Multiple-Arm Folded Monopole Antenna Operating Extremely Close to a Conductive Plane

Milan POLÍVKA, Milan ŠVANDA, Petr ČERNÝ

Dept. of Electromagnetic Field, Czech Technical University in Prague, Technická 2, 166 27 Prague 6, Czech Republic

polivka@fel.cvut.cz, svandm1@fel.cvut.cz, cernyp1@fel.cvut.cz

Abstract. *The paper presents study of radiation properties of low profile folded multiple-arm dipole and design of monopole antennas operating extremely closely spaced above a conductive plane (as far as to 0.003 λ_0) intended to use for radiofrequency identification of moving sportsmen in mass race in frequency band at 869 MHz. It is shown that complex conjugate matched monopole prototype can have satisfactory radiation efficiency in spite of the extremely low relative antenna height above the conductive plane used as a shielding of human body or metallic objects.*

Keywords

folded dipoles, horizontal dipoles, patch antennas, radiofrequency identification, wire antennas, wearable antennas.

1. Introduction

Transponder antennas for UHF radiofrequency identification (RFID) has been recognized as one of the most sensitive components that affect the proper function of the whole system, especially in case when transponder (TAG) antennas are used for identification of human bodies. Detailed study on radio identification of sportsmen in mass races in European UHF band (869 MHz) has been published in [1]. Satisfactory operation of TAG antenna in the close vicinity to the human body, or generally dielectric object, without significant affecting its radiation and impedance properties is one of the main requirements for the RFID TAG antenna design. However not only technical performance of the TAG antenna but also convenience for wearable purposes (low weight, low profile, satisfactory footprint dimensions, flexibility, etc.) can affect its fruitfulness in mentioned application as sportsmen are not compliant to wear anything else than they just need for their competition.

Dipole type antennas designed to operate in a free space can not be usually used as fastening of the antenna is supposed to be directly on the human body. Namely frequency detuning with corresponding mismatching and increased dielectric loss take an important role in this case and can cause significant decrease of the reading distance or even malfunction of the system.

On the other hand, radiators with inherent presence of metallic plane as necessary part of their design, such as patch type antennas seems to be a good candidates for the mentioned application. However this sort of antennas suffer from fundamental limitation that corresponds with significant efficiency decreasing when relative patch height decreases below 0.01 λ_0 [2].

Another type of antennas designed to operate extremely closely space (< 0.01 λ_0) over conducting plane with remaining good radiation properties are folded multiple-arm wire dipoles that exhibit radiation resistance of the order of hundreds when operate in a free space [3]. Placing them over conducting plane decrease their radiation resistance however when a number of arms is chosen properly required input resistance can be achieved.

This paper deals with the design of folded multiple-arm dipoles and compare its performance properties with the test “free space” dipole. Special care is devoted to the maximum lowering of the profile of the antenna that is 0.9 mm which corresponds with relative height 0.003 λ_0 at 869 MHz over a conductive plane. On the other hand, decreasing of antenna footprint dimension is not a significant design issue as the position of the TAG is supposed to be integrated into the number label placed on a racer’s chest. First radiation efficiency versus the relative height of a simple and folded multiple-arm dipoles over the conducting plane is simulated and discussed. Influence of increasing of number of dipole arms on radiation and antenna efficiency, quality factor and bandwidth is presented. Further the design of folded multiple-arm dipole antenna with complex conjugate input impedance $Z_{ant} = Z_{chip}$* to the impedance of the RFID chip (Z_{chip} = 76 - j340 Ω) is considered for the European UHF RFID (865 - 869 MHz) frequency band. Impedance and radiation properties of the designed antenna are evaluated in monopole (quarter-wavelength) arrangement in order to avoid the usage of balun when coaxial feeding is used. Finally reading distance of the dipole design prototype is evaluated.

2. Horizontal Dipoles Placed above a Conductive Plane

2.1 Straight dipole above conductive plane

Let's consider a planar dipole of the width $w = 2$ mm with a zero thickness that is designed to operate in a free space at frequency 869 MHz. Analysis performed by the method of moment IE3D simulator predicts its half-wavelength $2l = 163.3$ mm at 869 MHz which corresponds to $0.473\,\lambda_0$ and the input impedance $Z_{ant} = 72.4\ \Omega$ when center fed. The dipole is then placed over an infinite conductive plane in the distance d/λ_0 which gradually decreases from 0.05 to 0.01.

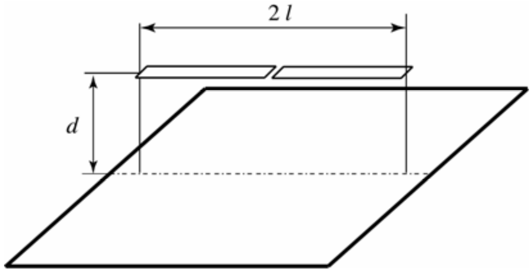


Fig. 1. Geometry of the straight planar dipole of the length $2l = 163.3$ mm and width $w = 2$ mm placed above infinite conductive plane.

The curves of the input impedance in Smith chart exhibite the typical decrease in the input resistance (indicating by shifting the curves to the left part of the Smith chart) in case the relative spacing d/λ_0 of the dipole above conductive plane decreases; see Fig. 2.

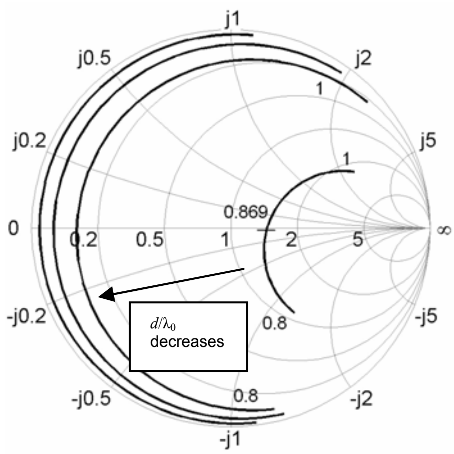


Fig. 2. Input impedance curves of the dipole in the Smith chart for frequency range from 0.8 to 1 GHz as a function of relative dipole height over conductive plane d/λ_0 = {free space, 0.05, 0.025, 0.01}

The crucial point is that if the relative distance d/λ_0 equals several hundredth, the size of the input resistance is equal to ones of ohms that predicts significant impedance mismatching when feed by 50 ohm feeder. However for practical usability it is significant radiation efficiency not antenna input impedance as the later can be match to the feeder by external matching network. Radiation efficiency defined as the ratio between the total radiated power and the input power (i.e. the incident power minus the reflected power at the antenna feeding port) and antenna efficiency defined as the ratio between the total radiated power and the incident power to the port are presented in Fig. 3. It can be seen that the decline in the radiation efficiency is not progressive as the decline in the antenna efficiency. As far as the relative dipole spacing $0.01\lambda_0$ over the conductive plane the radiation efficiency is concerned, it can be stated that it is higher than 50 % at the half-wavelength resonance, while the antenna efficiency drops to 1-2%.

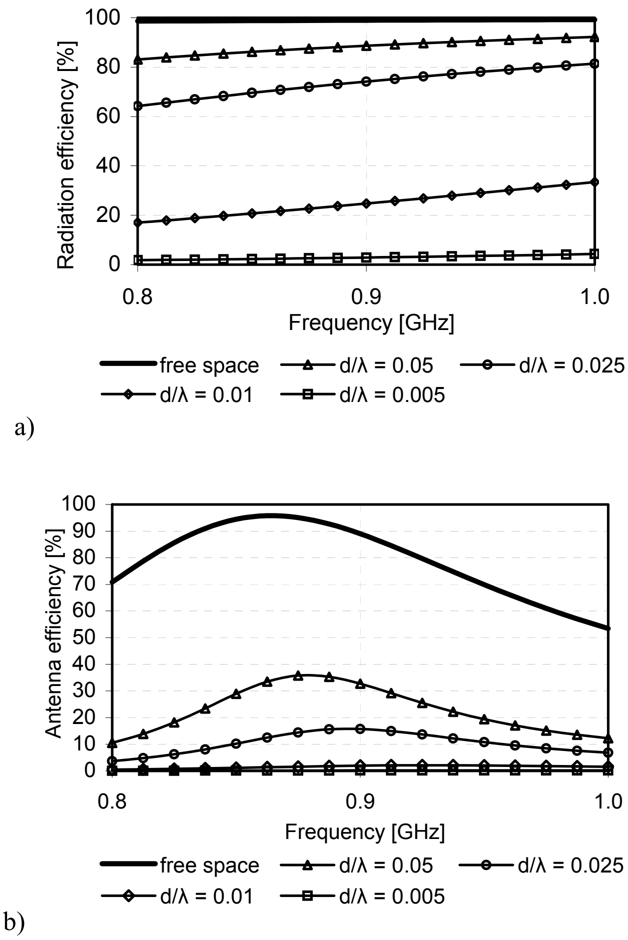


Fig. 3. Simulated frequency dependence of a) radiation and b) antenna efficiencies of straight dipole as a function of relative dipole height d/λ_0 = {free space, 0.05, 0.025, 0.01, 0.005}

When the distance of the dipole above conductive plane decreases quality factor increases and impedance bandwidth also decreases, and resonant frequency slightly increases. Simulated values of the bandwidth (for VSWR = 5.83, $|S_{11}|$ = -3 dB) as a function of dipole height above infinite conductive plane can be seen in Tab. 1.

d/λ_0 [-]	free space	0.05	0.025	0.01	0.005
f_r [MHz]	869	869	883	901	910
R_{ant} [Ω]	72.4	6.4	3.0	1.0	0.7
BW [%]	36	3.8	2.2	0.9	1.1

Tab. 1. Simulated half wavelength resonant frequency and impedance bandwidth evaluated for the dipole of the length $2l$ = 163.3 mm for different height above an infinite conductive plane

2.2 Folded multiple-arm dipole above conductive plane

As a dipole situated close to a conductive plane has usually a very low input resistance and consequently the radiation efficiency, it is necessary to apply some techniques to increase it. One of the possible ways is to use the folded and multiple-conductor (arm) dipole configuration [4]. High value of antenna input reactance (equal to hundreds of ohms) can be achieved by tuning the length of the dipole so that it operates over its half-wavelength resonance in the inductive region of the Smith chart close to the impedance Z = ∞ Ω. Using both of these techniques required value of Z_{ant} can be found. The increase of the input resistance of the multiple-arm folded dipole see Fig. 4 with the original length $2l$ = 163.3 mm, width w = 2 mm, spacing of dipole arms s = 1 mm, and relative distance above the conductive plane d = 1 mm ($d/\lambda_0 \sim 0.003$ at 869 MHz) as a function of the number N_{arms} of dipole arms can be seen in Fig. 5.

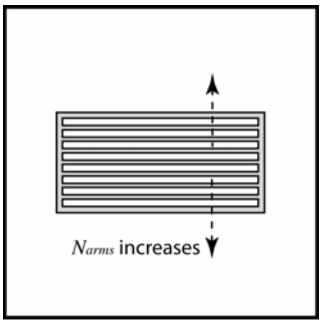
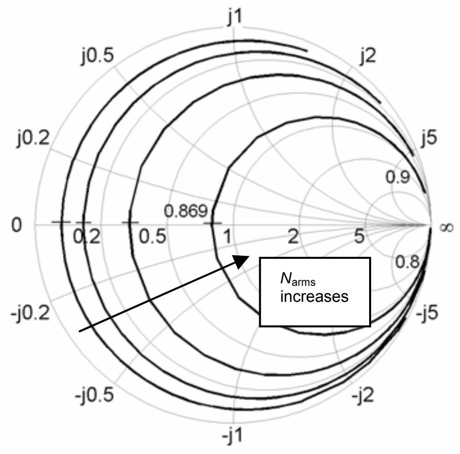


Fig. 4. Geometry of the multiple-arms folded dipole with the dipole length $2l$ = 163.3 mm spaced $d \sim 0.9$ mm (d/λ_0 = 0.003 at 869 MHz) above conductive plane, N_{arms} represents the number of arms.

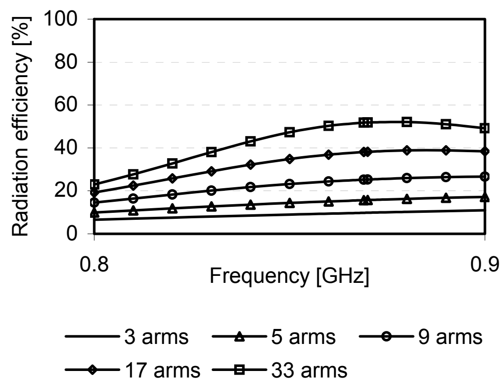
Increase of input resistance caused by the increase of number of arms N_{arms} coincidents with the increase of radiation efficiency as can be seen from Fig 6.



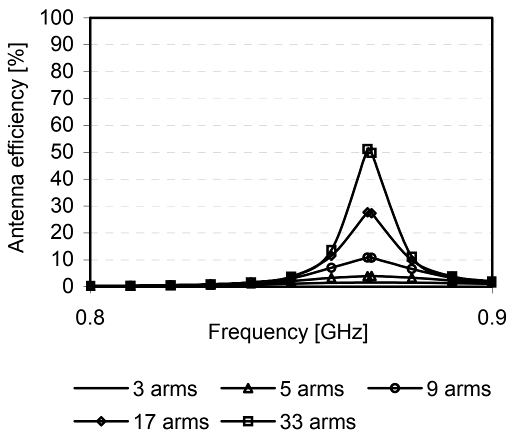
b)

Fig. 5. Input impedance curves of the multiple-arm folded dipole placed $d/\lambda_0 \sim 0.003$ above conductive plane in the Smith chart as a function of number of arms N_{arms} = {5, 9, 17, 33}.

Simulation of radiation and antenna (considered when $Z_{ant} = Z_{chip}$*) efficiencies versus number of arms N_{arms} of folded multiple-arm dipole predicts values about $\eta \sim 50$ % for N_{arms} = 33 at frequency f = 869 MHz.



a)



b)

Fig. 6. Simulated a) radiation and b) antenna efficiency ($Z_{ant} = Z_{chip}$* is considered) of multiple-arm folded dipole placed $d/\lambda_0 \sim 0.003$ above conductive plane; the number of arms N_{arms} is a parameter.

Impedance bandwidth and half wavelength resonant length at 869 MHz as a function of number of arms of multiple-arm folded dipole for constant height $d/\lambda_0 \sim 0.003$ above conductive plane can be seen in Tab. 2.

N_{arms}	3	5	9	17	33
2*l* [mm]	170.4	169.9	169.5	169.2	168.7
R_{ant} [Ω]	2.2	3.6	7.0	15.7	40.4
BW [MHz]	6.1	6.1	6.1	7.8	9.6
BW [%]	0.7	0.7	0.7	0.9	1.1

Tab. 2. Simulated impedance bandwidth and half wavelength resonance length at 869 MHz of multiple-arm folded dipoles spaced $d = 1$ mm ($d/\lambda_0 \sim 0.003$ at 869 MHz) above conductive plane.

3. Monopole antenna prototype for 869 MHz band

During the design of potencial RFID tag dipole antenna (with extremely low profile), several multiple-arms folded dipole configurations operating extremely close to the PEC plane (as far as to $d/\lambda_0 \sim 0.003$) has been studied in order to find the dimensions, and number of dipole arms for required Z_{ant} in 869 MHz band. In order to maintain the low relative permittivity of the space between dipole and conducting plane layered substrate consisting of 0.8 mm thin foam substrate ($\varepsilon_r \sim 1.29$, $\tan\delta \sim 0.01$) and 0.1 mm thin GIL GML 1100 the woven-glass laminate ($\varepsilon_r = 3.29$ +/-0.5, $\tan\delta = 0.003$) have been used. Foam substrate has been used in narrow strips with the width w_{foam} = 6 mm and spacing $w_{spacing}$ = 4 mm so that the dielectric constant of this layer has been supposed to be about $\varepsilon_r \sim 1.2$ for the simulation.

Verification of the designed antenna properties has been realized in monopole arrangement (see photograph in Fig. 7) in order to avoid the use of a balun between the antenna and feeding coaxial connector. The dimensions of realized 33-arm folded monopole prototype are: $l = 77$ mm, w = 2 mm, s = 1 mm with total folded monopole width $w_{ant} = 98$ mm. The size of the conductive and mirror planes are 120 × 121 mm (width × height) and 380 × 380 mm, respectively. Dielectric layer carrying the antenna is 110 × 121 mm (w × h), see Fig. 7. Simulated values of monopole input impedance has been calculated from dipole arrangement as simulation of monopole over infinite ground plane with vertical thin dielectric layers did not provide reliable values.

Considering the RFID application, the antenna and chip impedances are properly matched when their input impedances are complex conjugate. In our case the dipole type antenna input impedance has to be $Z_{ant} = 76 + j340$ Ω.

The input impedance of the monopole has half value of the dipole impedance and has to be properly taken into account thus $Z_{monopole} = Z_{ant}/2 = 38 + j170$ Ω is considered for transmission coefficient τ calculation here:

$$\tau = 1 - |\Gamma|^2 = \frac{4R_{ant}R_{chip}}{(R_{ant}+R_{chip})^2 + (X_{ant}+X_{chip})^2} \quad (1)$$

$$\Gamma = \frac{Z_{chip} - Z_{ant}}{Z_{chip} + Z_{ant}}, \quad 0 < |\Gamma| < 1 \quad (2)$$

where Γ is a reflection coefficient between antenna and chip impedances, R_{ant} and R_{chip} are antenna and chip input resistances, X_{ant} and X_{chip} represent antenna and chip input reactances, respectively.

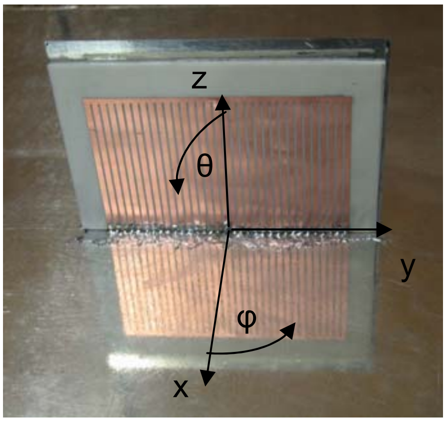


Fig. 7. Photograph of realized prototypes of 33-arm folded monopole antenna spaced $d = 0.9$ mm ($d/\lambda_0 \sim 0.003$ at 869 MHz) above conductive plane with mirror plane of 380 × 380 mm.

In order to maintain required X_{ant} the length of the dipole has been tuned so that the dipole operates over its half wavelength resonance and its impedance curve is situated in inductive region of the Smith chart as described before. Values of transmission coefficient τ, radiation and antenna efficiencies η_{rad} and η_{ant}, bandwidth *BW*, and gain *G* are summarized in Tab. 3.

	R_{ant} [Ω]	X_{ant} [Ω]	τ [%]	η_{rad} [%]	η_{ant} [%]	BW [%]	D [dBi]	G [dBi]
Simu-lated	36.7	269.0	36.3	30.2	10.9	-	10.8 [3)]	1.2 [3)]
Measu-red	66.6	81.8	79.6	22.0 [1)]	11.9 [1)] 28 [2)]	2.2	7.0 [2)]	1.5 [2)]

Tab. 3. Simulated and measured parameters of monopole prototype with N_{arms} = 33 of the length $l = 77.0$ mm and spacing $d = 0.9$ mm ($d/\lambda_0 \sim 0.01$) over the conductive plane at $f = 869$ MHz. [1)] Wheeler cap method, [2)] far field distance method of monopole arrangement, [3)] dipole arrangement over infinite conductive plane

Measured value of antenna efficiency has been evaluated by the two methods: by Wheeler cap method with 120 × 120 × 120 mm cap and by far field distance method from measured gain and directivity calculated from measured radiated patterns. Radiation patterns Measured at frequency 869 MHz in E and H planes are presented in Fig. 8.

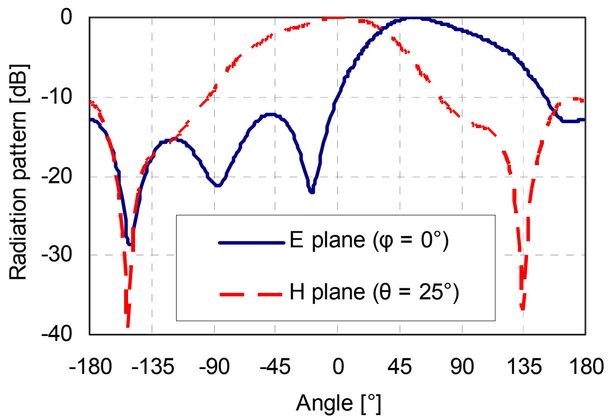


Fig. 8. Measured radiation patterns in E and H planes of realized monopole prototype at $f = 869$ MHz

4. Conclusion

Meandered wire antennas operating close to a PEC plane, using multiple-arm folded techniques have been explored. The aim was to find the approach for the design of RFID transponder antennas with the extremely low profile operating close to PEC plane and required complex input impedance. As a reference, the RFID chip impedance $Z_{chip} = 76 - j340\ \Omega$ in 869 MHz band has been considered. Antenna radiation efficiency of simulated dipoles and realized monopole (30 and 22 %) is a little bit lower than predicted in case of free space dipoles (about 50 %) due to the presence of dielectric and foam substrates. The practical gain limitation is done by the impedance mismatch due to the antenna impedance variations. The bandwidth limitation is the price for extremely low profile placement ($d/\lambda_0 \sim 0.003$) of horizontal dipole above conductive plane. However in RFID applications in UHF range where operational bandwidth is several MHz this multiple-arm folded dipole technique can provide sufficient TAG antenna performance properties.

Acknowledgment

This work has been conducted at the Department of Electromagnetic Field of the Czech Technical University in Prague and supported and by the two projects of the Grant Agency of the Czech Republic No. 102/08/1282 "Artificial electromagnetic structures for miniaturization of high-frequency and microwave radiation and circuit elements", and doctoral project no. 102/08/H018, further by the Czech Ministry of Education, Youth and Sports in the frame of the Research Project in the Area of the Prospective Information and Navigation Technologies MSM 6840770014, and by the COST project IC0603 "Antenna Systems & Sensors for Information Society Technologies".

References

[1] ŠVANDA, M., POLÍVKA, M., HUDEC, P., Application of the UHF RFID System for the Identification of sportsmen in Mass Races, *Proceedings of the European Microwave Association*, to be presented in December 2007 issue.

[2] LEE, K. F., CHEN, W., Advances in Microstrip and Printed Antennas, New York, John Wiley & Sons, 1997.

[3] BALANIS, C., A., Antenna Theory, Analysis and Design, second edition, John Wiley & Sons, Inc., New York, 1997.

[4] BEST, S. R., Improving Performance Properties of a Dipole Element Closely Spaced to a PEC Ground Plane, *IEEE Antennas and Wireless Propagation Letters,* vol. 3, 2004, p. 359-363.