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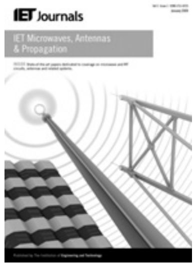

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Multi-arm cylindrical folded dipole antenna for collinear arrays

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Abstract: A radiating element suitable for electrically long VHF/UHF collinear arrays is presented. Collinear arrays with an isotropic radiation pattern in the horizontal plane and vertical polarisation are usually made of stacked cylindrical dipoles. The proposed array element consists of a slotted cylindrical dipole and belongs to the class of transmission-line folded antennas. The structure of the proposed array element allows an easy and firm mechanical attachment to the metallic antenna mast, and at the same time it ensures a satisfactory isolation performance. Two prototypes operating at 300 MHz have been manufactured and characterised. The design procedure is described and measurements of the reflection coefficient and the isolation between adjacent elements are shown.

1 Introduction

In the VHF/UHF frequency bands, linear arrays of vertical dipoles are commonly used to implement antennas with an omni-directional radiation pattern in the H-plane [1–6]. Among some applications, it is worth mentioning the air traffic control systems operating in the 108–156 and 225–400 MHz frequency bands, where a number of dipoles (between two and six) are vertically aligned and placed at a proper distance to meet the isolation specification. The dipoles are usually realised with half-wavelength-long empty cylindrical metallic tubes. The latter are concentric to a metallic tube (antenna mast) that acts as a mechanical support for the entire array, as well as a grounding and lightning protection component. The dipoles are separately fed through coaxial cables that lie side by side inside the metallic tube. Such antennas are required to provide vertical polarisation, an omni-directional radiation pattern in the H-plane and at least 27 dB port isolation between adjacent elements [7, 8].

The realisation of a VHF/UHF electrically long collinear dipole array (a tall vertical structure with six or more radiating elements) characterised by an inter-element isolation greater than 27 dB is a challenging task from the electrical as well as mechanical points of view. The most important issues concerning electrically long collinear dipole arrays are the in-air inter-dipole mutual coupling, as well as the mutual coupling effects that are due to parasitic currents excited on the metallic mast and to those currents generated on the external conductors of the coaxial cables running inside the antenna mast. The parasitic currents excited on the external conductor of the coaxial cables are usually caused by a non-ideal feeding balun, whose performance is significantly limited by severe space constrains. The above issues must be considered during the design process; in particular, how and where the connection point between the dipoles and the antenna mast is realised should be carefully considered.

A common configuration is shown in Fig. 1, where a cylindrical dipole is concentric to a metallic tube. The dipole ends are connected to the metallic tube through metallic screws or plates. This antenna arrangement resembles a cylindrical folded dipole (C-FD), where the external cylinder (the dipole) is fed and the internal metallic tube acts as the other arm of the folded dipole. However, when such a dipole structure is used in a collinear array, adjacent elements must be electrically separated through non-conductive tubes, usually made of Teflon.

Indeed, if the metallic tube is longer than the dipole, the currents induced along the internal tube would increase the mutual coupling and reduce the resonant frequency of each dipole. Moreover, when non-conductive tubes are used, an additional grounding component is needed for safety and protection requirements. Finally, it is worth mentioning that the internal metallic tube is useful to shield the radiating arms of the dipole from the feeding cables that lie inside the tube, as well as to reduce spurious radiation from parasitic currents that could be excited on the outer conductor of the coaxial cables.

This paper is intended to present a radiating element suitable for VHF/UHF electrically long collinear arrays, whose layout allows one to use a single robust long metallic grounding tube (without non-conducting sections), yet preserving a satisfactory isolation between adjacent dipoles. The paper is organised as follows. The antenna layout is presented in Section 2. Simulation results and measurements on some prototypes are shown in Section 3, by referring to a collinear array operating at around 300 MHz. The results of a parametric study are summarised in Section 4 and concluding remarks are drawn in Section 5. Numerical simulations were performed through the commercial software CST MWS®.

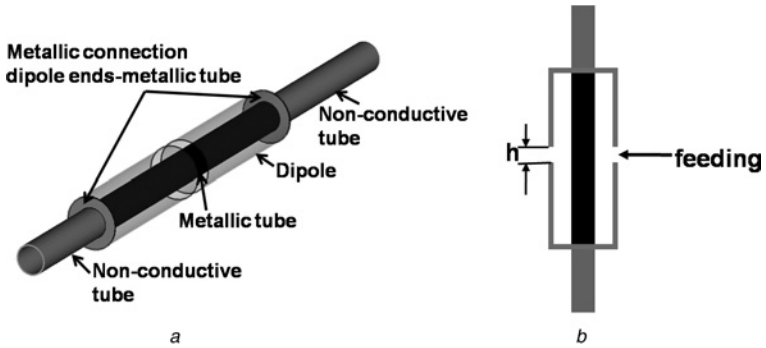

Fig. 1 *Typical cylindrical folded dipole (C-FD) configuration used to implement electrically long collinear arrays*

a 3D view
b Section view
Non-conductive parts are needed to isolate adjacent dipoles of the collinear array

2 Multi-arm cylindrical folded dipole antenna design

The proposed radiating element (see Fig. 2) is a multi-arm half-wavelength folded dipole antenna whose branches are wrapped around a cylindrical metallic tube at a proper distance from the cylinder itself (the latter acts both as a grounding system and a cylindrical reflector). Hereafter, the proposed element will be named as multi-arm cylindrical folded dipole (MAC-FD). If there are no space constrains, a balun can be used to feed the MAC-FD antenna through a coaxial cable.

Although the MAC-FD may look like a 'birdcage' antenna, it is worth mentioning that it belongs to the class of transmission-line folded antennas and exhibits different properties than birdcage coils used in magnetic resonance imaging (MRI) systems and birdcage dipoles. Indeed, MRI birdcage coils are required to produce a highly homogeneous magnetic induction over a large volume within the coil, in the near-field antenna region, with a minimal radiation outside the coil [9]. Moreover, the proposed antenna is different from those named as birdcage dipoles, where each one of the two cylindrical dipole arms is replaced by a wireframe structure with a large radius, thus resembling a birdcage. A large radius is used to obtain broader impedance bandwidths and the wireframe structure allows to keep the antenna light [10, 11]. In the proposed MAC-FD antenna, the 'birdcage' resemblance is obtained by wrapping a grid of parallel strips around a supporting tube. The folded geometry is adopted to increase the dipole input impedance, in order to compensate for the shorting effect that arises when the dipole is mounted close to the internal tube (the antenna mast that works as a cylindrical metallic reflector).

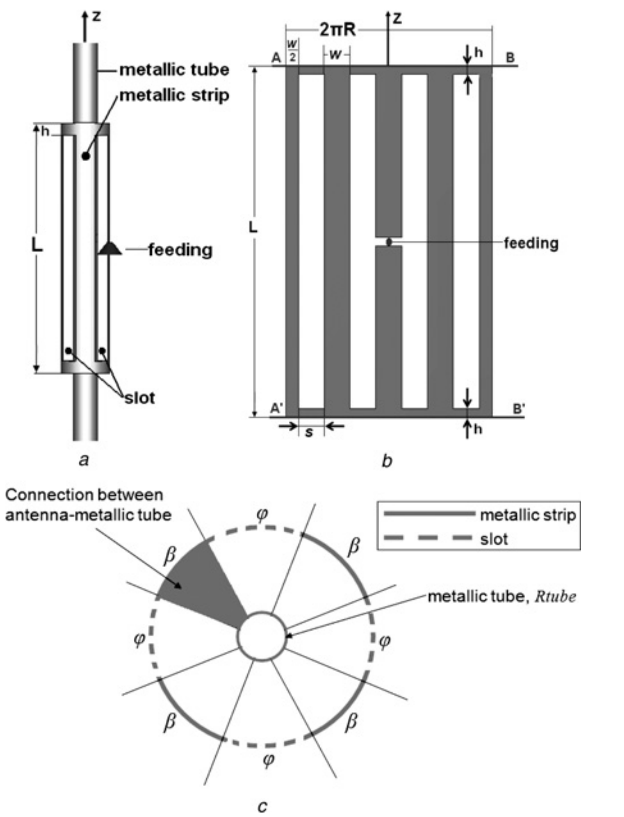

Fig. 2 *Multi-arm cylindrical folded dipole (MAC-FD) with four slots*

a 3D view
b View of the 'unwrapped' dipole (section AA′B′B takes a cylindrical shape once the edges AA′ and BB′ are wrapped around *z*-axis to overlap)
c Cross-section view

The layout shown in Fig. 2 is for a four-slot (or equivalently, four metallic strips) configuration. The metal strips are connected together at the upper and lower ends of the dipole. One of the metallic strips is cut at its centre to obtain the feeding point. The metallic grounding tube can be attached to the centre of one or more metallic strips (possibly all, except for the strip containing the feeding point), as usually happens in folded dipole antennas [12]. Indeed, since the centre point of each strip is at zero potential and the metallic tube is grounded, this solution does not introduce a current perturbation and the electrical behaviour of the dipole is preserved.

Two MAC-FD antennas are studied, namely MAC-FD-2S and MAC-FD-4S, with two slots (two metal strips) and four slots (four metal strips), respectively. Their geometrical parameters are summarised in Table 1. The antennas were designed to operate at around 300 MHz. The MAC-FD-4S is made of four vertical slots and four vertical metal strips, all with the same width ($w = s = 31.4$ mm). As shown in Fig. 2*c*, the antenna presents eight equal 45° wide sectors ($\beta = \varphi = 45^\circ$, $R = 40$ mm). The MAC-FD-2S is made of two vertical slots and two vertical metal strips ($w = 165$ mm, $s = 55$ mm). It presents four unequal sectors ($\beta = 135^\circ$, $\varphi = 45^\circ$, $R = 70$ mm). The radius of the supporting metallic tube is $R_{\text{tube}} = 20$ mm, for both antennas.

In Table 1, the geometrical parameters of the C-FD shown in Fig. 1 are also listed, as such dipole will be used as a reference for performance comparison. All the antennas were designed to provide a nominal 50 Ω input impedance

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Table 1 Geometrical parameters of MAC-FD and C-FD antennas

	MAC-FD-4S	MAC-FD-2S	C-FD
R, mm	40	70	35
L, mm	410	410	410
circumference, mm	251.2	440	219.8
s, mm	31.4	55	–
φ, °	45	45	–
w, mm	31.4	165	–
β, °	45	135	–
$R_{tube} = 20$ mm			
$h = 10$ mm			

at 300 MHz. Numerical simulations were performed using the time-domain solver of the commercial software CST MWS on an IntelCore2QuadCPU@3 GHz PC. Dipoles were fed at their centre through a balanced input. The number of hexahedrons was around 500 thousands for a single-element MAC-FD-4S (800 thousands for MAC-FD-4S). Computational time was around 10 min for a single element and around 30 min for two adjacent elements on a metallic tube. A vanishing thickness has been considered for the conductor used to model the internal metallic tube and the dipole arms.

3 Antenna performance

For each configuration in Table 1, two prototypes (denoted as A and B in the following) were fabricated and characterised. The antennas were made by wrapping a copper foil tape on a plastic cylindrical support. Fig. 3*a* shows a fabricated prototype of the MAC-FD-2S (without the inner metallic tube); the inner metallic tube is visible in Fig. 3*b*, where the photo of a MAC-FD-4S prototype is shown.

Fig. 4 shows the simulated and measured reflection coefficient for both configurations. A frequency shift between simulated and measured data was noticed, which is probably due to both inaccuracies in the prototype manufacturing and numerical errors.

Fig. 5 shows the simulated radiation patterns and gain for the C-FD, the MAC-FD-2S and the MAC-FD-4S. As expected, the proposed antennas behave like conventional dipoles with a doughnut-like radiation pattern in the E-plane and an antenna gain greater than 2 dBi. Since the distances between the strips, as well as those between the strips and the metallic tube surface are small with respect to the radiation wavelength (less than 0.1λ, at 300 MHz), an almost omni-directional radiation pattern is achieved in the H-plane.

a   *b*

Fig. 3 *MAC-FD antenna prototypes*

a MAC-FD-2S
b MAC-FD-4S

The mutual coupling between the dipoles of a collinear array is affected by (a) the direct in-air coupling between adjacent dipoles, (b) the coupling due to the currents induced in the supporting metallic mast and (c) the currents induced on the outer conductor of the coaxial cables running inside the metallic tube. Since in the proposed MAC-FD antenna it is possible to use a single long metallic tube, the coaxial cables are completely shielded from the dipoles. Direct coupling between dipoles and coupling effects related to the currents induced on the external surface of the metallic mast can be reduced by increasing the inter-element distance.

Isolation measurements for two-element arrays have been performed to account for all possible coupling effects. Measurements were aimed to show that an array of two MAC-FD antennas attached to a single long metallic tube

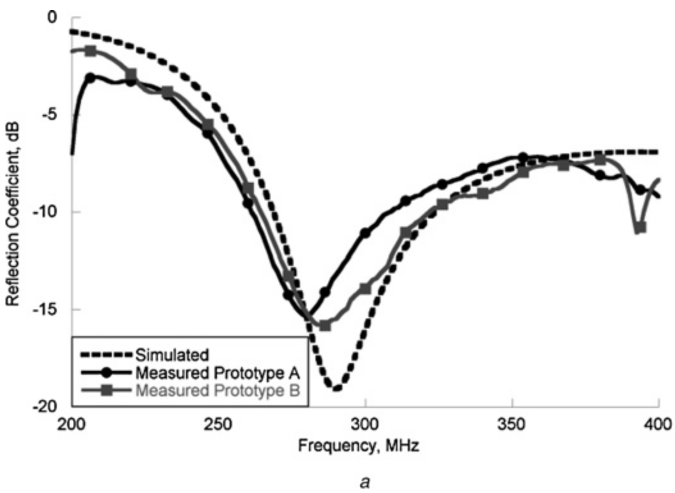

Fig. 4 *Simulated and measured reflection coefficient*

a Prototypes A and B for the MAC-FD-2S antenna
b Prototypes A and B for the MAC-FD-4S antenna

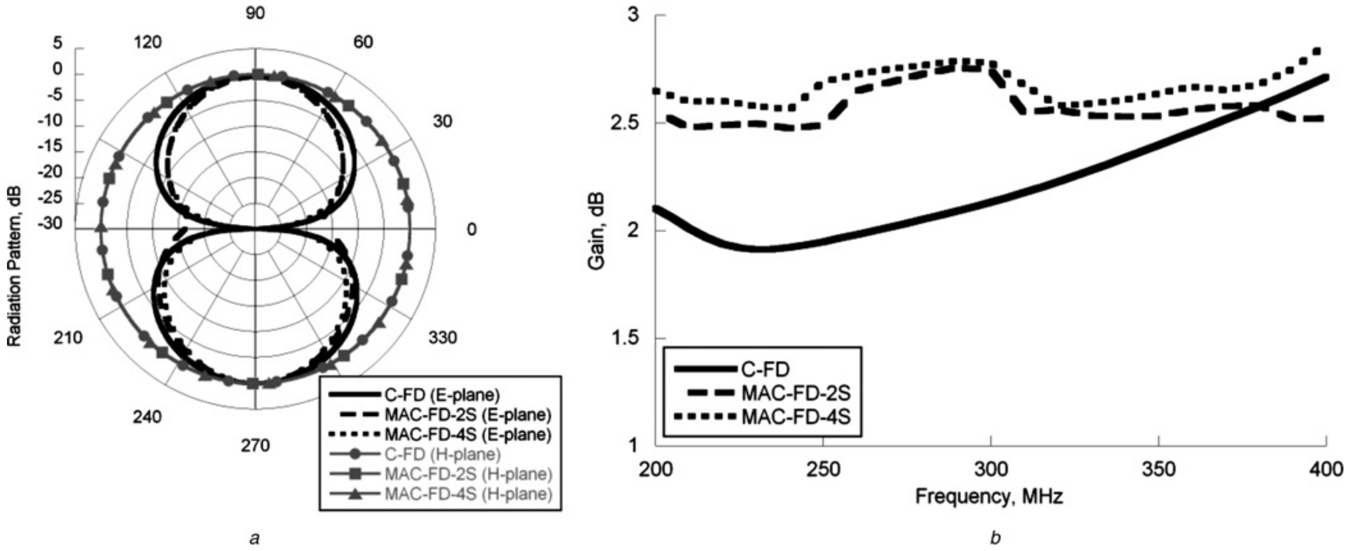

Fig. 5 *Comparison between the radiation performance of the C-FD and the MAC-FD antennas with two (MAC-FD-2S) or four (MAC-FD-4S) slots*

a Simulated radiation patterns
b Simulated gain

can provide a coupling level lower than that one achievable between two C-FD antennas separated by a Teflon tube, for a given inter-element distance. For all measured arrays, the feeding cables lie inside the supporting mast and a balun was used for unbalanced-to-balanced transformation. Measurements have been carried out in an open space with no surrounding buildings. The lower antenna was at 3.3 m from the ground (see photos in Fig. 6). A comparison with numerical results obtained for a pair of free-space isolated dipoles was also considered.

Measured mutual coupling (S12 parameter) is shown in Fig. 6 for a two-element array. For the array made of two MAC-FD-2S an average isolation (in the 250–350 MHz frequency range) equal to 30 and 39 dB has been obtained, for $D = 0.9$ and 1.6 m (corresponding to an inter-element distance equal to 0.9λ and 1.6λ, at 300 MHz), respectively (Fig. 6*a*). In the above frequency range, the array of two MAC-FD-4S elements provides 33 and 35 dB average isolation for $D = 0.9$ and 1.6 m, respectively (Fig. 6*b*). For the array of two C-FD, an average isolation of 12 and 18 dB was obtained, when the inter-element separation varies from 0.9 up to 1.6 m. An average improvement of around 10 dB is gained with the proposed configuration. From Fig. 6 it also appears that MAC-FD isolation results are quite close to those relevant to a couple of free-space isolated dipoles, for which a minimum inter-element distance of almost one wavelength is required to provide an isolation greater than 30 dB.

4 Design criteria

In this section, performances of the proposed MAC-FD antenna are numerically analysed as a function of some key design parameters.

In Fig. 7, the antenna input impedance is plotted as a function of the number of slots: $n = 2$, 4, 6 and 8. In Fig. 7*a* the antenna radius is $R = 40$ mm and in Fig. 7*b* it is equal to $R = 70$ mm. The slot angular width is $\varphi = 30^\circ$ and the strip sector width β is 150° ($n = 2$), 60° ($n = 4$), 30° ($n = 6$) and 15° ($n = 8$).

Both graphs show that the input impedance increases when the number of slots (strips) increases. This is in agreement with the folded dipole property, namely the input impedance increases if the number of arms is augmented [12]. For the proposed antenna, increasing the number of strips is useful to compensate for the shorting effect of the inner metallic tube whose distance from the MAC-FD is electrically small. Also, by comparing Figs. 7*a* and *b* it can be noticed that greater impedance values are obtained by enlarging the radius of the dipole from $R = 40$ to 70 mm, as expected since the distance of the radiating arms from the metallic mast increases and the shorting effect is lower. The metallic tube radius was fixed to $R_{tube} = 20$ mm.

Fig. 8 shows the input impedance when the ratio between the slot and strip widths (φ/β) is varied. For a given value of φ/β, the sector angular widths can be evaluated by considering that $(\varphi + \beta)n = \beta(1 + \varphi/\beta)n = 360^\circ$, where n denotes the number of slots/strips. In Fig. 8*a*, which is relevant to the MAC-FD-4S antenna, it can be noticed that the input impedance does not significantly change when φ/β varies between 0.2 and 3. As far as the MAC-FD-2S antenna is concerned, the input impedance variations become visible only when φ/β is greater than 1 (Fig. 8*b*).

In Fig. 9, the input impedance for a MAC-FD-4S with $\varphi/\beta = 1$ is shown. When the antenna radius increases, the input impedance increases as expected since the dipole moves far from the shorting metallic mast.

The proposed antenna should be shorter than a half-wavelength dipole (as for a conventional resonant dipole). Also, the ratio between the radii of the dipole and the antenna mast should be increased to reduce the shorting effect of the internal metallic tube. On the other hand, the minimum mast radius has to meet mechanical robustness requirements, especially for tall arrays. The above-mentioned shorting effect can be effectively counteracted by increasing the number of slots/strips, to meet 50 Ω input impedance specifications, at the expense of a narrower impedance bandwidth. Finally, the ratio between strip and slot widths does not significantly influence antenna input impedance behaviour.

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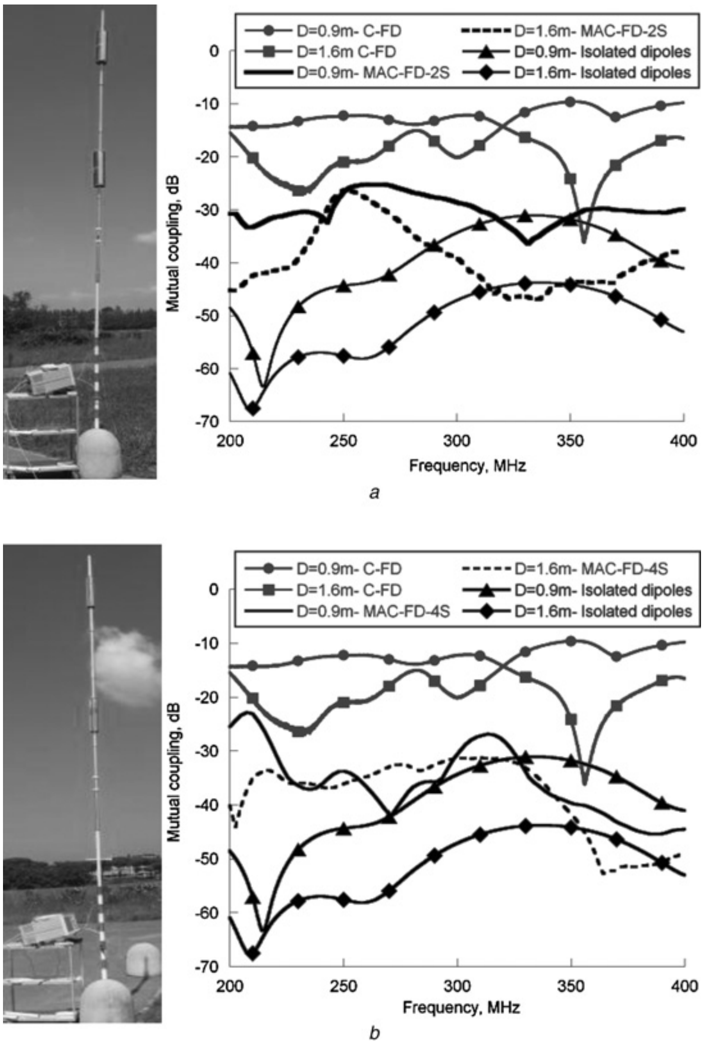

Fig. 6 *Measured mutual coupling between*

a Two adjacent MAC-FD-2S on a metallic tube
b Two adjacent MAC-FD-4S on a metallic tube
For comparison purposes, measured mutual coupling between two adjacent C-FD separated by a piece of PTFE tube and simulated mutual coupling between two free-space isolated dipoles were also considered. Two inter-element distances were considered: $D = 0.9$ and 1.6 m (corresponding to $D = 0.9\lambda$ and $D = 1.6\lambda$ at 300 MHz, respectively)

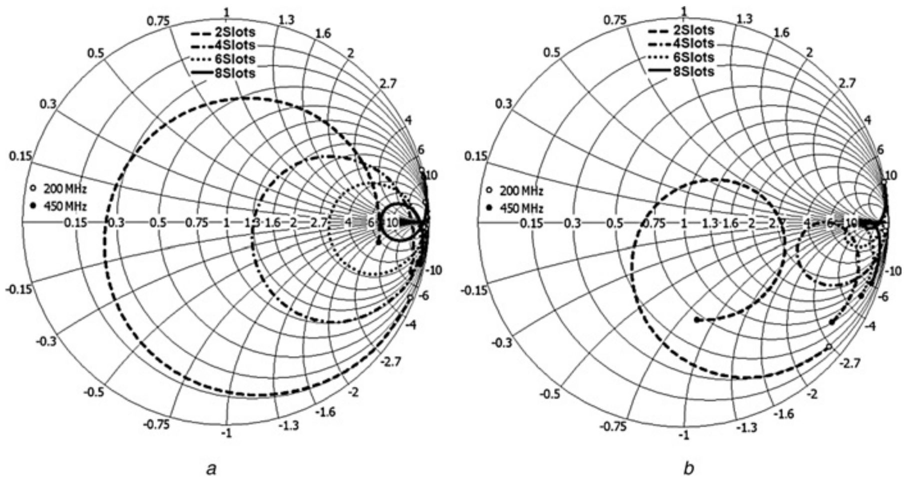

Fig. 7 *Simulated input impedance as a function of the slot number*
Width of the slot sector is $\varphi = 30^\circ$, and the width of the strip sectors is $\beta = 150^\circ$ for two slots, $\beta = 60^\circ$ for 4 slots, $\beta = 30^\circ$ for 6 slots, $\beta = 15^\circ$ for 8 slots. The radius of the MAC-FD is

a $R = 40$ mm
b $R = 70$ mm
All the remaining geometrical parameters are as those in Table 1

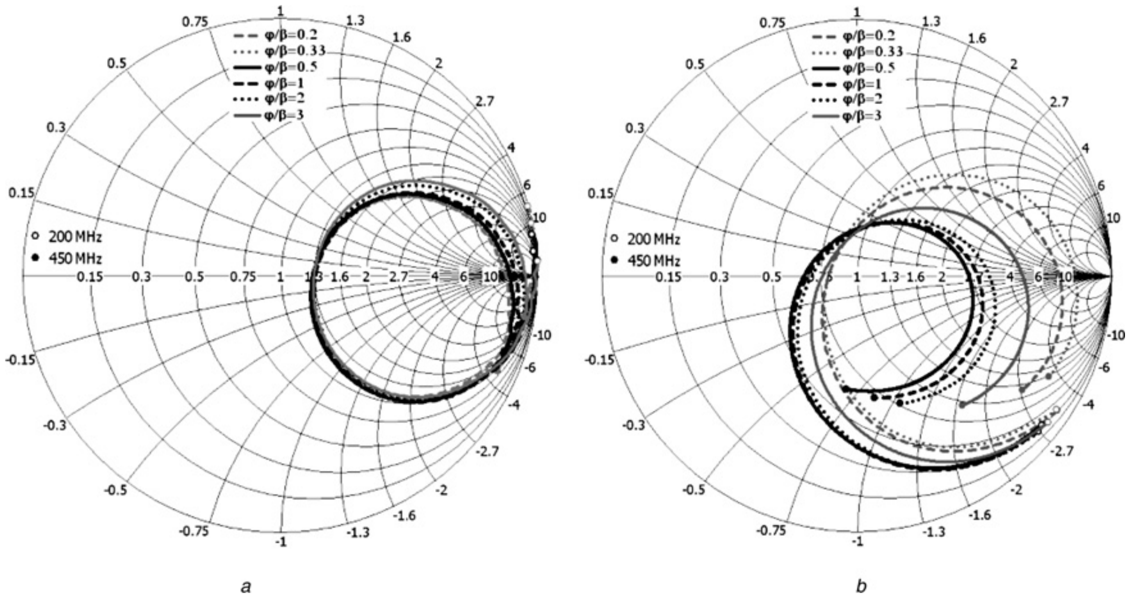

Fig. 8 *Simulated input impedance as a function of the ratio between the slot width and the strip width (φ/β)*
a MAC-FD-4S
b MAC-FD-2S
All the remaining geometrical parameters are as those in Table 1

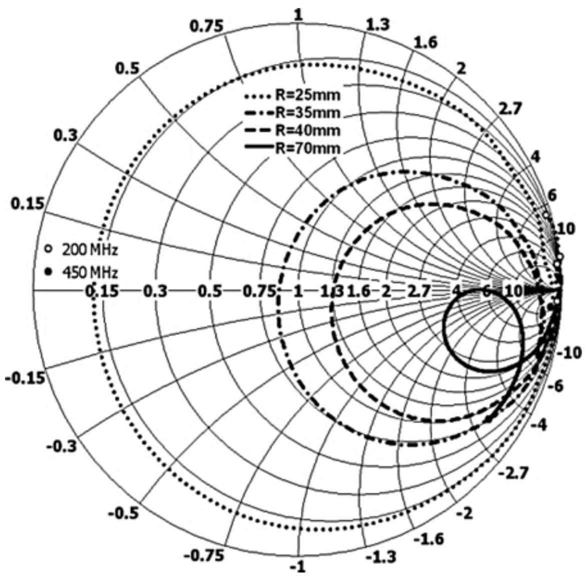

Fig. 9 *Simulated input impedance for the MAC-FD-4S ($\varphi/\beta = 1$, $R_{tube} = 20$ mm), as a function of the dipole radius R*
All the remaining geometrical parameters are as those in Table 1

5 Conclusions

A multi-arm cylindrical folded dipole suitable for electrically long collinear dipole arrays has been proposed. The designed antenna faces with some electrical and mechanical issues related to the positioning and attachment of cylindrical dipoles at the metallic antenna mast. Prototypes of two different multi-arm cylindrical folded dipoles operating at around 300 MHz were designed and characterised, and they have been used for isolation measurements in a two-element collinear array. It has been experimentally shown that the multi-arm cylindrical folded dipoles can guarantee a better isolation performance with respect to conventional cylindrical folded dipoles often used to implement VHF/UHF collinear arrays. Finally, a parametric analysis was performed to highlight the influence of some key design parameters on the antenna performance.

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7 References

1 Faigen, I., Ergene, A.: 'Broadband dipole antenna system with coaxial feeding-line coated with ferrite particles to reduce line currents', USA Patent 4218687, August 1980
2 Griffee, L.V.: 'Dual band collinear dipole antenna', USA Patent 4410893, October 1983
3 Patrick, P., Haitu, D.: 'Multiple band collinear dipole antenna', USA Patent 2010/0302116A1, December 2010
4 Joffe, E.B.: 'A comparison of the coupling between collocated VHF antenna on a common mast in various configurations', IEEE Int. Symp. on Electromagn. Compat., USA, August 1997, pp. 488–493
5 Kaegebein, D.P.: 'Parallel fed collinear antenna array', USA Patent 6057804, May 2000
6 Price, E.G., Gordon, R.F.: 'Parallel fed collinear dipole array antenna', USA Patent 6720934, April 2004
7 Campbell, D.: 'Highly decoupled collinear antennas', Proc. Int. Symp. on Antennas Propagation, 1978, vol. 16, pp. 439–445
8 Wasylkiwskyj, W., Kahn, W.K.: 'Mutual coupling and element efficiency for infinite linear arrays', *Proc. IEEE*, 1968, **56**, (11), pp. 1901–1907
9 Jin, J.: 'Electromagnetic analysis and design in magnetic resonance imaging' (CRC Press, 1998, 1st edn.)
10 Ahmad, M.I., Ahmed, M.M., Shah, I.U.: 'Design and analysis of cross cage dipole antenna', Proc. Int. Conf. Advances in Space Technologies, 2006, pp. 75–80
11 The ARRL Antenna Book: 'The ultimate reference for amateur radio antennas, transmission lines and propagation' (ARRL, 2007, 21st edn.)
12 Balanis, C.: 'Antenna theory-analysis and design' (John Wiley & Sons, 1997, 2nd edn.)

doi: 10.1049/iet-map.2011.0438