Design Apollonian Gasket Antenna for Millimeter-Wave Applications

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Abstract. Fractal geometry has been widely adopted in the design of various antennas for a wide variety of communications applications. The proposed antenna design is based on fractal geometry of second iterations Apollonian Gasket. This type of fractal can produce an antenna that is miniaturized and multiband. The proposed antenna design built using the FR-4 AS substrate with 4.4 and a loss tangent of 0.002 with a thickness of 1.2 mm. The results show that the proposed antenna offers multiband that suitable for the indoor wireless environment and millimeter-wave applications with high gains and bandwidth enhancement. This antenna also gives good radiation patterns for multiband. Modeling and performance evaluation of the proposed antenna has carried out using CST Microwave Studio (CST MWS).

Keywords. Fractal, Fractal Antenna, Millimeter Wave, Microstrip Antenna

1. Introduction
The evolution in wireless communications necessitated the use of antennas appropriate to this development, such as millimeter-wave communication. The millimeter-wave section of the electromagnetic spectrum is generally known as the frequency band (30- to 300-GHz) or the wavelength range (1-cm to 1-mm). Use this EM spectrum region for advanced wireless communication has a numeral advantage such as large bandwidth for highly secure and high data rate communication. The short-wavelength permits high directivity antennas with rational size. That leads to being suitable for high-resolution radar and compact system. Millimeter waves can propagate over challenging weather environments and be extra easily than an optical wave. Finally, the millimeter-wave system's transmitter and receiver are suitable for integration with the RF system for more consistent, lightweight, and low-cost. The matching between different techniques to obtain a more effective and high-performance antenna to serve the user requirements. One of these techniques is the use of fractal geometry in antenna design for miniaturization and multiband and is the most critical requirement for any millimeter-wave system. A microstrip antenna has some advantages like small size, wide bandwidth impedance, lightweight in [1],[2]. Besides these properties, the microstrip antenna often suffers from narrow bandwidth. To overcome these drawbacks, slot structures with different shapes have been used to design a microstrip antenna with a wideband and broadband concept [3]. Fractal antennas are a perfect solution for advanced communication systems that required...
antennas with wideband and minimal dimensions as compared with traditional antennas. One of the most advantages of fractal geometry is size reduction and multiband characteristics. There are different techniques used in antenna research to minimize antenna size and obtain multiband characteristics in a microstrip patch. In [3], designing two wearable RFID textile tag antennas depended on two types of fractal geometry gained. A fractal antenna using double E shaped slots cut out DGS proposed in [4]. In [5], a doubled band of microstrip patch antenna depended on David fractal geometry for GSM, and WiMAX applications presented. A 40GHz super wideband antenna utilized a novel fractal geometry to a wire monopole and wire square loop antenna offered in [6 - 9]. In [10], an octagonal fractal microstrip patch antenna for super wideband applications offered. A new fractal Sierpinski antenna with a multiband behavior over five bands presented in [11]. A survey of different techniques to reduce wire and patch antenna-using fractals given in [12]. The definitive antenna topology gained by the collection of Koch fractal geometry, meandering slits, and defected ground structure, to realize a new hybrid construction with compact footprint, perfect structural conformability, and improved impedance bandwidth with a center frequency at 2.45GHz to work in the Industrial, Scientific, and Medical (ISM) bands presented in [13].

In [14], an ultra-wideband fractal antenna for 5G applications was proposed. In [15], a snowflake as the structure completed utilizing star-shaped fractal geometry applied for a super wideband microstrip antenna for 5G communication presented. Bow Tie multiband antenna with the circular arm and two orbicular slots in the ground plane for satellite applications proposed in [16]. A new Koch microstrip patch antenna is presented in [17]. In [18], a Yagi-Uda fractal antenna for wireless Local Area Network (WLAN) applications was proposed. In [19], fractal antenna arrays analyzed on multi-input multi-output (MIMO) radars for their applicability proposed. The fractal MIMO concepts presented are used to improve angular resolution and reduce the sidelobe's level for a given number of transmitting and receiving antennas. [20] proposed a CPW-fed Apollonian Gasket Fractal (AGF) antenna laden with a Tri-mode Electric Ring Resonator [TERR] to apply multiple frequency bands. In [21], a new fractal antenna in star-shaped form for multiband applications was demonstrated. In [22], Inscribed Fibonacci Circle Fractal in a given circular radiator for size reduction and ultra-wideband antenna operation presented. [23] proposed a novel planar circular Apollonian fractal-shaped UWB monopole antenna with band-rejection capability. In [24], the Fast design of multiband fractal antennas for NB-IoT applications by the system-by-design approach presented. In this paper, a high gain printed circular patch Apollonian Gasket fractal slot antenna has been presented for millimeter-wave wireless communication requirements. The slot structure of the proposed antenna was designed by applying the Apollonian Gasket fractal on the radiator. The antenna has fed with a 50Ω coaxial probe.

2. Apollonian gasket fractal geometry

An Apollonian Gasket is a type of fractal consist of a chain of circles overlapping inside one large circle and tangent to all others close. These are also called "Kissing Circles" or "Soddy Circles."

An Apollonian Gasket created by the following procedure, [25]:

1. Start withdrawing a large circle.
2. Within the circle that all touch one another. It tangent to one side.
3. In the gaps between these circles, draw smaller circles that are as large as possible without overlapping any nearby circles.
4. Continue in this way, filling each new gap with a large circle that will fit without overlap.

Whole integral Apollonian gasket shapes may calculate utilizing an unpretentious. Diophantine quadratic equation with constraints. When $A$, $g$, $n$, $\mu \in \mathbb{N}$ that are solutions to quadratic equation, [26],

$$A^2 + \mu^2 = gn$$

with constraints

$$0 \leq \mu \leq \frac{A}{\sqrt{2}}$$

$$2\mu \leq g \leq n$$
Each solution to (1) matches to an Apollonian gasket for the next quintet of the major bends (curvatures):

\[ (A_0, A_1, A_2, A_3, A_4) = (-A, A + g, A + n, A + g + n - 2\mu, A + g + n + 2\mu) \]

Remember that 4 pairwise tangent circles which be in the Descartes configuration. Assume e, f, h and j are curvatures of that 4 circles. Then, the Descartes circle formula can be:

\[ (e^2 + f^2 + h^2 + j^2) = (e + f + h + j)^2 \]  \hspace{1cm} (2)

This formula is utilized to obtain the curvature of the 4th circle j, given the first three, because it is a quadratic equation, it produces two solutions, like \( j_1 \) and \( j_2 \) like that:

\[ j_1 + j_2 = 2(e + f + h) \]  \hspace{1cm} (3)

The Boyd dual is a name that called to the circles \( j_1 \) and \( j_2 \). This article produced an Apollonian window \((-1, 2, 2, 3, 3)\), as shown in Figure (1), with a radius of the largest circle is 2.75mm. The radius of 2 next large circles is 1.375mm. Finally, the radius of the two last circles is 0.6875mm.

![Figure 1. Apollonian window with labels.](image)

Figure (2) shows the initial, first, and the second iteration of the Apollonian Gasket fractal. There is no well-defined measurement for an Apollonian Gasket because it is only approximately self-similar.

![Figure 2. Different iteration stages of Apollonian Gasket fractal (a) 0th iteration, (b) first iteration, and (c) second iteration.](image)

3. Design antenna

In this paper, a microstrip circular-shaped patch antenna will be designed based on the second iteration Apollonian Gasket fractal geometry as it is applied on the edges of the radiator, as shown in Figure (3). The initial iterated level antenna consists of a circle patch, with a radius of 1.375 mm as shown in Figure (2a), and then it is divided into two smaller congruent circles where the open central circle is dropped \((n=1)\) as shown in Figure (2b). The remaining circles are divided into two smaller congruent circles which each central circle is dropped \((n=2)\), as shown in Figure (2c). The antenna printed on an FR-4 substrate with a dimension of \((W_s \times L_s)\) and thickness \(h=1.2\) mm with relative permittivity of \(\varepsilon_r=(4.4)\) and loss tangent of 0.002. A ground plane with dimensions of \((W_g \times L_g)\) is designed on the other side of the substrate. A coaxial probe technique feeds the patch, placed at the point \((1.25, -1)\). Table (1) summarizes the dimensions of the modelled.
4. Results and discussion
According to the fractal iterations level, it is evident that the resulting structures have an increasing number of sub-slots, which therefore increase the corresponding lengths of radiating edge. This leads considerably to become smaller and smaller in the resultant antenna. Furthermore, the geometric similarity of the resulting structure makes the equivalent antenna more possible. Results of the proposed Apollonian Gasket fractal antenna with a given substrate for 0th, 1st, and 2nd iterations in terms of return loss, gain, and bandwidth is simulated and discussed in this section. The geometry for 0th iteration of proposed antenna (shown in Figure (2a)) is done by take a whole circle of radius $R_1$. Simulated return loss ($S_{11}$) curve of 0th iteration antenna is shown in Figure 4. The result shows that the antenna exhibit single band behavior resonates at 40.373 GHz with reflection coefficient $S_{11}$ -24 dB for a frequency range of (30-50) GHz.

![Figure 3. Structure of the proposed fractal antenna](image)

**Figure 3.** Structure of the proposed fractal antenna (a) front view, (b) side view.

**Table 1.** Summary of the modeled antenna dimensions in (mm).

| Variable | dimensions (mm) |
|----------|-----------------|
| $L_g$    | 6               |
| $W_g$    | 6               |
| $L_s$    | 6               |
| $W_s$    | 6               |
| $R_1$    | 2               |
| $R_2$    | 1.375           |
| $R_3$    | 0.6875          |
| $t$      | 0.035           |

To obtain the 1ST iteration of the proposed antenna, cut two circle slot of radius $R_2$, as shown in Figure (2b). The simulated return loss of the 1st iteration exhibits dual-band with resonance...
frequencies at 37.197 GHz and 44.42 GHz, as shown in Figure 5. By applying fractal geometry to the antenna making the matching gets enhanced and multiband fractal properties.

Finally, the 2nd iteration of the proposed fractal antenna by cutting two more circle slots of the 0th iteration with radius R3. Simulation results show that the proposed antenna offers quad bands resonant frequencies. A multiband resonant frequency is resonated at 31.52 GHz, 36.681 GHz, 39.261 GHz, and 44.712 GHz, as shown in Figure 6. For the second iteration, antenna input return loss (S11) is about (-15 dB to -37 dB), as shown in Figure 6. The lower and middle bands are suitable for wireless indoor environment requirements, while the upper band is used for millimeter-wave applications to satisfy the 5G mobile communication and radar system requirements.

Due to a multiband property and a good impedance matching, the proposed antenna behaves like a right radiator at all the resonant frequencies. Table 2 shows the proposed antenna bandwidth for a different number of iterations. The results show that the antenna has a bandwidth enhancement when the number of ideations is increased.
Table 2. The bandwidth of the proposed dual-band fractal antenna

| Iteration No. | Resonance Frequency (GHz) | Bandwidth (GHz) |
|---------------|---------------------------|-----------------|
| 0th           | 40.373                    | 2.54            |
| 1st           | 37.197                    | 2.17            |
|               | 44.42                     | 5.27            |
| 2nd           | 31.52GHz                  | 0.395           |
|               | 36.681                    | 3.099           |
|               | 39.261                    | 1.526           |
|               | 44.712                    | 2.211           |

Figure 7 illustrates the 3D gain of the proposed 2nd iteration fractal antenna. The gain of the first lower band (31.52GHz GHz) has a 6.06 dB value, as shown in Figure (7a), while the gain at the center frequency of the second lower band (36.681GHz) has a 6.49 dB value, as peak gain value shown in Figure (7b). The middle band of the center frequency (39.261 GHz) has 5.79 dB as shown in Figure (7c). Finally, the upper band at (44.712 GHz) has a gain value of 6.42 dB as shown in Figure (7d). The antenna can provide a directional antenna with a desirable gain value that makes it responsible for being operated in millimeter-wave applications from the gain results.

Figure 7. 3D gain of the 3rd iteration fractal antenna. (a) at 31.522 (b) at 36.681GHz (c) at 39.261 GHz (d) at 44.712 GHz.
5. Conclusion
In this paper, the 2nd iteration Apollonian Gasket fractal antenna with A coaxial probe technique feeding has been proposed. The presented antenna has offered a multiband performance, making it suitable for covering millimeter-wave applications that covered a broad area in wireless communication services. The antenna results show that the antenna provides a directional property with an enhancement in the bandwidth and radiation characteristics.

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