process can be found with more details in Ref. [10]. A photo of the filter is shown in Figure 3, and its experimental results are shown in Figure 4. The weight of the filter without connectors and screws for the lid is 57 g which is only 13% of the weight of an equivalent copper filter (423 g).

The results show an excellent agreement between simulated and measured frequency responses. There has been no tuning of the filter. The expanded view of $S_{21}$ parameter shown in Figure 4(a) exhibits a maximum insertion loss of about 0.23 dB for the simulation, and about 0.31 dB for the experimental results. This corresponds to resonator $Q$ values of 2873 and 2131, respectively. The degradation of $Q$ is because of the additional insertion loss of the connectors and the nonperfect copper. It can also be seen in the frequency responses presented in Figures 4(a) and (b), that there is a small frequency shift. It is about 12 MHz and can be accounted for by the differences between the designed filter dimensions and the fabricated filter ones. Comparison between the dimensions can be found in Table 1.

4. CONCLUSION

This article has demonstrated the first 3-D printed filter in the low GHz frequency range. The 3% bandwidth filter centered at 3 GHz shows an excellent S-parameter response with no tuning. The filter is made using specialized stereolithographic printing resulting in a very high dimensional accuracy structure. The advantages of making the filter by 3-D printing are clear, with the lightweight being particularly striking. However, the advantages of producing a complex structure quickly and with continuous metalization in high current areas are also of importance. Such filters can be relevant not only for prototyping but also in satellite applications where weight is important. Clearly integration of more complex structures in such applications is of great interest.

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The majority of the ultrahigh frequency near-field RFID reader antenna designs are based on the theory that try to ensure the current along with the loop sharing same phase and direction by the means of adding various capacitors. For example, in 2007, Dobkin et al. proposed a segmented loop antenna, with a diameter of 10 cm demonstrated desirable performance at 915 MHz, consists of a series of metal line sections and numbers of capacitors shaping a loop [3]. In Ref. [6], double-C shaped distributed capacitors. In 2013, Shi et al. presented a dual loop antenna composed of a main and a parasitic loop which both are constructed using segmented lines with fork-shaped capacitors [11]. And then, they proposed a grid-array antenna composed of two segment loops to enlarge the interrogation zone [10].

The major challenge with design of a near-field UHF antenna is how to cover an electrically-large but still near-field region with strong and uniform magnetic field distribution. In this article, we propose a near-field UHF RFID reader antenna based on Koch fractal structure. By optimizing the fractal structure, reading nulls should be avoided in the entire covered near-field region. Outside the restricted near-field region, the field strength or the read area should decrease as fast as possible so that a more precise position of the RFID tag can be located.

2. KOCH FRACTAL CONFIGURATION

Basic Koch fractal structure is depicted in Figure 1(a). For the need of designing near-field UHF RFID reader antenna, we modified the Koch fractal structure properly. As depicted in Figure 1(b), the modified Koch fractal can be defined by four variable namely a (mm), b (mm), N (recursive total number), and z. And the direction of one fractal structure of each line segment is changed, which can make the Koch curve more flexible and homogeneous to fill the space. At the same time, to lessen the chance of structure overlapping in the antenna optimization process, as the recursive total number (N) increases each time, only the lines generated in last fractal process will be replaced by fractal curves.

The advantages of using Koch fractal structure for UHF RFID reader antenna lie in its self-similarity and filling-ability. Due to the self-similarity, the four parameters can build a model.

When the Koch fractal is used as a UHF antenna due to the travelling-wave current on the fractal, radiation will occur at each turn of fractal structure. Therefore, by properly designing the fractal geometry, uniform near-field coverage can be acquired over the area covered by the Koch fractal.

As an antenna, Koch fractal can be fed either from the center as shown in Figure 2(a), or from the side as shown in

![Figure 2 Koch fractal antenna (a) fed from the center, (b) fed from the side](image)

Figure 2(b). For the side-fed structure, it is quite convenient to enlarge the near-field coverage area by forming networks.

3. KOCH FRACTAL NEAR-FIELD ANTENNA DESIGN

Filling ability is another feather that help facilitating the structure uniformity of the interrogation zone. In this study, to acquire a square interrogation zone, the modified Koch fractal transformation is applied to every side of a square with a perimeter of approximately 2λ at 915 MHz (viz., the size of the antenna is 160 mm × 160 mm).

The combination of model code and 4NEC2’s source code contributes to the rapid optimization and good results [12]. In this simulation, only one parameter is kept unchanged, while three parameters are varied at a time. In the code, ranges of the three parameters have been set. When the process is on, the figures of these ranges could be optimized. It is illustrated that the good results will be found as long as the boundary conditions problems being settled.

The objective functions for impedance matching ($f_1$) and magnetic field distribution ($f_2$) are defined as

$$f_1 = \frac{10}{|S_{11}(\text{dB})|},$$

$$f_2 = \frac{1}{\text{amp}}.$$
where $S_{11}$ means return loss at 915 MHz, $H_z$ represents $z$-component of magnetic field to be designed for uniform coverage, $\Omega$ represents the area to be covered in near-field region.

3.1. Center-Fed Koch-Fractal Antenna
First, we consider a center-fed Koch-Fractal Antenna covering a near-field square. The model of the antenna is shown in Figure 2(a).

Figure 3 shows the layout of optimized center-fed Koch-fractal antenna ($x = 68.45$, $a = 53.6$ mm, $b = 80$ mm, ratio $= a/b = 0.67$) and the current distribution. Figure 4 shows the distribution of amplitude of $z$-component of magnetic field, $|H_z| (A/m)$, in dB on the $xy$-plane of $z = 30$ mm. And the dynamic range of $|H_z|$ is measured to be less than 3.5 dB in the whole interrogation zone ($0 \leq x \leq 160$ mm, $0 \leq y \leq 160$ mm). Dynamic range of 3.5 dB indicates a quite satisfactory uniform coverage, which is superior to the results acquired in the present UHF near-field RFID reader antennas.

Figure 5 shows the simulated return loss at 915 MHz. It is observed that the optimized center-fed Koch-fractal antenna has a satisfactory input impedance matching over frequency band 904–930 MHz.

3.2. Side-Fed Koch-Fractal Antenna
However, in practical application, multiple RFID reader antennas may work together to enlarge the interrogation zone or realize hierarchical and regional position. In these cases, side-feeding should be adopted to facilitate placing and feeding antennas. Therefore, we consider a side-fed Koch-fractal antenna as shown in Figure 2(b).

Figure 6 shows the layout of optimized side-fed Koch-fractal antenna ($x = 54.28$, $a = 32.8$ mm, $b = 80$ mm, ratio $= a/b = 0.41$) and the current distribution. Figure 7 shows the distribution of amplitude of $z$-component of magnetic field, $|H_z| (A/m)$, in dB on the $xy$-plane of $z = 30$ mm. From Figure 7, it is measured that the dynamic range of $|H_z|$ is within $3$ dB in the whole interrogation zone ($0 \leq x \leq 160$ mm, $0 \leq y \leq 160$ mm).

Figure 8 illustrates the simulated return loss at 915 MHz. It is found that the optimized Koch-fractal antenna has a satisfactory input impedance matching over frequency band 909–920 MHz.

In conclusion, by applying modified Koch-fractal structures, the UHF RFID antenna can provide perfect impedance matching, as generating magnetic field distribution being more uniform than that of traditional near-field UHF loop antennas.
That is because the filling ability of modified Koch fractal structure can help antenna improve the structure uniformity. And owing to the Koch fractal structure’s self-similarity, a model of the antenna is built to optimize Koch fractal structures to acquire optimized current distribution, which can generate magnetic field in interrogation zone as uniform as possible.

4. FABRICATION AND TEST

Prototype of the designed side-fed Koch-fractal antenna is fabricated using copper wires on a paper board, as shown in Figure 9. The paper board has dimensions of $190 \times 190$ mm, thickness of 3.5 mm, and dielectric constant of $\varepsilon_r = 2.5$. At the feeding port, an SMA connector of 50 $\Omega$ input impedance is directly connected to the two ends of the feeding copper wire of the antenna, as shown in the zoomed picture in Figure 9.

The impedance matching of the prototype was measured using Agilent E5230A vector network analyzer. The simulated and measured return loss of the antenna plotted in Figure 10, show good agreement.

To verify the near-field coverage performance, the prototype of designed side-fed Koch-fractal antenna is applied to detect a single reference tag. In the detection setup shown in Figure 11, the antenna prototype is connected to Alien ALR 9900+ RFID reader, which may operate over 902–928 MHz RFID band with an output power of 24 dBm. Impinj button type near-field UHF tag, J41, with a loop-like antenna of diameter of 12 mm, is taken as reference tag.

As shown in Figure 11(a), a single J41 tag is supported by a square Styrofoam plate with dimension of $160 \times 160 \times 15$ mm and $\varepsilon_r = 1.11$. On the Styrofoam plate, local coordinates is set and the Styrofoam plate is gridded for easy positioning of the tag on the $xy$-plane. By raising the plate to different height, and deploying the reference tag at different coordinates in turn on the square Styrofoam, face-to-face to the Koch-fractal reader antenna, the coordinates (active grids) at which the reference tag can be interrogated by the RFID reader can be measured. And then by further analyzing the distribution of active grids, the near-field coverage performance of antenna prototype can be evaluated.

Figure 8 Return loss of the side-fed Koch fractal antenna

Figure 9 Photo of the side-fed Koch-fractal antenna prototype. [Color figure can be viewed at wileyonlinelibrary.com]

Figure 10 Simulated and measured return loss of the side-fed Koch-fractal antenna

Figure 11 (a) Near-field RFID measurement setup and (b) reference tag. [Color figure can be viewed at wileyonlinelibrary.com]

Figure 12 Measured reading rate against reading distance ($d$) of the side-fed Koch-fractal antenna prototype
can help facilitating the structure uniformity of the interrogation zone. And then due to the self-similarity, fractal structures’ parameters can be used to build a model, which combined with 4NEC2’s source code to obtain excellent results rapidly.

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A MODIFIED GAUSS-NEWTON ALGORITHM FOR FAST MICROWAVE IMAGING USING NEAR-FIELD PROBES

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ABSTRACT: In this work, effort has been made to reduce the reconstruction time of microwave tomographic images using the conventional Gauss-Newton (GN) algorithm. As the forward scattering solution takes the most percentage of the total time, a modification to the GN algorithm by employing a Taylor series approximation of the forward problem is proposed. This helps to avoid the time consuming forward scattering solution required in each iteration, as such, the image reconstruction time is only limited by the time of the algebraic calculations involving matrices and vectors. Moreover, unlike most other works, in this paper, the imaging domain along with the actual transceivers are