Design and performance of small electromagnetically coupled monopole antenna for broadband operation

J.H. Jung, H. Choo and I. Park

Abstract: An electromagnetically coupled small broadband monopole antenna has been investigated. The antenna structure consists of a circular disk-loaded monopole and a probe with a spiral strip line monopole packed within a small electrical volume. Broad bandwidth can be achieved through electromagnetic coupling between these two monopoles that generate two resonances closely spaced in frequency. The antenna with a circular disk has an electrical size kr of 0.563 and has 430 MHz of impedance bandwidth for VSWR < 2 with a centre frequency at 2.185 GHz, which is $\simeq$19.7% of a fractional bandwidth. Measured efficiency of the circular disk-loaded antenna is 98% at its centre band region. The gain of the antenna is $>$1.55 dBi and the antenna has good omni-directional radiation characteristics.

1 Introduction

An electrically small antenna is referred to as an antenna for which $kr < 1$, where k is the wave number at the centre frequency of the antenna and r is the radius of the smallest sphere that can enclose the antenna. These kinds of antennas have been investigated since the early days of the antenna development because of their theoretical and practical importance. It is well known that an electrically small antenna with high efficiency generally has a narrow bandwidth because the quality factor, Q, is very high. Since the quality factor is inversely proportional to the bandwidth, reducing its value is critical to achieving broad bandwidth.

The quality factor of a small antenna is closely related to the smallest sphere that can enclose the antenna, and it can be minimised through the effective use of the given sphere [1–4]. On the basis of this theory, several types of small antennas have been investigated to overcome the bandwidth problem. A multi-element disk-loaded monopole antenna with an electrical size of $kr = 1.0$ was first presented by Goubau *et al.* [5] and later by Friedman [6]. This antenna consists of two driven sectors and two shorted sectors, with adjacent sectors being interconnected by wires. It could achieve an impedance bandwidth of 62% based on VSWR$<$2 and a half power bandwidth (VSWR $<$ 5.8) of 82% by closely coupled radiating elements. A conical folded monopole antenna using folded spiral wires was presented in [7]. This antenna has an electrical size of $kr = 0.71$ and achieves an impedance bandwidth of 10.9% and a half power bandwidth of 28.6% by susceptance cancellation between the wires. This structure can improve the half power bandwidth up to 48% with the variation of the characteristic impedance of the feedline, but the matching circuit has to be added to the transceiver units. Disk-loaded monopole [8] with an electrical size of $kr = 0.63$ achieved an impedance bandwidth of 12.9% using the impedance transformation in parallel strip elements. A two-wire helix [9] and a square dual spiral [10] have an electrical size of $\simeq kr = 0.63$, and these structures have an impedance bandwidth of 12%. Several other types of electrically small antennas have also been investigated [11, 12]; however, enhancing bandwidth without sacrificing other antenna characteristics is extremely difficult due to fundamental limitations.

According to the circuit theory, it always has the effect of lowering the overall Q if the resonant circuit is coupled to the other circuitry, which usually operates as a matching circuit [13]. In the design of an electrically small antenna, a matching circuit can be employed, but this makes the antenna structure more complicated and requires additional space. However, if the small antenna has two radiating resonant circuits and one of the circuits is being function as a self-matching circuit to the other circuit, then the bandwidth of the antenna can be enhanced by using a mutual coupling between the two radiators that are located in very close proximity to each other.

In this paper, we present an antenna structure that greatly increases the bandwidth of an electrically small antenna with high efficiency. The proposed structure consists of a circular disk-loaded and a spiral strip line-loaded monopole packed within a small cylindrical structure [14]. Bandwidth enhancement can be achieved partly by cancellation of the reactance between the undriven disk-loaded monopole and the driven spiral strip line-loaded monopole, and partly by a higher order circuit operation due to a mutual electromagnetic coupling between the two monopoles. The experimental results showed that the circular disk-loaded monopole antenna enclosed within a sphere having $kr = 0.563$ has 430 MHz of impedance bandwidth for VSWR $<$ 2 with the centre frequency at 2.185 GHz.

2 Antenna geometry and parametric studies

The geometry of the antenna is shown in Fig. 1. The circular disk with a radius ρ is placed at a height h from the ground

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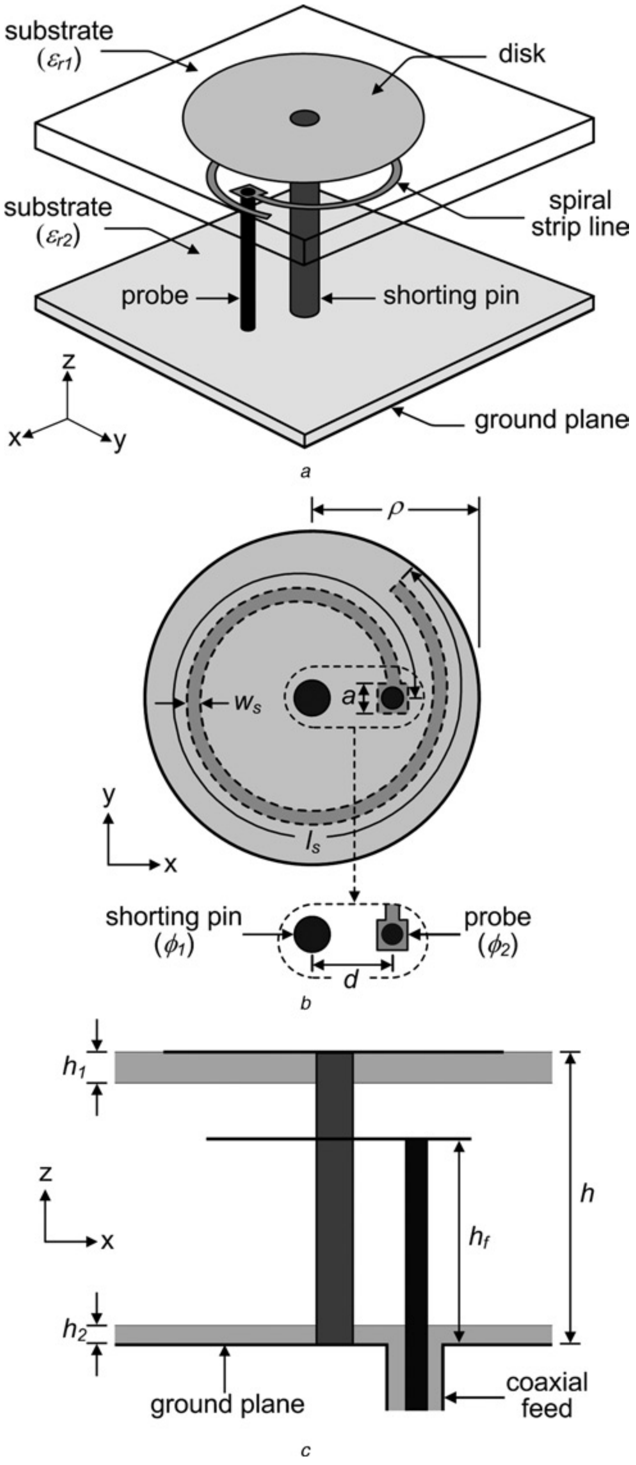

Fig. 1 *Circular disk-loaded monopole antenna*

a 3-dimensional view
b Top view
c Side view

plane, and the centre of the circular disk is connected to the ground plane by a pin with a diameter ϕ_1. The antenna is excited through a coaxial probe with a diameter ϕ_2, which is connected at the end of the spiral strip line located at h_f from the ground plane. The length and width of the spiral strip line are l_s and w_s, respectively. A small square patch of size a is formed at the end of the spiral strip line to connect with the probe since in most cases the probe diameter is wider than that of the spiral strip line. The total length of the probe and spiral strip line is $\simeq 0.25\lambda$ at the resonant frequency. The centres of the pin and probe are spaced d distance apart. The circular disk is placed on a substrate with a dielectric constant of $\varepsilon_{r_1} = 10.2$ and a thickness of $h_1 = 1.27$ mm (RT/Duroid 6010). The substrate for the ground plane has a dielectric constant of $\varepsilon_{r_2} = 3.38$ and a thickness of $h_2 = 0.81$ mm (RO 4003).

The IE3D simulator of Zeland Software was used to study the characteristics of the antenna under various design parameters. The initial design parameters for this parametric study are $\rho = 5.5$ mm, $h = 11$ mm, $\phi_1 = 1.6$ mm, $\phi_2 = 0.86$ mm, $h_f = 8.0$ mm, $l_s = 31.5$ mm, $w_s = 0.4$ mm and $d = 3.4$ mm. The input impedance characteristics with these design parameters are represented in Fig. 2 as the solid line. To determine the influence of top loading on an undriven monopole, we simulate the input impedance characteristics with the presence of only the spiral strip line loaded monopole (without the circular disk-loaded monopole), and the result is shown as the dashed line in Fig. 2. The impedance characteristics of this monopole are not very good because the height (h_f) of the spiral strip line is much lower than a wavelength of the resonant frequency. However, the impedance characteristics in the presence of both the spiral strip line-loaded monopole and the circular disk-loaded monopole show dual resonance at 2.02 and 2.28 GHz with good impedance matching.

To examine this more closely, we changed the distance, d, between the shorting pin of the circular disk and the probe on the spiral strip line from 2.5 to 12.5 mm (the circular disk-loaded monopole is moved away from the spiral strip line loaded monopole). As can be seen from Fig. 3, distance d has a strong influence on the electromagnetic coupling between the two monopoles. The impedance locus in the Smith chart moves to the right and its loop of the impedance locus enlarges as d increases from 2.5 to 8.5 mm, so the coupling between

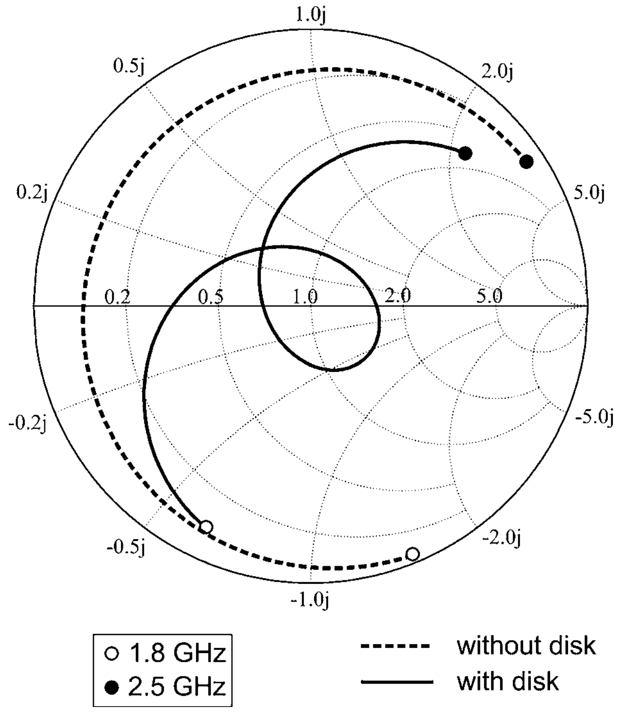

Fig. 2 *Impedance characteristics of the antenna that is composed of the probe with a spiral strip line feed only and the antenna that is composed of the probe with a spiral line and the shorted rectangular disk*

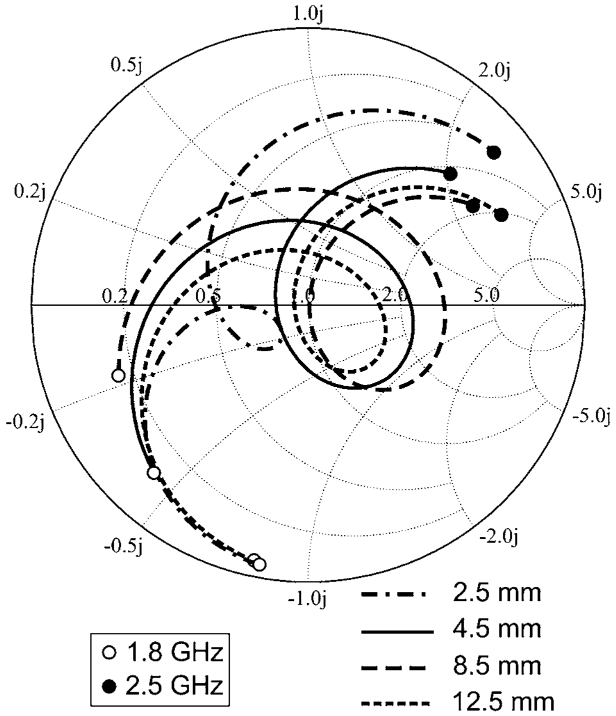

Fig. 3 *Variation of the impedance with respect to the distance of the shorting pin and the probe (the circular disk-loaded monopole is moved away from the spiral strip line loaded monopole)*

the two monopoles is maximised approximately when $d = 8.5$ mm. At that point, however, the loop of the impedance locus begins to shrink as d continues to increase, and thus the coupling begins to decrease. This clearly indicates that the electromagnetical coupling between the two monopoles makes the dual resonances resulting in broadband operation.

Fig. 4 shows the return loss of the antenna with a change of the circular spiral strip line length, l_s, from 29.5 to 33.5 mm. All other antenna parameters are the same as the previous case. As a result, the inductance of the spiral strip line increases and higher resonance frequency f_H decreases from 2.4 to 2.22 GHz. However, lower resonance frequency f_L maintains at $\simeq$2.02 GHz, which indicates that f_L is not closely related with the variation of the inductance.

Fig. 5 shows the variation of return loss of the antenna with respect to the diameter of the shorting pin. As the diameter of the shorting pin increases from 1.2 to 2.0 mm, lower resonant frequency f_L moves from 1.89 to 2.12 GHz and the higher resonance frequency is kept at $\simeq$2.28 GHz. As the diameter of the shorting pin increases, the capacitance in the shorted disk decreases. Therefore the resonance frequency of the shorted disk increases and thus resonance frequency f_L of the shorted disk is shifted to the higher frequency.

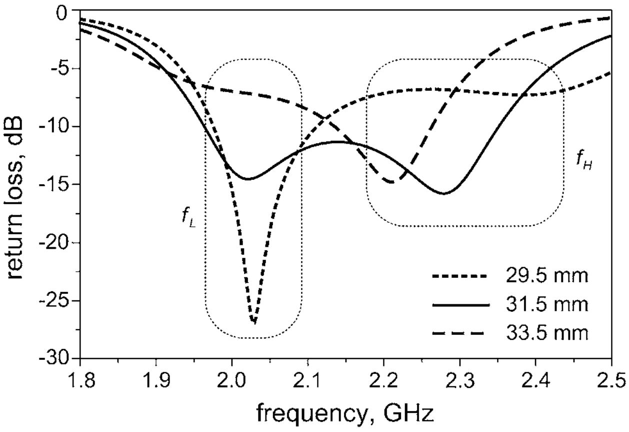

Fig. 4 *Variation of the return loss with respect to the circular spiral strip line length*

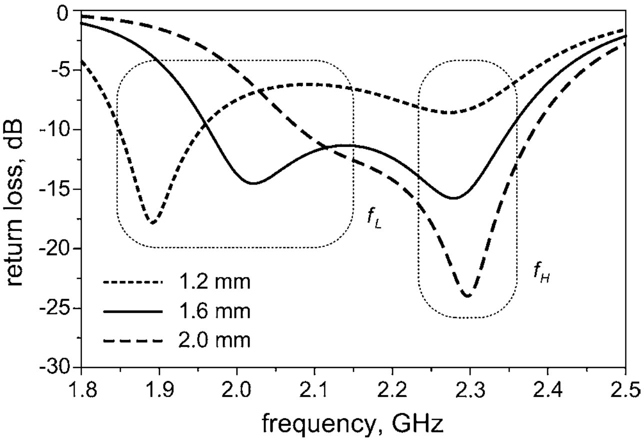

Fig. 5 *Variation of the return loss with respect to the shorting pin diameter*

From these parametric study results, we can see that the circular disk-loaded monopole and the probe with a spiral strip line monopole provide the lower and higher resonances, respectively. Therefore the frequency behaviour of the antenna can be manipulated by controlling the parallel capacitance of the circular-disk monopole, the series inductance of the probe with a spiral strip line monopole and the electromagnetic coupling between two monopoles so that its impedance variation is very small over a wide frequency range.

3 Equivalent circuit model

Section 2 presented a discussion of the antenna characteristics through EM-simulation. From these results, it can be considered that the proposed antenna comprises two monopoles, that is a circular disk-loaded monopole and a probe with a spiral strip line monopole. Therefore the antenna is expected to support a dual resonant mode. An equivalent circuit model that describes such dual resonance is shown in Fig. 6. The circular disk-loaded monopole is represented by the parallel resonant circuit, and the probe

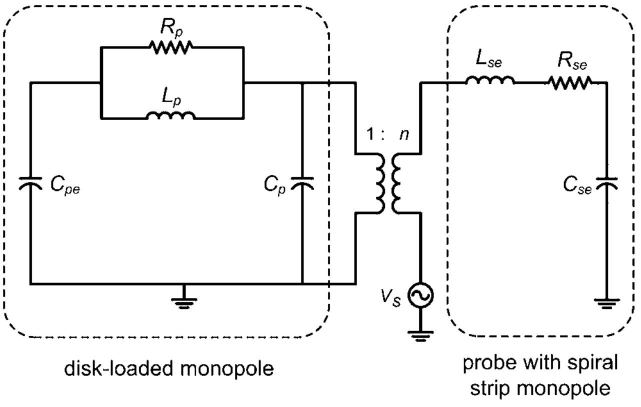

Fig. 6 *Equivalent circuit model*

with a spiral strip line monopole is represented by the series resonant circuit. In the parallel resonant circuit, C_p and C_{pe} are the internal and external capacitance, respectively. R_p and R_{se} denote the radiation resistance, and n is the turn ratio determined by electromagnetic coupling between the two monopoles.

Suppose that the space between the shorted disk and the ground plane is a free space, the values for C_p and C_{pe} can be acquired using the following equations [6, 15]

$$C_p = \frac{\varepsilon_o(\pi\rho^2)}{h} \tag{1}$$

$$C_{pe} = \varepsilon_o\rho\left[8 + \frac{2}{3}\ln\left\{\frac{1 + 0.8(\rho/h)^2 + (0.31\rho/h)^4}{1 + 0.9(\rho/h)}\right\}\right] \tag{2}$$

If we assume that the probe is a via, inductance L_p of the shorting pin can be obtained using the following equation [16]

$$L_p = \frac{\mu_o \times 10^9}{2\pi}\left[h \times \ln\left(\frac{h + \sqrt{(\phi_1/2)^2 + h^2}}{(\phi_1/2)}\right) + \frac{3}{2}\left(\left(\frac{\phi_1}{2}\right) - \sqrt{\left(\frac{\phi_1}{2}\right)^2 + h^2}\right)\right] \tag{3}$$

The probe with a spiral strip line can be modelled into an equivalent circuit of series RLC resonance circuit. Supposing that the spiral strip line is a straight strip line, inductance L_{strip} (nH) of the strip line can be obtained as follows [17]

$$L_{strip} = 2 \times 10^{-1} \times l_s \times \left[\ln\left(\frac{l_s}{w_s}\right) + 1.193 + 0.2235\left(\frac{w_s}{l_s}\right)\right] \times K_g \tag{4}$$

where

$$K_g = 0.57 - 0.145 \times \ln\left(\frac{w_s}{h_f}\right) \tag{5}$$

In addition, inductance L_{probe} (nH) of the probe can be calculated as follows

$$L_{probe} = \frac{\mu_o \times 10^9}{2\pi}\left[h_f \times \ln\left(\frac{h_f + \sqrt{(\phi_1/2)^2 + h_f^2}}{(\phi_1/2)}\right) + \frac{3}{2}\left(\left(\frac{\phi_1}{2}\right) - \sqrt{\left(\frac{\phi_1}{2}\right)^2 + h_f^2}\right)\right] \tag{6}$$

Therefore, total inductance L_{se} of the probe and the spiral strip line can be represented as the sum of L_{strip} and L_{probe}

$$L_{se} = L_{strip} + L_{probe} \tag{7}$$

The initial value of the parallel capacitance of the shorted disk can be determined by means of (1) and (2) and the series inductance of the probe with a spiral strip line can be determined using (7). However, the initial designing equations leave some matters, such as the variation of the dielectric constant of the substrates, and a coupling effect between the probe with a spiral strip line and the shorted disk, out of consideration. Therefore because it is difficult to draw an accurate result from only these equations, optimisation of the antenna through the EM simulation has been performed.

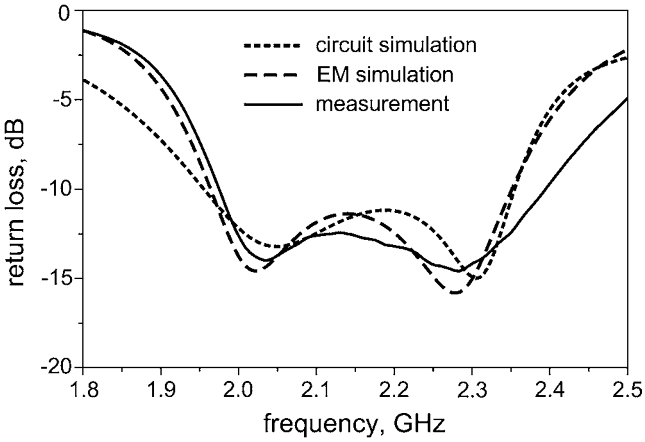

Fig. 7 *Return loss of the circular disk-loaded monopole antenna*

4 Measured results

Based on the parametric study in Section 2 with the circuit model interpretation in Section 3, we optimised the design parameters by using the EM simulator. Fig. 7 shows the return loss of the optimised circular disk monopole antenna. The design parameters of the antenna are provided in Table 1. The antenna was fabricated on a ground plane with the size of 50 × 50 mm^2, and the measurement was carried out by using an HP8510C network analyser. The measured results match well with the EM simulation as well as the equivalent circuit model results. The measured impedance bandwidth for VSWR < 2 is from 1.97 to 2.40 GHz, which is $\simeq$19.7% at the centre frequency of 2.185 GHz.

Figs. 8 and 9 plot the measured radiation patterns for the proposed antenna at 2.0 and 2.3 GHz, respectively. Both co- and cross-polarised components of the electric fields are plotted. The radiation pattern is observed to be nearly that of a conventional monopole antenna with good omni-directional characteristics in the azimuth plane. The cross-polarised component is mainly produced by the spiral strip line. The measured gain of the antenna is 1.55 and 2.5 dBi with a maximum value of $\simeq \theta = 45^\circ$ at 2.0 and 2.3 GHz, respectively. The average gain within the bandwidth is $\simeq$2.01 dBi.

Fig. 10 shows the measured efficiency of the antennas. Efficiency is an important concern in the design of

Table 1: Design parameters of the optimised circular disk-loaded monopole antenna

	Parameter	Size, mm
Shorted circular disk	ρ	5.5
	h	11.0
	ϕ_1	1.6
Probe with circular spiral strip line	w_s	0.4
	a	1.3
	ϕ_2	0.86
	l_s	31.5
	h_f	8.0
	d	3.4

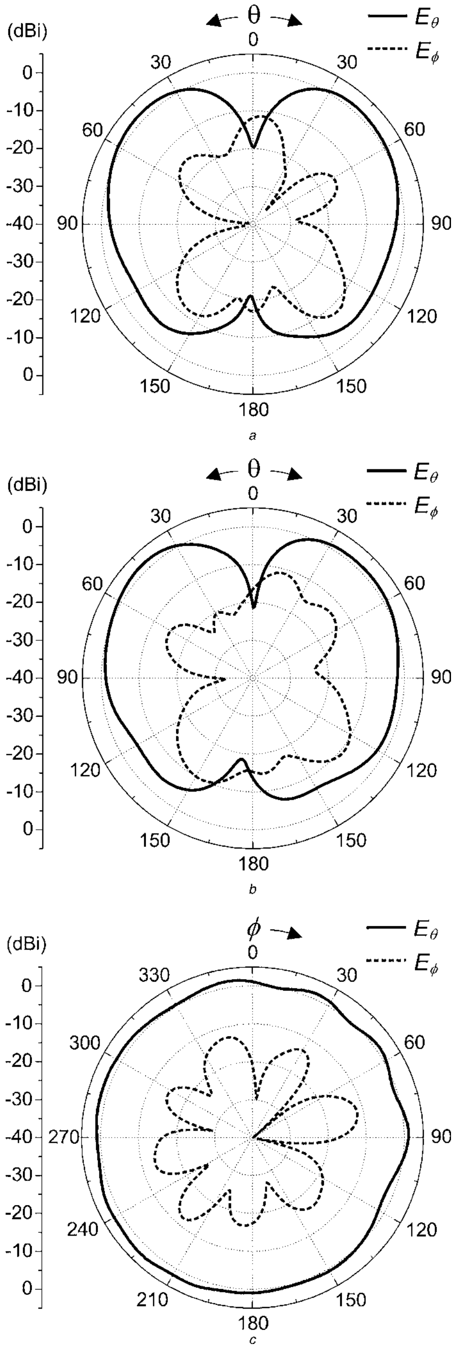

Fig. 8 *Measured antenna radiation pattern at 2.0 GHz*
a xz-plane ($\phi = 0^\circ$)
b yz-plane ($\phi = 90^\circ$)
c xy-plane ($\theta = 45^\circ$)

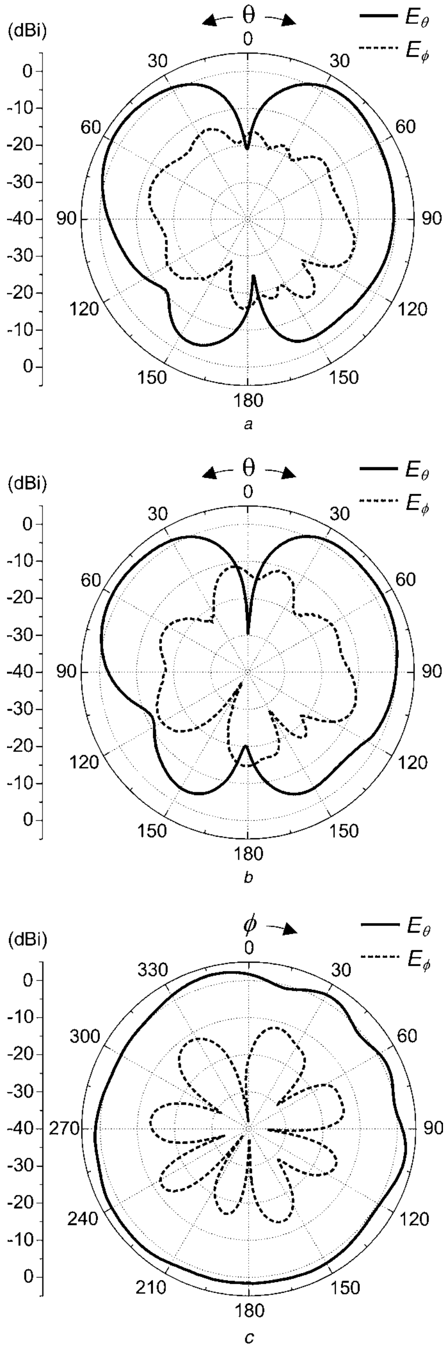

Fig. 9 *Measured antenna radiation pattern at 2.3 GHz*
a xz-plane ($\phi = 0^\circ$)
b yz-plane ($\phi = 90^\circ$)
c xy-plane ($\theta = 45^\circ$)

electrically small antennas. The Wheeler cap method is the standard method of measuring the efficiency of a small antenna [18, 19]. As stated in [7], the Wheeler cap method can obtain accurate efficiency in simple series or parallel RLC circuits, so this method is not strictly applicable to the proposed antenna. However, the measured efficiency should be valid near the centre band where the reactance is near zero. The measured efficiency of the circular disk-loaded antennas is 98% at its centre band region.

5 Conclusions

A small broadband antenna consisting of a disk-loaded monopole and a spiral strip line-loaded monopole is presented in this paper. The proposed antenna was able to control the resonance frequency by varying the capacitance and inductance of the two monopoles. Broad bandwidth was achieved through an electromagnetic coupling between these two monopoles which is able to generate two resonances spaced closely together in frequency. The circular disk antenna fits within $kr = 0.563$. Although the electrical dimensions of antennas are very small, the measured impedance bandwidth of the circular disk-loaded monopole antenna is 430 MHz (VSWR < 2) with the centre frequency at 2.185 GHz. It shows that the antenna has good measured efficiency of 98% around its centre band. In addition, the antenna has good omni-directional radiation characteristics and the gain of the antenna is >1.55 dBi within the entire bandwidth.

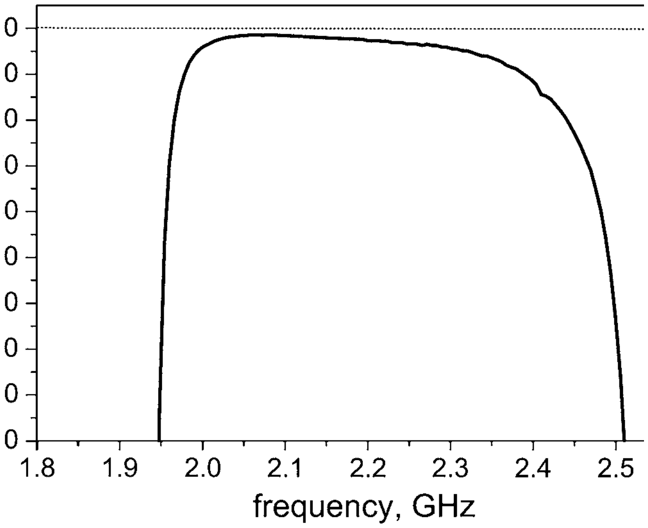

Fig. 10 *Measured efficiency against frequency for the proposed antenna using the Wheeler cap method*

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