International Journal on Wireless & Optical Communications

THE DESIGN OF THE MULTIPLE-ARM FOLDED DIPOLE ANTENNA OPERATING CLOSELY SPACED TO A PEC

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The planar multiple-arm folded dipoles operating closely spaced to a perfect electric conductor (PEC) plane were studied in order to find the approach for the design of the low profile dipole type antenna with a metallic shielding applicable for the radiofrequency identification (RFID) within 2.4 GHz band. The effect of applied multiple-arm folded dipole technique on the input resistance, radiation and antenna efficiency of treated dipole configurations is explored. The antenna prototype in the monopole configuration has been realized and measured to verify its performance properties.

Keywords: folded dipole, horizontal dipole over perfect electric conductor, multiple-arm dipole, low profile antenna, radiation efficiency.

1. Introduction

Low profile antennas operating closely spaced (< 0.05 λ) to a perfect electric conductor (PEC) plane are highly demanded in the field of Radio Frequency Identification (RFID) systems. The typical performance of the RFID transponder (TAG) antenna for warehouse purposes is a planar dipole etched on a thin substrate using a meandering technique in order to decrease the dipole footprint dimensions [1], [2]. However, the dipoles that are placed horizontally close to a PEC plane are usually considered as bad radiators. It is obvious from the following principle: the original and out-phase image currents below the PEC plane mutually cancel their radiation. In addition, the radiation efficiency declines. The aforementioned phenomenon is usually completed by the curves of input impedance with a significant decrease in the input resistance in case that the spacing of the dipole over PEC plane declines. Due to the impedance mismatch, the power transfer between the antenna and load impedances is low. Moreover, the input impedance of the typical chip used in RFID technology in HF and microwave bands is usually different from 50 Ω. It has input resistance in tens of ohms and input reactance in hundreds of ohms of negative value. As far as the reference is concerned, the input impedance Z_{chip} = 80 - j232 Ω of EM4222 chip [3] in 2.4 GHz band has been considered in the following paragraphs. Both the low radiation efficiency and the impedance matching to non-50 ohm chip impedances are necessary for a good performance properties of the RFID TAG antenna.

As shown later in the paper, the wire antennas operating in the close vicinity of a PEC plane can provide the input impedance values that are similar to the conjugate match values of the chip impedance in case that multiple-arm folded dipole technique and operation over its half-wavelength resonance are used. As a result, the specific arrangements of the wire antennas operating close to a PEC plane can lead to a satisfactory match to the impedance of RFID chips while maintaining a low profile. In case that antenna and chip impedances are properly matched, the radiation efficiency is considered to be the determinant of the quality of the radiator.

The antenna (overall) efficiency is defined as the ratio between the total radiated power and the incident power at the antenna feeding port. On the other hand, the radiation efficiency is defined as the ratio between the total radiated power and the input power (i.e. the incident power minus the reflected power). According to the aforementioned definitions, the radiation efficiency is always higher, or at least the same, as the antenna efficiency.

Owing to the position of the wire antenna (close to a PEC surface) its input resistance is decreased as far as to several ohms in half wavelength resonance for the spacing around hundredth of wavelength [1]. Fortunately, the radiation efficiency does not drop as fast as the input resistance. It maintains the reasonable values (i.e. over 50 %) as far as to the relative spacing 0.01 λ over a PEC plane.

2. Properties of straight dipole placed near PEC plane

Let us consider a planar dipole of the length $2l = 60$ mm and the width $w = 2$ mm that is, in the first step, situated in a free space. The dipole is analysed by the method of moments implemented in Zeland Software IE3D simulator with 20 cells per wavelength at the highest analysed frequency equal to 3 GHz. Its half wavelength resonant frequency equals 2.35 GHz and the input impedance $Z_{in} = 71.4\ \Omega$ (fed at the center). In the second step, the dipole is placed over the infinite PEC plane in the distance *d,* which gradually decreases to 0.005λ. The following curves of the input impedance in Smith chart indicate the typical fall in the input resistance in case that the dipole spacing is lowered; see Fig. 1b). The crucial point is that if the relative distance d/λ equals several hundredth, whereas the size of the input resistance amounts to ones of ohms. This can be simply explained by the image theory and by means of the influence of mutual coupling of the source and the image dipole currents formed by a pair of dipole-reflection plane. In theory, the input impedance active dipole of side-by-side λ/2 two element dipole array can be expressed as follows [4]:

$$Z_{in} = Z_{11} + Z_{12}\frac{I_1}{I_2}, \quad I_1 \approx -I_2 \qquad (1)$$

where Z_{11}, Z_{12} are respectively self and mutual impedances, I_1 and I_2 are currents in active and passive dipoles, being supposed to be of a comparable magnitude but an opposite direction. In case that the distance between the dipoles smaller then 0.3 λ, both real and imaginary components of the mutual impedance are positive [4, p. 419, fig. 8.21], while the second term in equation (1) is negative (due to the significant fall in Z_{in} of either active dipole or the dipole placed closely above the PEC.

However, the comparison of the decline in the radiation efficiency is not progressive (contrary to the decrease in the antenna efficiency); see Fig. 2. As far as the relative dipole spacing 0.01λ over the PEC 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%.

As the dipole situated close to a PEC plane shows usually a very low input resistance, it is necessary to apply specific techniques to increase it. One of the possible ways is to use the multiple-conductor (arm) folded dipole configuration described in [5], [6]. The physical relation of the input impedance Z_{in} and the number N_{arm} of the dipole arms in the multiple-arm folded dipole configuration may bee expressed as follows:

$$Z_{in} \approx N^2_{arms} Z_{11} \qquad (2)$$

However, it is necessary to point out that the above-mentioned relation is valid uniquely provided that the dipoles are closely spaced and the magnitudes of all dipole currents are supposed to be the same see [4]. The effect of decreasing dipole Z_{in} (when closely spaced to a PEC plane) is thus compensated by the increase of Z_{in} caused by the multiple-arm folded dipole configuration resulting in the approximate linear dependence of Z_{in} (N_{arms}) as empirically verified by simulation results presented in chap. 3.

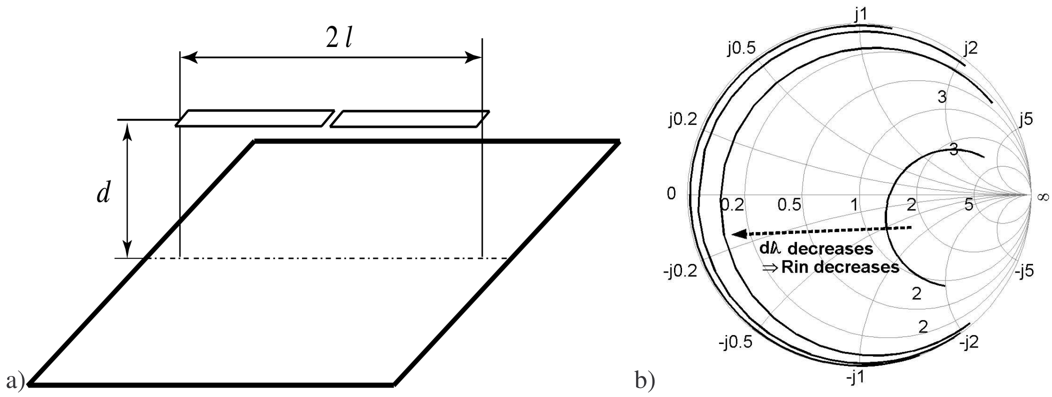
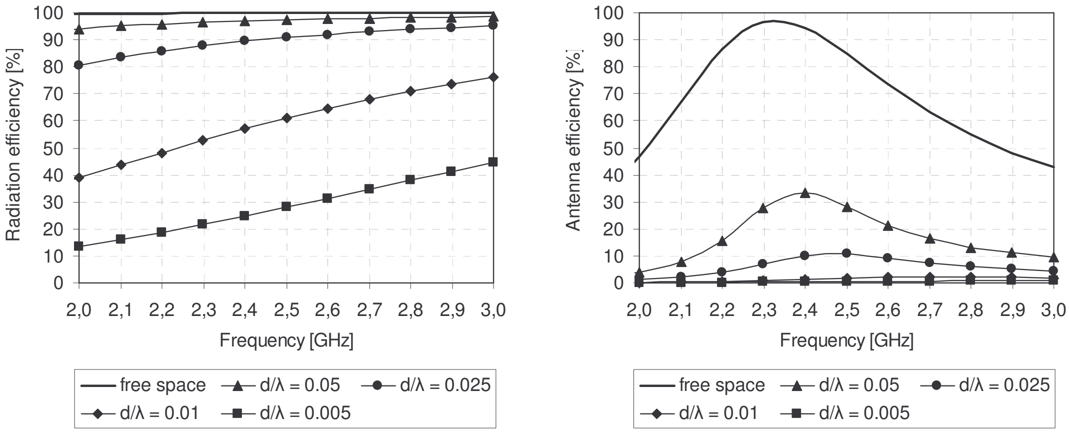


Fig. 1. a) Geometry of straight planar dipole of length $2l$ = 60 mm and width w = 2 mm situated close to infinite PEC plane (d/λ = 0.05, 0.025, 0.01, 0.005), and b) its input impedance in Smith chart within the frequency range from 2 to 3 GHz



a) b)

Fig. 2: Simulated a) radiation and b) antenna efficiency of straight dipole (half-wavelength resonance at 2.35 GHz) as function of frequency with spacing d/λ over PEC plane as parameter.

3. Multiple-arm folded dipole closely spaced to a PEC plane

The high value of antenna input reactance (equal to hundreds of ohms) can be achieved in case that the dipole operates over its half-wavelength resonance, see Fig. 3b. A simultaneous use of the multiple-arm folded dipole configuration leads to the required value of Z_{in}. Considering the multiple-arm folded dipole with the original length $2l = 60$ mm, width $w = 2.2$ mm, spacing of arms $s = 0.8$ mm and the relative spacing over the PEC plane $d/\lambda = 0.01$ ($d = 1.04$ mm), the increase in the input resistance as a function of the number N_{arms} of dipole arms is depicted in Fig. 3 b).

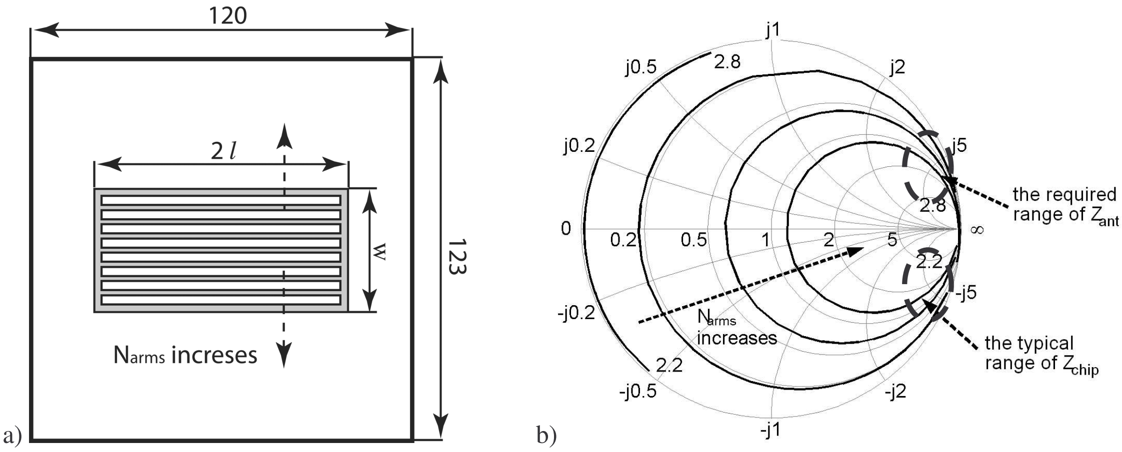


Fig. 3: Geometry of multiple-arms folded dipoles with dipole length $2l = 60$ mm, spaced $d/\lambda \sim 0.01$ ($d = 1.04$ mm) over PEC plane (a), and their input impedance in Smith chart in frequency range 2.2 ÷ 2.8 GHz (b), N_{arms} represents number of arms ($N_{\text{arms}} = 1, 7, 15, 23$).

During the design of the RFID tag antenna, several multiple-arms folded dipole configurations operating extremely close to the PEC plane (as far as $d \sim 1$ mm, $d/\lambda \sim 0.01$) have been studied in order to find the dimensions and number of arms N_{arms} for required Z_{in} in 2.4 GHz band. In order to maintain a low relative permittivity of the space between the dipole and the PEC plane, a layered substrate consisting of 0.8 mm thin air substrate (with several strip foam spacers, $\varepsilon_r \sim 1.3$) and 0.24 mm of GIL GML 1100 the woven-glass substrate ($\varepsilon_r = 3.29$ +/-0.5, $\tan\delta = 0.003$) was placed between the folded dipole and the PEC plane. The finite size of the PEC plane 120×123 mm was used. The corresponding values of R_{in} and X_{in} of investigated antenna structures are presented in Table 1.

Table 1. Simulated parameters of multiple-arm folded dipole for dipole length $2l = 51.0$ mm and spacing $d/\lambda \sim 0.01$ ($d = 1.04$ mm) over finite sized PEC plane for frequency ($X_{\text{in}} = 232\ \Omega$).

N_{arms}	f *[GHz]*	R_{in} *[Ω]*	η_{rad} *[%]*	τ *[-]*	η_{ant} *[%]*
2	3.15	5.4	64.5	0.237	15.3
7	2.61	13.4	73.8	0.492	36.3
15	2.47	34.5	83.4	0.842	70.2
23	2.42	65.5	86.9	0.990	86.0

4. Design of monopole type antenna for 2.4 GHz band

The verification of the designed antenna properties was carried out in the monopole arrangement (see Fig. 4) in order to avoid the use of a balun situated between the antenna and the coaxial connector. The monopole input impedance is of a half value (compared to the dipole), thus $Z_{monopole} = Z_{dipole} /2 = 40 + j116\ \Omega$ is considered for further evaluation. The dimensions of the tuned 23-arm folded monopole prototype follow: l = 25.5 mm, w = 2.2 mm, s = 0.8 mm with a total folded monopole width W = 68 mm. The size of the PEC plane amounts to 120 × 123 mm, and the size of mirror PEC plane is 143 × 143 mm.

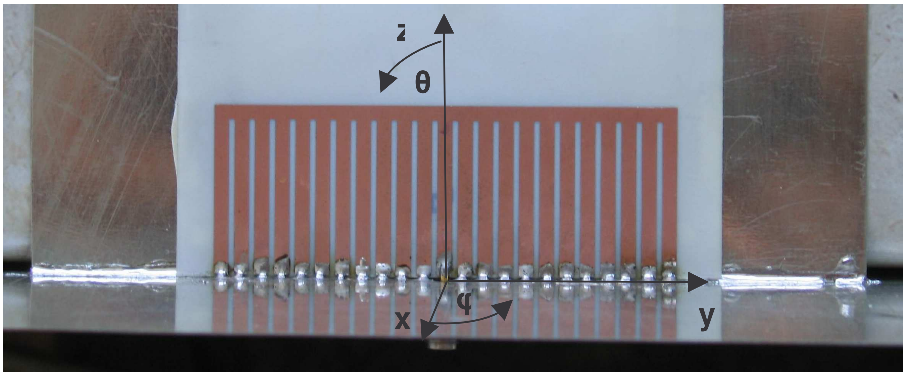


Fig. 4. Photograph of realized prototype of 23-arm folded monopole antenna closely spaced over PEC plane (in the vertical position, d ~ 1 mm, d/λ ~ 0.01).

Considering the RFID application, the antenna and the chip impedances are properly matched provided that their input impedances represent a complex conjugate. Consequently, the power transmission coefficient τ is calculated by means of the following equation:

$$\tau = 1 - |\Gamma|^2 = \frac{4R_{ant}R_{chip}}{(R_{ant}+R_{chip})^2 + (X_{ant}+X_{chip})^2}, \quad 0 \le \tau \le 1 \tag{1}$$

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

where Γ is reflection coefficient between the antenna and the chip impedances, R_{ant} and R_{chip} represent the antenna and the chip input resistances, X_{ant} and X_{chip} stand for the antenna and the chip input reactances respectively. Comparison of the measured and the simulated transmission coefficient is shown in Fig. 5. There is a minimum frequency shift between the maximum values - about 20 MHz (~ 0.8 %). It is assumed that the aforementioned inaccurance is attributable to the unprecise spacing of the dielectric substrate carrying the antenna over the PEC plane.

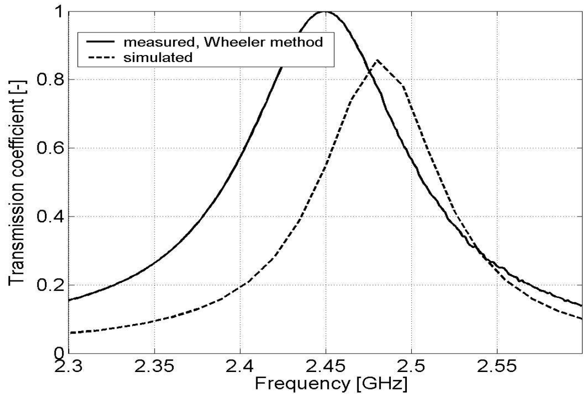


Fig. 5. Comparison of simulated and measured transmission coefficient of 23-arm folded monopole antenna closely spaced over PEC (d ~ 1 mm, d/λ ~ 0.01).

Firstly, the radiation efficiency was measured first by Wheeler cap method [6], i.e. calculated from the measured R_{monopole} and R_{loss}, with the cap of the $123 \times 123 \times 123$ mm. Secondly, the antenna efficiency was evaluated from the radiation efficiency and the power transmission coefficient τ, calculated from the measured value of Z_{monopole} and the declared value $Z_{\mathrm{chip}}/2$ (i.e. the correction for the monopole comparison) that is supposed to be constant over 2.4 GHz band. Thirdly, the antenna efficiency was evaluated from the measured gain and the directivity (calculated as the arithmetic average of the directivities D_{E} and D_{H} in E a H planes evaluated from measured radiation patterns); see Fig. 7. The frequency dependence of the simulated and the measured efficiencies by Wheeler method are presented in Fig. 6.

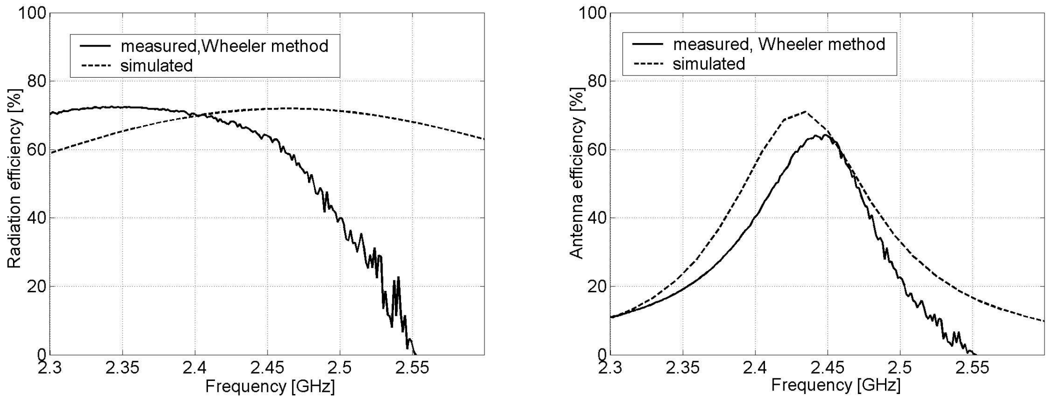


Fig. 6. Comparison of simulated and measured radiation (left) and antenna (right) efficiencies of 23-arm folded monopole antenna closely spaced over PEC (d ~ 1 mm, d/λ ~ 0.01).

The values of the simulated and the measured (i.e. calculated) directivity and gain, radiation and antenna efficiency together with the input resistance R_{monople} and reactance X_{monopole} (at the frequency at which the transmission coefficient τ reaches the highest value) are mentioned in Table 2.

Table 2. Simulated and measured parameters of 23-arm folded monopole for spacing $d/\lambda \sim 0.01$ (d = 1.04 mm) over PEC plane for frequencies with maximum τ. 1) Wheeler cap method, 2) far field method.

	f *[GHz]*	$R_{monopole}$ *[Ω]*	$X_{monopole}$ *[Ω]*	τ *[-]*	η_{rad} *[%]*	η_{ant} *[%]*	D *[dBi]*	G *[dBi]*
simulated	2.48	80	94	0.85	71.8	44.5	8.9	5.4
measured	2.45	42.1	117.6	0.999	64.0 1)	64.0 1) 45,7 2)	9.6 2)	6.2 2)

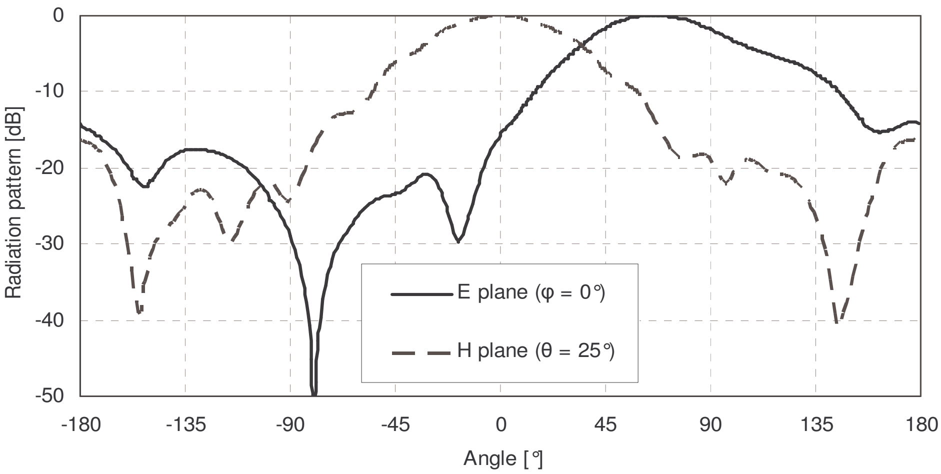


Fig. 6. Measured radiation pattern of 23-arm folded monopole antenna placed $d \sim 1$ mm ($d/\lambda \sim 0.01$) over PEC.

5. Conclusion

Several configurations of the multiple-arm folded dipole antennas operating close to a PEC plane have been explored. The aim was to find the approach for the design of extremely low profile dipole type antennas operating above PEC plane that would be applicable in RFID in case that the transponder antennas require a complex input impedance. Although the radiation efficiency remains on the acceptable level (measured $\eta_{ant} \sim 50$ %) at the center frequency, it is crucial to stress that the practical use has it limits be cause of the impedance mismatch. The latter is attributable to the antenna impedance variations and the related drop in antenna gain that occurs at the band limits. The efficiency and the bandwidth limitations result from the extremely low profile placement (i.e. $d/\lambda \sim 0.01$) of the horizontal folded dipole configuration above the PEC plane. Nevertheless, in case of RFID applications in UHF and microwave range (where the operational bandwidth is of several ones or tens of MHz) the aforementioned multiple-arm folded dipole technique is able to show sufficient TAG antenna performance properties.

Acknowledgements

The research was undertaken at the Department of Electromagnetic Field of the Czech Technical University in Prague and supported by two projects of the Grant Agency of the Czech Republic “Artificial electromagnetic structures for miniaturization of high-frequency and microwave radiation and circuit elements” no. 102/08/1282, and doctoral project “Modeling and simulation of field” no. 102/08/H018. Moreover, it was also supported by the Czech Ministry of Education, Youth and Sports within 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”.

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