Shielded Micro-Coplanar CRLH TL Zeroth-Order Resonator Antenna: Critical Performance Evaluation

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Abstract. *The attention of this paper is focused on the four unit cell zeroth-order resonator antenna (ZORA), manufactured on a shielded micro-coplanar composite right/left-handed (CRLH) transmission line structure. The antenna was designed to achieve a broadside patch-type radiation pattern. The dimensions of the antenna element follow: 15.6 × 9.35× 3.1 mm (i.e. 0.27 × 0.16 × 0.05 λ_0 at the measured zeroth-order resonance f_0 = 5.14 GHz) with the shielded plane of the size of 60 × 40 mm (approx. 1.0 × 0.7 λ_0). The measured gain and the antenna efficiency are equal to 4.6 dBi and 48 %, respectively. The performance of the proposed ZORA is subject to critical evaluation based on the comparison with the reference quarter-wavelength patch antenna (QWPA) that has the same dimensions. It has been found that ZORA provides comparable or even better parameters to those of QWPA, except of the bandwidth, which is much narrower in case of ZORA. In comparison to QWPA, the main advantage of the proposed ZORA might be then seen in the possibility to produce the entire ZORA structure by means of the integrated microstrip technology with air bridges. In 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.*

Keywords

Antenna efficiency, composite right/left-handed transmission line, patch antenna, radiation efficiency, zeroth-order resonator.

1. Introduction

Zeroth-order resonator antenna (ZORA) manufactured on the composite right/left handed microstrip transmission line (CRLH MS TL) structure has been fabricated by several authors, yet usually with a relatively low efficiency value (ranging up to approx. 50 %); see e.g. [1]-[5]. The radiation patterns of these antennas are typically monopolar due to the fact that the shunt inductances formed by vertical vias play an important role in the radiation process. In addition to the mentioned drawback, their vertical height significantly affects the radiation efficiency, as shown e.g. in [6].

Quite apart from it, in this paper, the attention is paid to a ZORA structure, implemented in the CRLH shielded micro-coplanar transmission line (CRLH SM-CP TL) that was first introduced in [7]. It exhibits a broadside radiation pattern, which is typical for patch-type antennas. This phenomenon arises from the predominantly horizontal position of shunt inductances of M-CP TL that form air bridges between signal and ground conductors. In order to critically evaluate the performance of the proposed ZORA, while comparing it to the "traditional" antennas (see comprehensive summary and recommendations of e.g. Ikonen in [8]) we went further and compared it with a quarter-wavelength patch antenna (QWPA) showing the same size and composition of substrates.

2. CRLH SM-CP ZORA

The four unit cell CRLH SM-CP TL ZORA model, implemented in MoM simulator IE3D on the dielectric substrate (GIL GML 1000) of thickness h_1 = 1.5 mm is depicted in Fig.1.

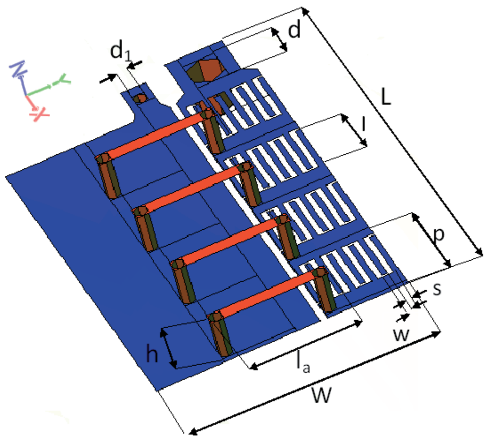

Fig. 1. Schematic view of four-element CRLH SM-CP TL ZORA carried out on GML 1000 substrate (ε_r = 3.05, tanδ = 0.003) of height h_1 = 1.5 mm with air bridges forming shunt inductors of height h_2 = 1.6 mm (shielded plane with substrate is not displayed here).

The ZORA height 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 resonance $f_0 = 5.14$ 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 equivalent circuit model of the unit cell without radiation losses corresponds to the scheme indicated in Fig. 2.

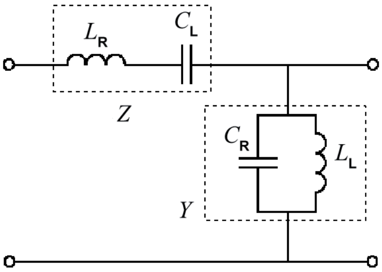

Fig. 2. Scheme of equivalent circuit of infinitesimal CRLH TL unit cell, formed by inherent series inductor L_R and shunt capacitor C_R, artificially inserted series capacitor C_L and shunt inductor L_L.

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 [9], $f_0 = 4.95$ GHz.

The EM simulation model of the unit cell was designed as unbalanced, so that it is possible to carry out the circuit elements in the microstrip technology. The results show slightly different resonant values than those calculated from the circuit model. It results from the simplicity (the lossless model and the no-coupling are considered). The resonant frequencies of the negative modes bellow 3 GHz are, from the radiation point of view, insignificant as they provide very low antenna efficiency; see Tab. 1. Dispersion diagram in Fig. 3 indicates the propagation gap ranging from 4.3 to 6.0 GHz.

m	-3	-2	-1	0
f [GHz]	1.80	2.60	3.1	4.95
G [dBi]	-10.8	-16.9	-7.3	4.9
D [dBi]	4.5	6.0	6.0	7.0
η [%]	2.9	0.5	5.0	61.6

Tab. 1. Simulated parameters of ZORA for negative and zeroth-order resonances.

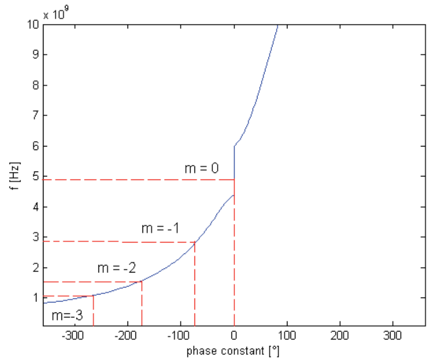

Fig. 3. Dispersion relation of CRLH S-MC TL unit cell: $C_R = 0.9$ pF, $L_R = 1.15$ nH, $C_L = 0.6$ pF, $L_L = 1.5$ nH, unbalanced case with propagation gap within frequency band from 4.3 to 6.0 GHz.

As it can be seen in Fig. 4a, 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 as well as the measured frequency dependence of the reflection coefficient S_{11} in the close region of the designed zeroth-order resonance are shown in Fig. 5. The simulated reflection coefficient of the zeroth-order mode reaches $f_0 = 4.95$ GHz ($|S_{11}| = -9.3$ dB), while the measured one equals $f_0 = 5.14$ GHz ($|S_{11}| = -7.3$ dB). Thus there is a relative frequency shift 3.8 %. This effect can be caused by several reasons; for instance by the fabrication tolerance (see the photograph of the manufactured prototype in Fig. 4b).

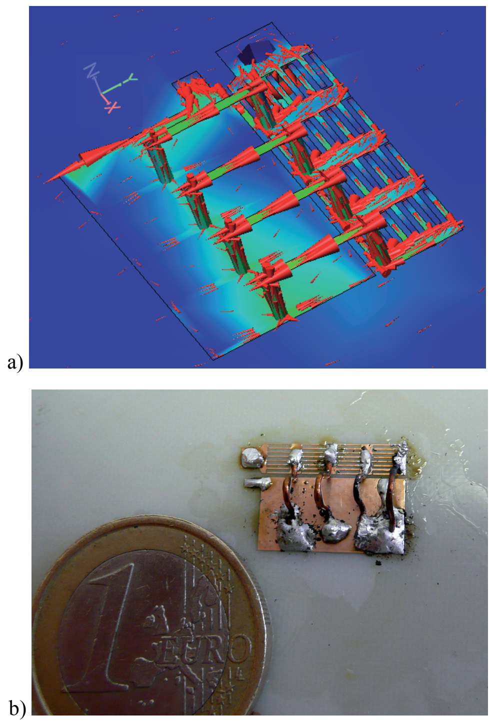

Fig. 4. a) Vector current density distribution of ZORA at zeroth-order resonance frequency $f_0 = 4.95$ GHz and b) photograph of proposed ZORA.

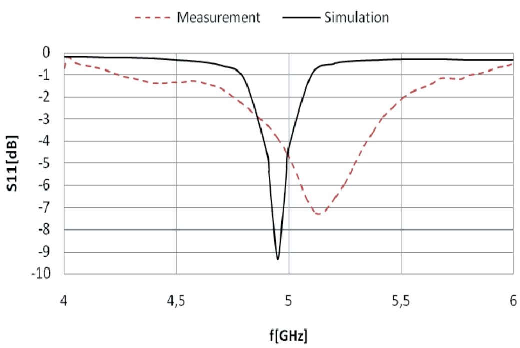

Fig. 5. Measured and simulated reflection coefficient of realized ZORA in close range around f_0.

According to the literature, the value of ZOR antenna efficiency does not usually exceed 50 %. The frequency dependence of the efficiencies of the discussed ZORA is shown in Fig. 6, where the max value for zero-th mode reaches nearly the level of 70 %. The efficiencies presented in this paper are defined as follows:

Radiation efficiency = Radiated Power/Input Power,
Antenna efficiency = Radiated Power/Incident Power

where the input power is the power delivered at the port, and the incident power represents the power passing through the reference plane of the port.

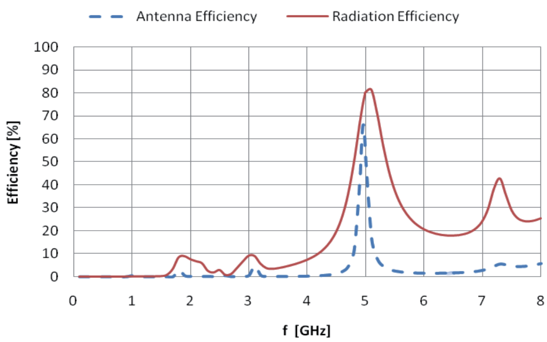

Fig. 6. Simulated radiation and antenna efficiency of ZORA.

A comparison of the simulated and measured parameters of ZORA with its simulated results for the zeroth-order mode can be seen in Tab. 2.

$m = 0$	simulation	measurement			
		φ = 0°	φ = 45°	φ = 90°	φ = 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. Simulated and measured parameters of ZORA 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 evaluated directivity in directions corresponding to φ = 0°, 45°, 90°, 135°; where φ stands for the angle counted in spherical coordinates from the x-axis.

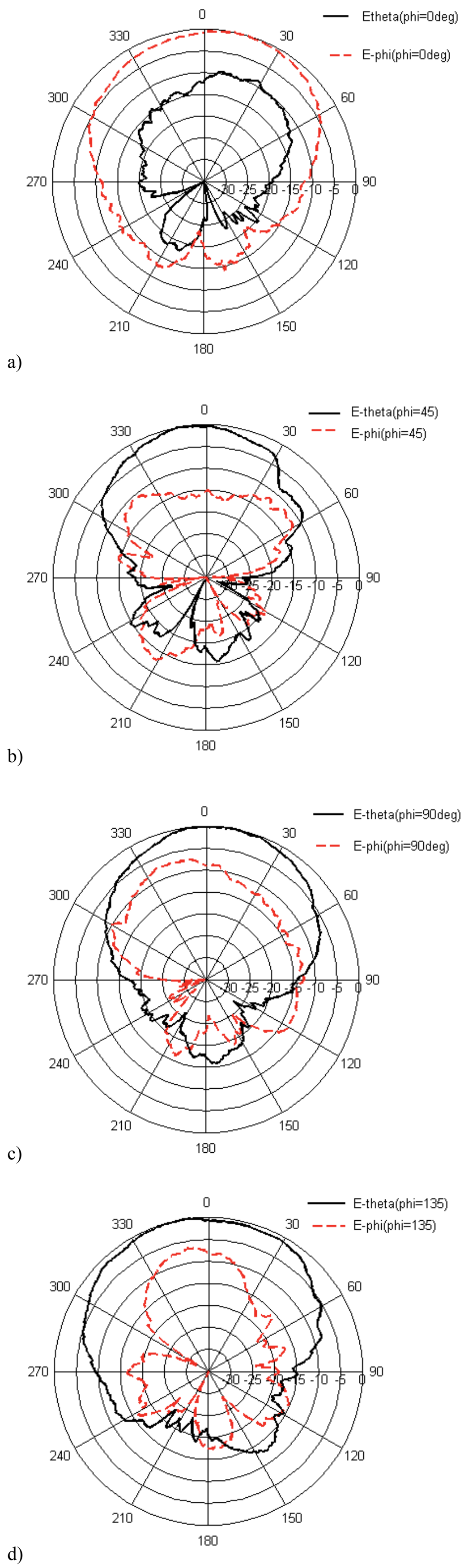

Fig. 7. Measured radiation patterns of antenna in planes: a) φ = 0° (xz plane), b) φ = 45°, c) φ = 90° (yz plane) and d) φ = 135°.

3. Comparison with Reference Quarter-Wavelength Patch Antenna

In order to critically evaluate the parameter performance of the CRLH SM-CP ZORA, the reference quarter-wavelength patch antenna (QWPA) model was designed and compared with the proposed ZORA model. Both basic modes TM_{10} and TM_{01} of QWPA have been considered for analysis in Zeland IE3D software (see results in Fig. 8, 9, and 10 and Tab. 3). Comparison of uniquely the simulation (and not the measured models) enables to avoid the performance differences that are caused by the fabrication tolerances.

Both QWPA structures occupy the same volume (e.g. $L \times W \times h = 15.6 \times 9.35 \times 3.1$ mm) and show the identical composition of substrates as well as the size of ground plane as ZORA shielded plane. They are fed by a coaxial pin of the diameter $d = 1.25$ mm which is located at the distance l from the shorting wall. The QWPA model operating on the TM_{10} mode has the edge of the size W shorted (see Fig. 8) while the second one operating on TM_{01} mode has the edge of the size L shorted (see Fig. 9). The resonance frequencies are $f_{TM10} = 3.52$ GHz and $f_{TM01} = 5.80$ GHz, respectively. Such significant frequency shift between TM_{10} and TM_{01} QWPA is done by different resonant length, i.e. L and W, respectively.

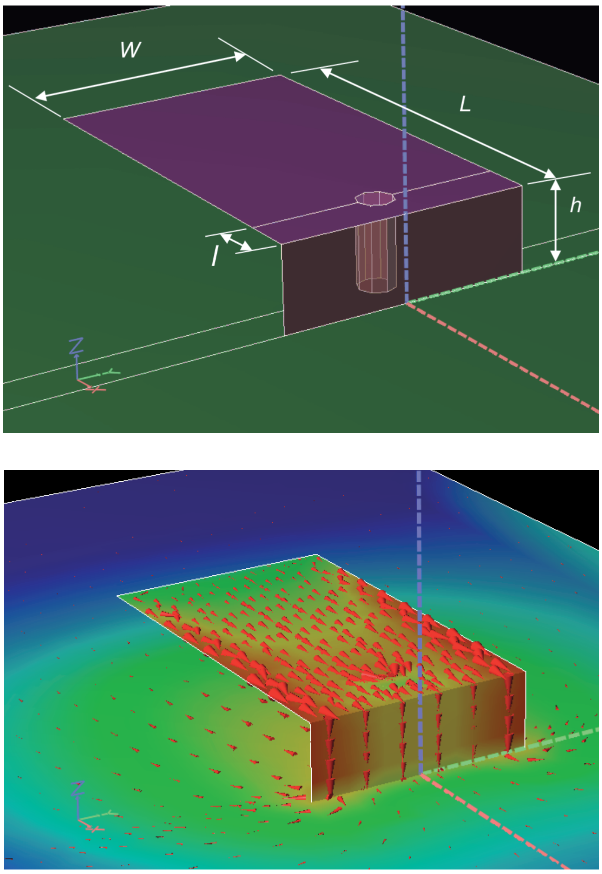

Fig. 8. QWPA operating on TM_{10} mode: a) schematic view and b) vector current distribution at f = 3.52 GHz (substrate is not displayed here).

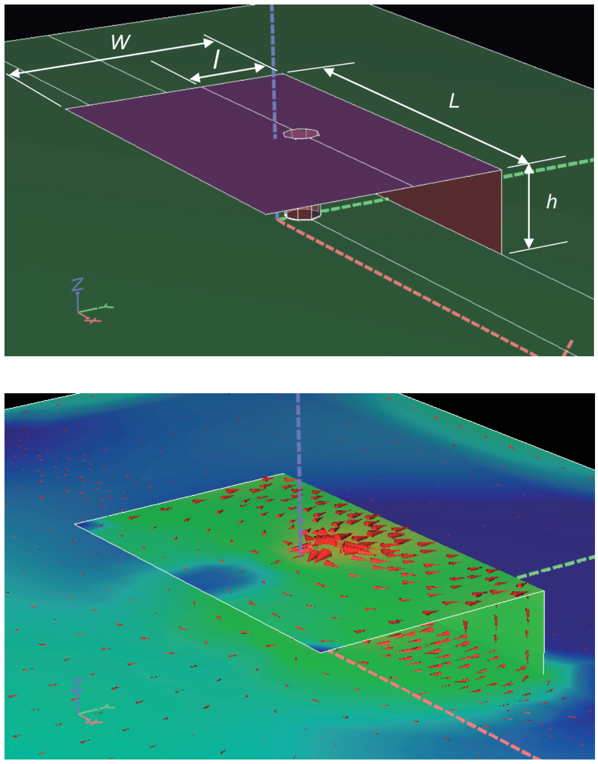

Fig. 9. QWPA operating on TM_{01} mode: a) schematic view and b) vector current distribution at f = 5.81 GHz (substrate is not displayed here).

The resonance frequency of TM_{10} QWPA is by approximately 29 % lower then that of ZORA while resonance frequency of TM_{01} QWPA is by approximately 17 % higher then that of ZORA. As ZORA is not perfectly matched, the criterion for evaluation of the bandwidth has been set at the level of $|S_{11}| = -6$ dB, which represents the value that is still acceptable in the mobile phone technology. The simulated bandwidth of ZORA is about four and 24 times narrower than the bandwidth of TM_{10} and TM_{10} QWPA, respectively. The directivity of ZORA is about 1 and 2 dB higher than TM_{10} and TM_{10} QWPA, respectively. The antenna efficiency of ZORA is by a few percent higher than the antenna efficiencies of both QWPA; see Tab. 3.

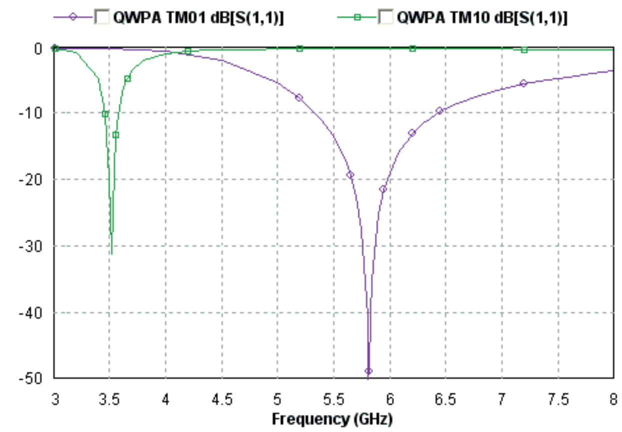

Fig. 10. Simulated reflection coefficient of both TM_{10} and TM_{01} QWPA.

	ZORA, m = 0	QWPA (TM_{10})	QWPA (TM_{01})
	Φ = 45°	φ = 0°	φ = 90°
f_0 [GHz]	4.95	3.52	5.81
Δf_0 [%]	--	- 28.9	+ 17.2
BW [MHz]	72 / 200$^{1)}$	217	2075
BW [%]	1,5 / 4.0$^{1)}$	6.2	35.8
G [dBi]	4.9	3.4	2.4
D [dBi]	7.0	5.9	5.0
η [%]	61.6	57.8	56.0

Tab. 3. Simulated parameters of ZORA and QWPAs. BW is related to $|S_{11}|$ = -6 dB, $^{1)}$ measured value.

4. Summary

A novel small broadside-radiated ZOR antenna of the relative size of $0.27 \times 0.16 \times 0.05\ \lambda_0$, implemented in the CRHL shielded micro-coplanar TL was designed and measured. In comparison to the previously published designs of ZOR antennas, the type of its radiation characteristic is considered 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. Nevertheless, the narrow bandwidth represents the limiting factor for real applications.

Furthermore, the ZORA performance was subject to critical comparison with the reference “traditional” antenna (QWPA) that showed the same size and composition of used substrates. To sum up the results of this comparison, it can be concluded that the presented ZORA exhibits a worse performance only in case of the bandwidth. The gain and antenna efficiency are even a little bit higher than in case of QWPA. Yet the authors are persuaded that ZORA bandwidth performance (as a general kind of antenna) might be further improved, since it represents a relatively new type of antenna.

Thus to date, the only difference considered by the authors as a possible advantage of ZORA over QWPA, can be found in the implementation technology. The ZORA structure might be completely produced by means of the integrated microstrip technology with the air bridges. Unlike it, the same sized QWPA requires the use of either the foam substrate or plastic support pins or application of the ridged self-supporting metal plates. From the point of view of the series production, this approach turns out to be more complicated and might result in additional costs.

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References

[1] SCHÜSSLER, M., OERTEL, M., FRITSCHE, C., FREESE, J., JAKOBY, R. Design of periodically L-C loaded patch antennas. In *Proc. of 27th ESA Antenna Technology Workshop on Innovative Periodic Antennas*. Santiago de Compostela (Spain), 2004.

[2] SCHÜSSLER, M., FREESE, J., JAKOBY, R. Design of compact planar antennas using LH-transmission lines. In *IEEE MTT-S International Microwave Symposium Digest*, 2004, p. 209-212.

[3] SANADA, A., KIMURA, M., AKAI, I., KUBO, H., CALOZ, C., ITOH, T. A planar zero-th order resonator antenna using lefthanded transmission line. In *Proc. of European Microwave Conference*. Amsterdam (the Netherlands), 2004.

[4] QURESHI, F., ANTONIADES, M. A., ELEFTERIADES, G. V. A compact and low-profile metamaterial ring antenna with vertical polarization. *IEEE Antennas and Wireless Propagation Letters*, 2005, vol. 4, p. 333-336.

[5] PARK, J.-H., RYU, Y.-H., LEE, J.-G., LEE, J.-H. A zeroth-order resonator antenna using epsilon negative meta-structured transmission line. In *Proc. of IEEE Antennas and Prop. Symposium*. Honolulu (Hawai), 2007.

[6] VRBA, D., POLÍVKA, M. Radiation efficiency improvement of zeroth-order resonator antenna. *Radioengineering*, 2009, vol. 18, no. 1, p. 1-8.

[7] VRBA, D., POLÍVKA, M. Zeroth-order resonator antenna realized on shielded micro-coplanar transmission line. In *Proceedings of the 3rd Conference on Antennas and Propagation EuCAP 2009*. Berlin (Germany), 2009.

[8] IKONEN, P. Electrically small metamaterial-based antennas – have we seen any real practical benefits? In *Proceedings of the 3rd Conference on Antennas and Propagation EuCAP 2009*. Berlin (Germany), 2009.

[9] CALOZ, C. ITOH, T. *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*. New Jersey: John Wiley & Sons. 2006

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