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REGULAR ARTICLE

Analysis of a Low-Profile Electrically Small Circular Slotted Circular Patch Antenna for Bluetooth Applications

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A low-profile, electrically small circular slotted circular patch antenna is designed and analysed for bluetooth applications that utilises the frequency range of 2.4 GHz. This antenna has a microstrip feed line and a pair of circular slots configured as DGS. This patch antenna overcomes the impedance matching problem by using two circular slots as DGS. Miniaturization and optimal impedance matching are achieved through proximity to the microstrip input line. The FR4 substrate used for the antenna simulation has a thickness of 1.6 mm, ε_r of 4.4 and tanδ of 0.02. An antenna's basic structure consists of a feeding line that is connected to the antenna to provide 50 Ω impedance matching. This antenna resonates at 2.40 GHz and is one of the smallest electrically compact ones, having overall dimensions of 24 × 24 × 1.6 mm^3. At 2.40 GHz, a bandwidth of 2.43 GHz to 2.38 GHz was attained with a VSWR of 1.23 and an S_{11} of – 28.8 dB. To reduce the size of ESA and accomplish efficient impedance matching, the proposed antenna uses two circular slots as DGS. The advantages of the proposed antenna include its small size, simple design and simplicity of integration into small devices. These results make the circular slotted circular patch antenna appropriate for Bluetooth applications.

Keywords: Circular slotted circular patch ESA, DGS, HFSS, Compact size, Metamaterial (MM).

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1. INTRODUCTION

The research of electrically small antennas (ESAs) has attracted a lot of attention lately due to the growing demand for wireless communications, small electronic devices, and sensor networks. ESAs offer benefits such as compact size, simple design and seamless integration into miniature devices; yet they exhibit low radiation resistance and high reactance owing to their limited 'λ' value [1]. Two techniques have been employed to enhance the impedance matching of ESAs. Using matching networks is one method [1-4], although in this case, the entire structure, including the antenna and matching circuit, is usually not ESA. An alternate technique that is more beneficial than matching networks is to modify the antenna structure. Ziolkowski and Erentok [5] suggested using antennas inspired by MMs. To maximize matching at the resonant frequency and achieve high radiation efficiency without the need of a matching network, the MM-inspired ESA's basic concept is to position a single MM unit-cell adjacent to the driven element and utilize its characteristics [5-8]. The NFRP element serves as the primary radiating element of the antenna at its operating frequency. The 2.4 GHz frequency spectrum is utilised in wireless communication systems [9-10]. The physical limitations of ESAs for omni directional antennas are elaborated in [11]. Another MM-inspired ESA with two different substrates and a novel feeding method was presented by the authors in [12]. At 2.4 GHz, bandwidth of the ESA was 0.5 GHz. ESAs are suggested in [13]. Metallic curved strips are used in the best design to improve performance. The simulation results showed a bandwidth of 22.4 MHz with an impedance of – 10 dB. In [14], a low-profile CPW-fed ESA were first presented. Bandwidth has been improved to 0.2 GHz by the addition of chip inductors to the antenna.

The novel ESA proposed in this article is intended to operate at 2.4 GHz. To reduce the size of ESA and accomplish efficient impedance matching, the proposed antenna uses two circular slots as DGS. The advantages of the proposed antenna include its small size, simple design and simplicity of integration into small devices. It is a good option for small wireless devices because of these qualities.

2. DESIGN METHADOLOGY AND GEOMETRY

An ESA is designed by employing a circular patch. The antenna also has a rectangular bar attached to it, and the two are connected by an impedance of $Z_0 = 50$ Ω. The FR4 substrate used for the antenna simulation has a thickness of 1.6 mm, ε_r of 4.4 and tanδ of 0.02. An antenna's basic structure consists of a feeding line that is connected to the antenna to provide 50 Ω impedance

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matching. The FEM and MOM are used in HFSS V13 to simulate this circular slotted ESA. Because the ground plane is intended to be DGS, a positive gain value beneath the substrate is made possible. This circular slotted antenna is appropriate for Bluetooth applications since it demonstrates resonance at 2.4 GHz. The dimensions are much smaller in compared to other ESAs available in the literature. The circular slotted ESA's top and bottom surfaces are depicted in Figure 1. Higher return loss values are achieved by this structure's ability to resonate at the designated frequencies.

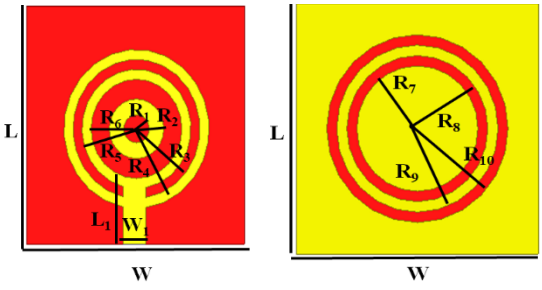
$$L = \frac{C}{2F_r\sqrt{\varepsilon_{reff}}} - 2\Delta l \quad (1)$$

$$a = \frac{F}{\sqrt{1+\frac{2h}{\Pi\varepsilon_r}\left[\ln\left(\frac{\Pi f_r}{2h}\right)+1.7726\right]}} \quad (2)$$

$$F = \frac{8.791*10^9}{f_r\sqrt{\varepsilon_r}} \quad (3)$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+\left[\frac{12h}{w}\right]\right]^{-1/2} \quad (4)$$

In the circular patch, 'a' stands for the radius, which is found using equation (2), and 'L' stands for the patch's length, which is acquired using (1). The variable 'h' indicates the material's thickness. F is generated from the application of equation (2). f_r stands for the substrate's centre frequency.



(a) (b)

Fig. 1 – Circular-slotted ESA (a) Top surface (b) Bottom surface

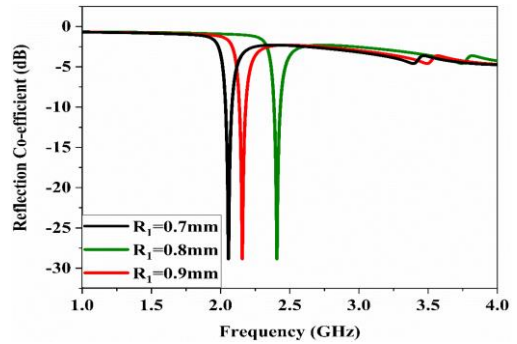
Table 1 – Measurements of circular-slotted ESA

Parameter	Values(mm)
L	24
W	24
L_1	2.5
W_1	5.7
L_2	4.5
R_1	0.8
R_2	1.4
R_3	7
R_4	6
R_5	5
R_6	3
R_7	6
R_8	7
R_9	8
R_{10}	9

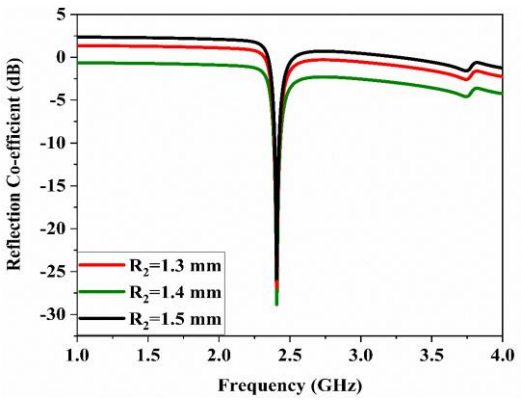
A circular slot generates the capacitance effect, whereas the rectangular bar improves an antenna's capacity to work efficiently. The European Space Agency (ESA) is primarily concerned with impedance matching due to the antenna's minuscule size, which results in low radiation and high reactance. Capacitance and inductance are provided by this circular slot and this rectangular bar, respectively. By varying the size of the rectangular bar and the circular slot, the antennas can achieve various resonance frequencies.

3. PARAMETRIC ANALYSIS OF THE CIRCULAR SLOTTED ESA

This parametric analysis is essential because it offers a thorough summary of the antenna's properties, allowing for a more thorough comprehension of the parameters related to ESAs. The software program An-soft HFSS, which is based on the FEM analysis, was utilised to carry out the evaluation. A comprehensive parametric examination of the geometrical properties of the circular slotted ESA is typically required to achieve the best possible performance from ESAs. Two separate graphs that show the performance of the circular slotted ESA by altering the radius of R_1 and R_2 in millimetres (mm) are shown in Figure 2 (a). The various coloured curves illustrate different values of reflection coefficient. The black solid line corresponds to R_1 = 0.7 mm, green solid line signifies R_1 = 0.8 mm and the black solid line represents R_1 = 0.9 mm. Significant reflection coefficient is observed at approximately 2.4 GHz. Among all the alternatives, with R_1 = 0.8 mm, the structure demonstrates optimal performance at 2.4 GHz achieving – 28.8 dB making the circular slotted ESA suitable for Bluetooth applications.



(a)



(b)

Fig. 2 – Parametric analysis of the circular-slotted ESA (a) By varying R_1 (b) By varying R_2

Figure 2 (b) demonstrates the execution of parametric

analysis through the variation of R_2 parameter, with values adjusted from 1.3 mm to 1.5 mm. Reflection coefficient improves by varying R_2. Best performance of the circular slotted ESA is observed at $R_1 = 0.8$ mm and $R_2 = 1.4$ mm.

4. RESULTS AND DISCUSSION

Figure 3 presents simulated S_{11} for a compact circular slotted ESA at 2.4 GHz. At 2.4 GHz the circular slotted ESA offers a return loss of – 28.8 dB. The circular slotted ESA provides a bandwidth for return loss below – 10dB, specifically ranging from 2.43 GHz-2.38 GHz. VSWR, which represents the ratio of power transmitted from the antenna's source to the load, is generally expected to be below 2. It is generally accepted that any antenna should maintain a VSWR of less than 2, which can be precisely characterized as the power transmitted from the antenna's source to the load. Figure 4 presents VSWR for a compact circular slotted ESA at 2.4 GHz. The VSWR of the circular slotted ESA is measured to be less than 2, specifically at 1.23. Fig. 5 illustrate the radiation pattern of the circular slotted ESA. Analyzing this pattern allows us to draw the conclusion that the antenna exhibits a bidirectional radiation pattern at a resonating frequency of 2.4 GHz at different values of θ and Φ by considering co-polarization and cross-polarization of the antenna. Figure 6 illustrates the total gain of the circular slotted ESA, with maximum value of 1.8 dBi at 2.4 GHz. The distribution of the *E*-Field for the circular slotted ESA is illustrated in Fig. 7. Maximum value of 400 vm^{-1} has been observed. The current distribution of the circular slotted ESA is shown in Fig. 8. The maximum field distribution is represented by the colour red. Maximum value of 50 Am^{-1} has been observed at 2.4 GHz. The distribution of surface currents on the antenna is crucial

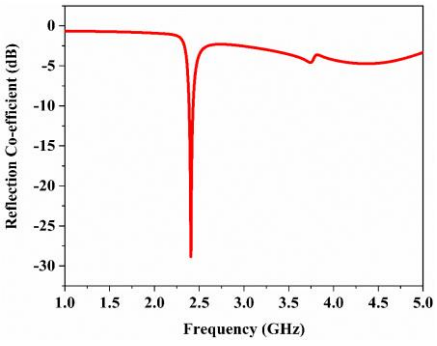


Fig. 3 – Reflection Co-efficient of the circular-slotted ESA

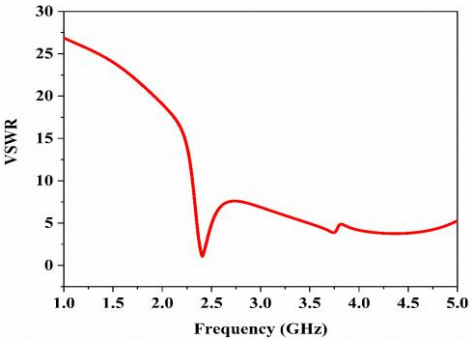


Fig. 4 – VSWR of the circular-slotted ESA

for determining the regions of radiation, with red colour signifying the areas of maximum radiation intensity. Both the antenna's centre and its edges exhibit the maximum radiation levels, as shown in Figure 8.

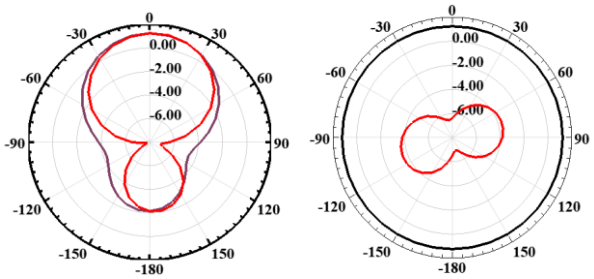


Fig. 5 – Radiation pattern of the circular-slotted ESA (a) *E*-plane, (b) *H*-plane

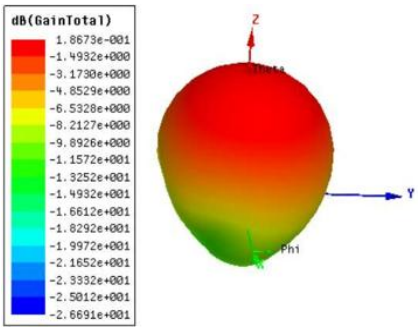


Fig. 6 – Gain of the circular-slotted ESA

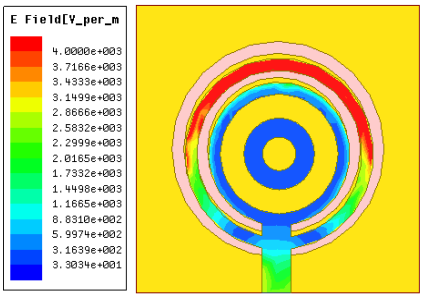


Fig. 7 – *E*-field distribution of the circular-slotted ESA

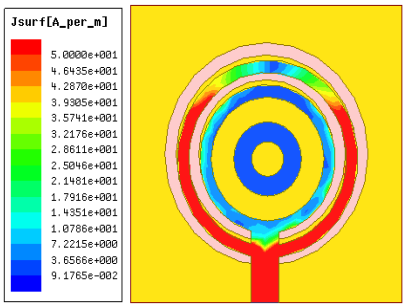


Fig. 8 – Circular-slotted ESAs Surface current distribution

As shown in Table 3, the antenna's performance is compared to the antennas reported in references [13-18]. In ESAs, bandwidth and gain are traded off. Gain, bandwidth and antenna size have all been carefully balanced in the suggested antenna. The suggested ESA offers positive gain and is distinguished by its small size and low profile. The PCB method is an effective way to design it and it is composed of a single layer.

Table 2 – Comparison table for circular-slotted ESA

Ref	Overall Size (λ_0)	Resonant Frequency	Number of Layers	Antenna Height (λ_0)	Gain (dB)
[13]	0.2010 × 0.061	0.58	Single layer	0.003	– 2.4
[14]	0.062 × 0.118	2.36	Single layer	0.024	– 1.9
[15]	0.08 × 0.0479	2.4	Single layer	0.012	– 1.9
[16]	0.05 × 0.05	0.5	Six layers	0.02	≈ – 2.1
[17]	0.1 × 0.06	2.42	Single layer	0.0080	– 8.72
[18]	≈ 0.10 × 0.10	2.45	Single layer	0.013	– 15.40
This Paper	0.192 × 0.192	2.4	Single layer	0.012	1.8

5. CONCLUSION

Circular slotted ESA at 2.4 GHz is designed and proposed. This antenna consists of two circular slots in the ground plane and a microstrip feed line. With total measurements of 24 × 24 × 1.6 mm^3 (0.192 × 0.192 × 0.0128 λ_0^3), this antenna is one of the smallest ESA at 2.4 GHz, where it is intended to resonate. The performance of the antenna is analysed both analytically and practically. It might be a great option for upcoming small wireless systems that need a performance-enhancing, simplified ESA configuration.

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Аналіз низькопрофільної електрично малої кільцевої щілинної антени з круглим випромінювачем для застосувань у системі Bluetooth

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Розроблено та проаналізовано низькопрофільну, електрично компактну мікросмужкову антену з круглими щілинами, призначену для систем Bluetooth, що працюють у частотному діапазоні 2,4 ГГц. Антена містить мікросмужкову лінію живлення та пару круглих щілин, реалізованих як дефектна структура заземлювальної площини (DGS). Використання цих двох круглих щілин (DGS) дозволяє вирішити проблему узгодження імпедансу. Мініатюризація та оптимальне узгодження імпедансу досягаються завдяки розташуванню щілин поблизу вхідної мікросмужкової лінії. Для моделювання антени використано підкладку FR4 товщиною 1,6 мм із діелектричною проникністю ε_r = 4,4 та тангенсом кута діелектричних втрат tanδ = 0,02. Основна конструкція антени включає лінію живлення, під'єднану таким чином, щоб забезпечити узгодження імпедансу на рівні 50 Ом. Антена резонує на частоті 2,40 ГГц і є однією з найбільш електрично компактних; її габаритні розміри становлять 24 × 24 × 1,6 мм^3. На частоті 2,40 ГГц досягнуто робочої смуги частот (від 2,38 ГГц до 2,43 ГГц) із коефіцієнтом стоячої хвилі (КСВ) 1,23 та рівнем відбиття S_{11} = – 28,8 дБ. Для зменшення розмірів електрично компактної антени та забезпечення ефективного узгодження імпедансу в запропонованій конструкції застосовано дві круглі щілини (DGS). Перевагами цієї антени є малі розміри, проста конструкція та легкість інтеграції в малогабаритні пристрої. Завдяки таким характеристикам мікросмужкова антена з круглими щілинами добре підходить для використання в системах Bluetooth.

Ключові слова: Кругова мікросмужкова антена (патч-антена) із кільцевими щілинами, DGS, HFSS, Компактний розмір, Метаматеріал (ММ).