that ZOR antenna provides comparable or even better parameters to those of QWPA, except of the bandwidth, which is much narrower in case of ZOR antenna. In comparison to QWPA, the main advantage of the proposed ZOR antenna might be then seen in the possibility to produce the entire ZOR antenna structure by means of the integrated microstrip technology with air bridges. On the contrary to it, the fabrication of the QWPA requires the use of either the foam substrate or plastic support pins or the application of ridged self-supporting metal plates.

b) In comparison of measured efficiencies for ZOR antenna and 3D loop antenna we found that loop antenna can reach higher radiation efficiency, in here described case almost 90%. On the other hand we found that ZOR antenna can work at lower frequency in condition of same size of loops.

c) Electrically small triple-arm low profile ($\lambda_0/20$) monopole antenna with small footprint ($\lambda_0/10$) was proposed and realized. Both EM simulation and method of induced EMF shows that the rule telling, that increase of input resistance for N closely spaced monopoles should be proportional to N^2, is also valid even for distance of monopoles up to $\lambda_0/10$. The measured radiation efficiency of described novel antenna is 81.7 % and bandwidth corresponding to $VSWR = 2$ is 0.83 %. Proposed structure is simple, and might be completely produced in single layer microstrip technology with linear vertical vias, potentially with additional air substrate layer to improve bandwidth. Quality factor Q calculated from bandwidth is equal to 85, which is 7.5 times higher value then Chu-McLean limit. However if we consider the more realistic bound done by Thal it is just 4.5 times, and considering the cylindrical geometry it is just only 2.2 times the Gustafsson bound (Q_Gustafsson is equal to 39.4).

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List of candidate's works relating to the doctoral thesis

1.   Publikace vztahující se k tématu dizertační práce

Publikace v impaktovaných časopisech

[1] Polívka, M. - Vrba, D.: Shielded Micro-Coplanar CRLH TL Zeroth-Order Resonator Antenna: Critical Performance Evaluation. *Radioengineering*. 2009, vol. 18, no. 4, p. 368-372. ISSN 1210-2512.

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- Dakhli N, Choubani F, David J: Multiband small zeroth-order metamaterial antenna. *APPLIED PHYSICS A-MATERIALS SCIENCE & PROCESSING*. ISSN 0947-8396.

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Awards:

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Funkční vzorek

Polívka, M. - Vrba, D.: Electrically Small Spiral Transmission Line Feed Triple-Arm Folded Monopole Antenna.. 2011

Member of organizing committee:

PIERS 2007 (Progress In Electromagnetics Research Symp.)
ESHO 2007 (Europ. Soc. for Hyperthermic Oncology)
COMITE 2008 (Conference on Microwave Technique)
ISMOT 2011 (Int. Symp. on Microwave and Optical Technology)

Projekty granty

Czech Science Foundation projects :	No. 102/08/1282 "Artificial electromagnetic structures for miniaturization of high-frequency and microwave radiation and circuit elements"
	Doctoral project No. 102/08/H018 "Modelling and simulation of fields"
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Reviews

14x reviews for journal PIER & JEMWA
1x reviews for Radioengineering Journal

2.   Publikace ostatní

Publikace v impaktovaných časopisech
Žádné ostatní publikace.

Publikace v recenzovaných časopisech
Žádné ostatní publikace.

Patenty
Multi frequency microwave processing of materials

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SUMMARY

This dissertation thesis.statement is arranged into 6 chapters (including Conclusions). The work here described comes out from main research projects in which the author was involved.

The Introduction" contains above all the current state of the art in research of electrically small antennas and then the identification of the main scientific and research aims of this dissertation work.

The first chapter: "Improvement of Radiation Efficiency of the Zeroth-Order Resonator Antenna" deals with very detailed analysis of Zeroth-Order mode Resonator Antenna structures implemented in microstrip line technology. Dominantly radiating parts are identified and the way how to improve efficiency of ZOR antenna in general is presented here. By using these methods then the efficiencies of ZOR antennas can be increased up to 97 %

The second chapter: "Shielded Micro-Coplanar CRLH TL Zeroth-Order mode Resonator Antenna" is focused on the proposal of a new type of Zeroth-Order mode Resonator Antenna implemented in micro-coplanar waveguide technology. This new structure has similar radiation pattern like a patch type antenna, which is demonstrated in the second part of this chapter, where a comparison with Quarter-Wavelength Patch antenna (QWPA) is given. The new antenna shows better parameters (e.g. gain, radiation efficiency) in comparison of QWPA and can be easily utilized into electronic devices.

Motivation for chapter 3 "Comparison of small 3D multi-loop and micro-coplanar ZOR antennas" was to compare a new multi-loop antenna developed in the frame of this dissertation thesis for the purpose to have an antenna with similar current distribution and dimensions as ZOR antenna. The principle of a folded monopole is used to developed a novel loop antenna. The result of the comparison of this 3D multi-loop antenna and the Micro-Coplanar CRLH TL Zeroth-Order mode Resonator Antenna (see chapter 2) is that a 3D-LA can reach a higher efficiency while the ZOR antenna can work at lower frequency.

The fourth chapter: „Radiation Equivalent Circuit Model of Zeroth-Order Resonator Antenna" deals with significant improvement of in literature generally used lossless equivalent circuit model for ZOR antenna presented in chapter 1. A new radiation equivalent circuit model was extended by the implementation of radiation resistance, loss resistance and mutual coupling among all inductive posts and the feeding pin. Implementation of these new elements resulted in a much better agreement between simulated and measured real and imaginary part of input impedance of ZOR antenna implemented in microstrip line technology.

The fifth chapter: "Electrically Small Spiral Transmission Line-Feed Triple-Arm Folded Monopole Antenna" was motivated by our intention to develop a new type of antenna with similar dimensions to the ZOR antenna described in ref. [10]. Secondly our intention was to verify the relation of the input impedance of the folded monopole antenna with respect to the number of monopoles. Therefore this chapter deals with by us proposed novel self-resonant electrically small spiral transmission line-feed triple-arm folded monopole antenna which occupies low profile cylindrical geometry with circumscribing sphere of radian length $ka = 0.44$. The analysis of radiation resistance as a function of the number of monopoles for $N = \{2, 3, 4\}$ was performed by the aid of EM simulation as well as by the method of electromotoric forces. For experimental verification this type of antenna was implemented.

In the last part there are general conclusions coming out from this dissertation thesis. Further in this chapter we tried to identify several problems, which can represent scientific and research follow up to the main aims of this dissertation thesis.

RÉSUMÉ

Účel:

Cílem této dizertační práce je představit návrhy několika nových uspořádání elektricky zmenšených antén. A to především těch, které pracují na principu rezonátoru s modem nultého řádu (ZOR). Dále pak ověřit (jak teoreticky tak i experimentálně) jejich pracovní princip a dále navrhnout nové principy umožňující zlepšení anténních parametrů diskutovaných antén, zejména jejich vyzařovací a anténní účinnosti.

Metody:

Na samém začátku naší práce bylo pomocí analytických metod identifikováno několik předpokladů (hypotéz) vedoucích ke zlepšení vlastností elektricky zmenšených antén. Následně byly tyto hypotézy ověřovány pomocí simulátoru elektromagnetického pole využívajícího momentovou metodu. Dále pak také byly tyto hypotézy ověřovány i experimentálně, tj. byly proměřovány parametry konkrétních navržených a realizovaných antén a výsledky měření byly porovnávány s výsledky simulací. Hypotéza základního významu prezentovaná v této disertaci je založena na studii rozložení proudu podél anténní struktury a z ní pak vyplývajícího kritéria, respektive principu, pro optimalizaci základních parametrů elektricky zmenšených antén. Další v této práci ověřené hypotézy byly zaměřeny na realizaci technologicky nových typů antén pracujících na principu rezonátoru nultého řádu. Přínosnou se ukázala také hypotéza, na jejímž základě byl vylepšen náhradní obvod elektricky zmenšených antén. Na jejím základě pak byla pak udělána obvodová analýza vstupní impedance ZOR antény a její výsledky byly porovnány s měřením.

Výsledky a závěry:

Disertační práce byla napsána s motivací jednak sumarizovat poznatky z oblasti ZOR antén, a pak vytvořit nové poznatky k této vědecky i technologicky zajímavé problematice. ZOR antény jsou evidentně velmi perspektivní technologií pro další vývoj elektricky zmenšených antén, proto jim je věnována podstatná část této disertační práce. Hlavní výsledky mojí disertační práce pak lze stručně sumarizovat takto:

Návrh několika nových typů ZOR antén se zlepšenou vyzařovací účinností.

Studie a identifikace dominantně vyzařujících částí studované ZOR antény.

Identifikace nových myšlenek pro návrh ZOR antén.

Návrh nového ekvivalentního obvodového modelu ZOR antén.

Kritické porovnání parametrů ZOR antén a některých jiných elektricky zmenšených antén.

Klíčová slova: Rezonátor nultého řádu, elektricky malé antény, vyzařující účinnost, náhradní obvodový model, kompositní pravo/levo-točivé struktury.