A RFID Tag Antenna Design Based on Sierpinski Fractal Structure

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Abstract: Based on Sierpinski fractal structure, a design of a loaded inductive loop monopole antenna at 2.45 GHz for RFID applications is described in the present paper. Two measures have been adopted to miniaturize the volume of tag antenna. One is Sierpinski fractal technology; the other is mirror image method. To realize flexibly impedance conjugate matching between IC chip and tag antenna, the match loop is introduced and loaded to the main tag antenna. Return loss of the designed antenna approaches to −29.6 dB at 2.45 GHz. Its bandwidth (S11<=−10 dB) is 2.41 GHz~2.50 GHz, and the relative bandwidth reaches to 3.7%. Its input impedance is (28.3+j200.9) Ω that is close to conjugate value of the supposed IC chip input impedance of (30−j200) Ω. Simulation results demonstrate that the designed antenna exhibits good performances and can meet RFID application requirements entirely.

Keywords: RFID, Tag Antenna, Sierpinski Fractal, Inductive Loop

1. INTRODUCTION

Radio-frequency identification (RFID) which emerged in the 1990s is an automatic identification technology. It uses a wireless wave to exchange data, for the purposes of automatically identifying and tracking tags attached to objects in a non-contact manner. With the rapid development of industrial automation and Internet of Things (IoT), RFID technology has attracted much attention and is gaining great progress recently. Lots of practical applications can be found in various areas, like distribution logistics, electronic toll collection, animal tracking, and intelligent transportation systems [1-4]. Usually, RFIDs can be classified by the operating frequency of system. They worked in low-frequency (LF), high-frequency (HF), and ultra-high frequency (UHF) and microwave frequency bands (especially 2.45 GHz and 5.8 GHz), respectively [4]. Generally the higher the operating frequency is, the longer is the read rang and the higher is data transmission speed. Therefore RFID systems show the growing trend to design higher frequency [5-7]. In our work the operating frequency is 2.45 GHz.

A RFID system uses tags, or labels attached to the objects to be identified. The tags contain at least two parts: an integrated circuit (IC chip) and an antenna for receiving and transmitting the signal [8, 9]. The antenna plays an important role in transferring data, and therefore the design of high performance tag antenna becomes a most challenging task in RFID system [7]. The design requirements of tag antenna are becoming increasingly rigorous with the more popular applications of RFID. Nowadays the trend to miniaturize tag antenna is likely to continue for the purpose of concealing or embedding in other items conveniently [10-12].

There are many approaches to miniaturize tag antenna. One of them is based on a fractal theory and technology. The fractal owns the characteristics of self-similarity and space self-filling ability. If they are applied to antenna areas, the former can make an antenna has the multiband property and the latter can miniaturize the size of an antenna [13]. For the purpose of miniaturizing tag antenna, the Sierpinski fractal theory and technique [14, 15] are employed in the present paper. In addition, the input impedance of tag antenna has to be a complex conjugate of that of IC chip for maximum power transfer [2, 16]. However the IC chips made from different manufacturers have the different input impedances. Usually the input impedance of tag antenna needs to be adjusted flexibly to conjugate match that of the IC chip, owing to a big and costly investment in design and manufacturing a new IC chip. To conquer this problem, an inductive loop is introduced and loaded to the main antenna in our work. Numerical results demonstrate that the value of input impedance of the designed antenna can be varied easily through tuning the parameters of inductive loop. The relevant performances of tag antenna designed in the present paper are calculated by HFSS. And the results show that the designed antenna can satisfy the requirements of practical RFID applications. The rest of this paper is organized as follows. The design and analysis of tag antenna are described in Section II, involving fractal theory and Sierpinski fractal structure, Sierpinski fractal monopole antenna (SFMA), simulation results, and impedance analyses. A brief summary is given in the last Section III.

2. ANTENNA DESIGN AND ANALYSIS

2.1. Fractal Theory and Sierpinski Fractal Structure

The concept of fractal was originally coined by Mandelbrot in 1975 [17]. It implies broken or irregular fragments and can thus be used to characterize a family of complicated forms which own an inherent self-similarity in their geometrical structure [13]. From then on many well-known and significant fractals have been constructed successively, such as Koch fractal [18], Minkowski fractal [19, 20], Hilbert fractal [21, 22], and Sierpinski triangle fractal [23, 24], as shown in Fig. (1). It can be observed that fractals are typically self-similar patterns, and may be exactly the same at every scale, or, nearly the same at different scales. In the present paper, we are only concerned on Sierpinski fractal structures. There are three

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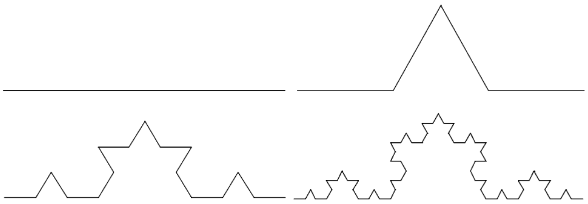
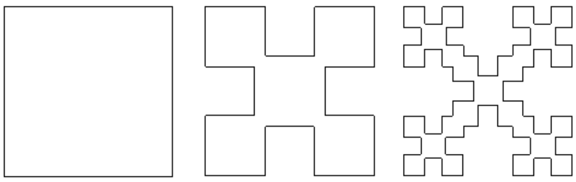
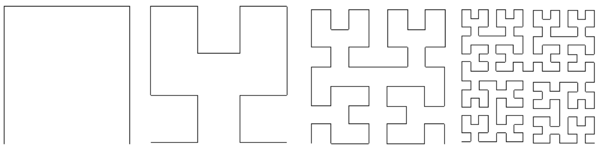
kinds of Sierpinski fractal structures, i.e., Sierpinski triangle, Sierpinski carpet and Sierpinski curve. It is named after the Polish mathematician Wacław Sierpiński for his outstanding contribution. The Sierpinski triangle may be constructed from an equilateral triangle by repeated removal of triangular subsets: (1) Start with an equilateral triangle; (2) Subdivide it into four smaller congruent equilateral triangles and remove the central one; (3) Repeat step 2 with each of the remaining smaller triangles. The fractal dimension of Sierpinski triangle may be calculated by: $D = \log 3/\log 2 = 1.58$.



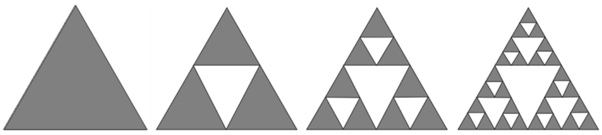
(a) 0～4 order Koch fractal



(b) 0～3 order Minkowski fractal



(c) 0～4 order Hilbert fractal



(d) 0～4 order Sierpinski triangle fractal

Fig. (1). Geometries of fractals

2.2. Sierpinski Fractal Monopole Antenna (SFMA)

Fractals have found lots of important and significant applications in many fields of science and engineering [13]. One such application is to analyze and design fractal antennas, in which fractal geometry is combined with electromagnetic theory in order to develop a new class of antennas which are multi-band and/or compact in size [25], such as Koch fractal antenna [18], Minkowski fractal antenna [20], and Hilbert fractal antenna [26]. Similarly, Sierpinski fractals have been exploited to design an innovative antenna. For example, Sierpinski triangle fractal is used to construct a dipole antenna with the dimensions of 88 mm×48.6 mm and the read range of 5.9 m for RFID application [27]. In article [28] the authors design a tie knot antenna based on Sierpinski triangle fractal. It works at UHF bands of 915 MHz and its size is around 96 mm×48 mm. This antenna is improved by [29], in which the capacitive loading technique is utilized to tune the input impedance of tag antenna for conjugate matching to that of the IC chip. The antenna designed in ref. [29] has the sizes of 96 mm×54 mm and the input impedance of (22+j195) Ω. Other Sierpinski fractal antennas can be found in refs. [30, 31].

In this paper we propose a novel monopole antenna based on Sierpinski triangle fractal, named as Sierpinski fractal monopole antenna (SFMA), as illustrated in Fig. (2). The proposed antenna is composed of three parts, a two-order Sierpinski triangle fractal used as radiation arm, a match circuit with inductive loop (see Fig. (3)), and a ground plate. The monopole antenna can produce the equivalent performances of dipole antenna by using the mirror image effect of the ground plate. Moreover, its dimensions are much smaller than the dipole one. This is helpful to miniaturize the sizes of tag antenna. The epoxy_Kevlar is selected as substrate material in our design. Its relative dielectric constant is $\varepsilon_r = 3.6$ and loss tangent is $\tan\delta = 0$. The total sizes of the substrate are 24.9 mm×23.2 mm×1 mm. They satisfy entirely the requirements of miniature antenna. In order to construct antenna model conveniently, the height and width of the smallest triangle in radiation arm are taken as L and 2×W, respectively. H is the substrate height. R represents the ratio of the half width W to height L and is used to adjust the form of smallest triangle. Table 1 gives the sizes of the designed SFMA.

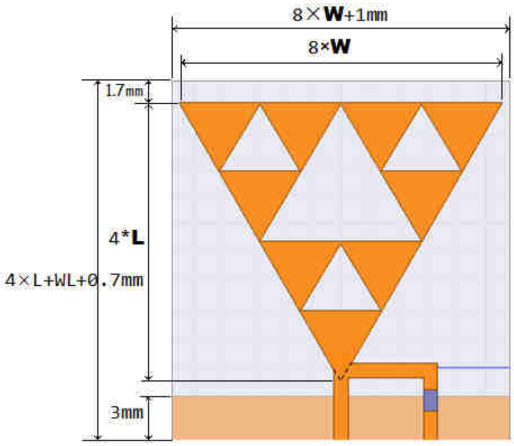


Fig. (2). Configuration of the SFMA.

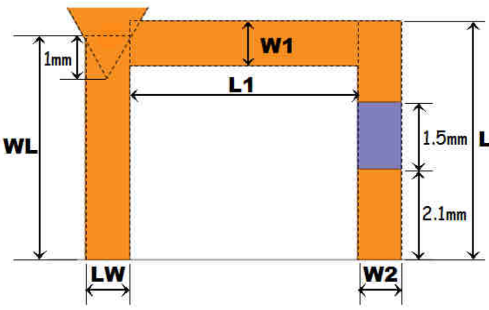


Fig. (3). Match circuit

Table 1 Parameters of the designed SFMA (mm)

Parameter	L	W	H	R	WL	LW	L1	W1	L2	W2
Value	4.8	R×L	1	0.577	5	1	5.2	1	5.3	1

2.3. Simulation Results

The performances of the designed SFMA can be analyzed by HFSS. The 3D simulation model of SFMA in HFSS is shown in Fig. (4). The return loss S11 as a function of frequency is plotted in Fig. (5). It can be seen from Fig. (5) that the resonating frequency point is just located at the expect value of 2.45 GHz. The value of return loss is S11=–29.5999 dB and the operating bandwidth (S11<=–10 dB) is about 90 MHz (2.41~2.50 GHz), which meets the bandwidth demand of RFID tag applications. Fig. (6) depicts the input impedance of SFMA. One can find that the input impedance of designed antenna is inductive strongly due to the loaded inductive loop. The input impedance at 2.45 GHz is Ztag=(28.3460+j200.9991) Ω, which is near to conjugate value of the supposed IC chip input impedance of Zchip=(30–j200) Ω. This means an excellent match between the IC chip and the SFMA. The simulated 3D gain pattern is illustrated in Fig. (7). It can be seen distinctly that the maximum total gain is Gtotal=2.0408 dB and closely locates in Y-Z plane. Obviously it is an omnidirectional antenna. Fig. (8) presents the 2D radiation patterns of SFMA. The maximum gain in Y-Z plane is Gy-z=2.0325 dB, which is a little smaller than the maximum total gain Gtotal.

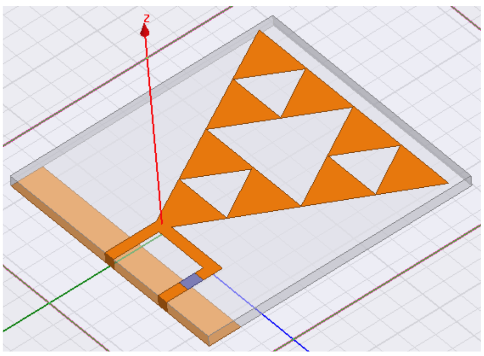


Fig. (4). Simulation model of SFMA in HFSS

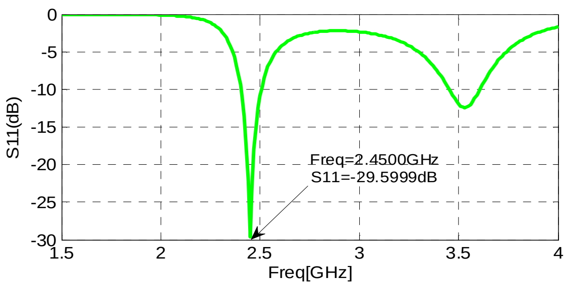


Fig. (5). Return loss S11 of SFMA versus frequency

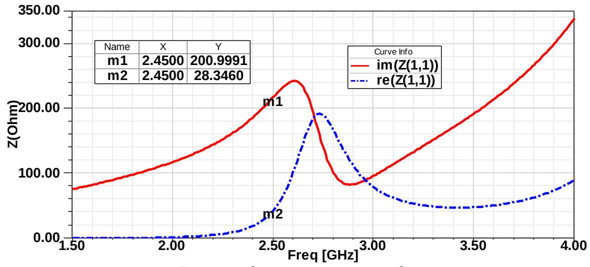


Fig. (6). Input impedance of SFMA versus frequency

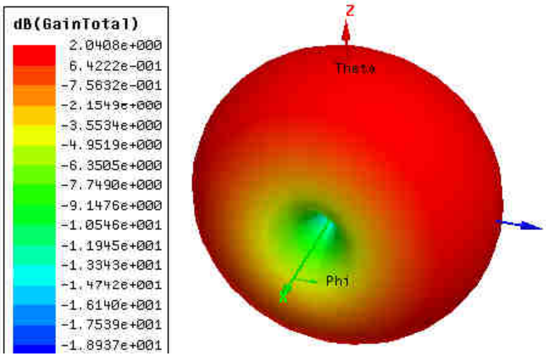


Fig. (7). Simulated 3D gain pattern

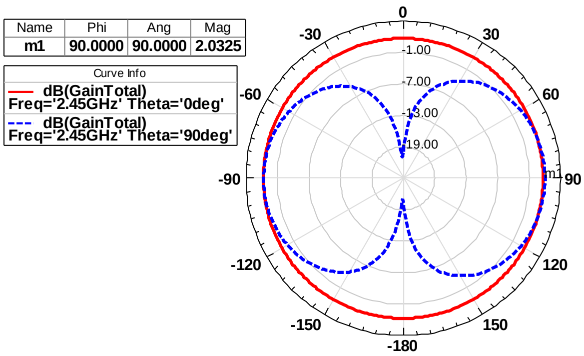


Fig. (8). 2D radiation patterns in X-Y and Y-Z plane

The maximum read range is considered as the most important tag performance characteristic [2]. The tag read range for the far field passive RFID system can be calculated from two ways: one is a data link from reader to tag; and the other data link is from tag to reader. Usually, the reader is more sensitive when compared with the tag. Therefore the read range is mainly determined by the tag antenna. If the IC chip is more sensitive and its threshold voltage is lower, it means that the less power is necessary to active this IC chip. The Friis free-space formula can be employed to compute the read range and defined as [2]:

$$R_{\max} = \frac{\lambda}{4\times\pi}\sqrt{\frac{P_t G_t G_r \tau \rho}{P_{th}}} \qquad (1)$$

where λ is the wavelength, P_t denotes the power transmitted by the reader, P_{th} represents the minimum threshold power necessary to active the IC chip, G_t and G_r mark the gains of the read and the tag antennas, respectively. τ and ρ are the power transmission factor and mismatch factor, respectively. Now let us estimate the maximum read range. λ =0.1224 m at f =2.45 GHz. Referring to the practical reader antenna, we get P_t =1 W and G_t =8 dB=6.3096 W. Under the condition of polarization match and maximum radiated direction, τ and ρ can reach to 1. The typical value of threshold power is P_{th} =–8~–20 dBm, and in our calculation we take the average value P_{th} =–14 dBm=0.0398 mW. From Fig. (7) one can get G_r =2.0408 dB=1.5999 W. Substituting above values into Eq. 1, we obtain readily R_{max} =4.9067 m.

2.4. Impedance Analyses

As mentioned above, the suitable impedance match between the IC chip and tag antenna is extremely important in RFID system. Consequently, the influences of designed antenna parameters on input impedance should be investigated. First the effect of substrate height H on input impedance is examined, as showed in Fig. (9). Both the real and imaginary parts of input impedance rise with the increase of substrate height H. Moreover the rising amplitudes of them are almost identical. The main radiation sides of the proposed antenna are triangle waists. And thus the triangle waists have an important influence on input impedance. Fig. (10) depicts the influence of height L of the smallest triangle on input impedance. It can be seen that the real and imaginary elements increase slowly. This is because the waist change is little when height L varies. Parameter R (=W/L) determines the shape of the SFMA. Fig. (11) illustrates the influence of ratio R on input impedance. One can observe that within the scope of 0.4~0.7 the input impedance increases, but at the range of 0.7~0.8 the real part grows successively and the imaginary reduces, when the ratio R rises. The input reactance and resistance as a function of frequency are displayed in Figs. (12) and (13), respectively. If L remains unchanged, as the ratio R grows larger, the width of triangle grows wider and the radiation side grows longer. This leads to decrease the value of frequency corresponding to the maximum of reactance and resistance. Within the range of 0.6~0.7, there exits a peak value of reactance. One can also change the input resistance by tuning the ratio R, because the resistance is quite heavily influenced by the ratio R.

Last we study the effect of inductive loop on input impedance. The inductive loop proposed in our work can be considered as the deformation of T-shape match circuit. The parameters relevant to the loop are LW, WL, L1, L2, W1 and W2 (see Fig. (3)). Figs. (14)~(19) depict the influences of these parameters on input impedances, respectively. The parameter LW determines the width of connected line between radiated body and ground plate. So it has a great influence on input impedance, as illustrated in Fig. (14). The input impedance decreases greatly as the parameter LW increases. However we can find from Fig. (15) that the input impedance is not almost affected by the parameter LW. When the parameters L1 and L2 raise and thus the circumferences of the loop grow larger, the values of input reactance exhibit the great rising trend and yet the quantities of input resistance increase slowly. As the parameter W1 increases and the empty part in match loop become smaller, the input impedance decreases heavily. However the input impedance rises slowly when increasing the parameter W2 and hence the area of match loop.

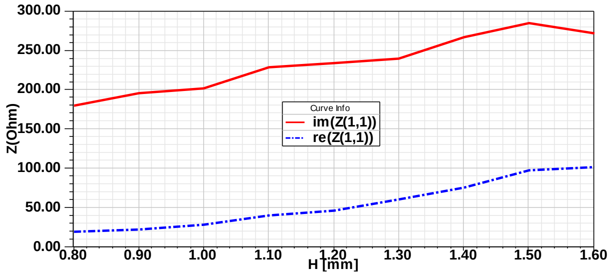


Fig. (9). Influence of substrate height H on input impedance

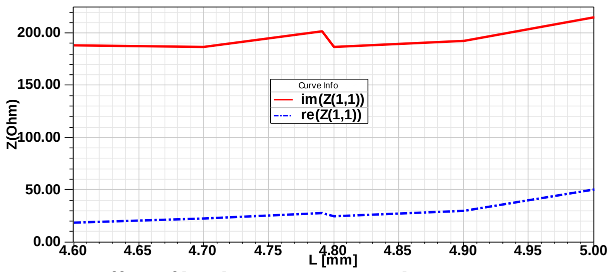


Fig. (10). Effect of height L on input impedance

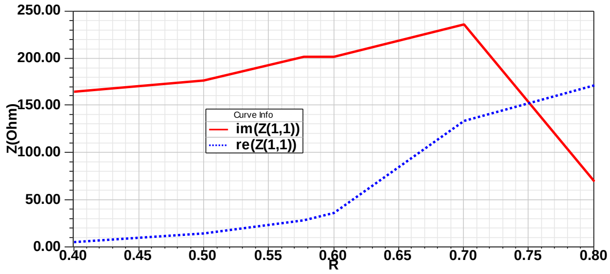


Fig. (11). Effect of ratio R on input impedance

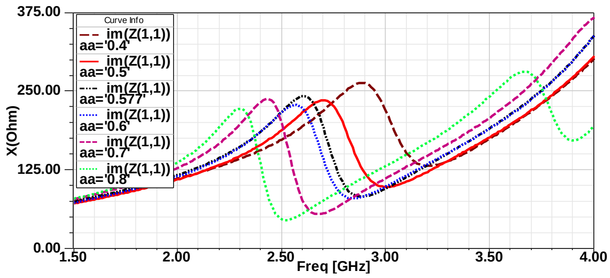


Fig. (12). Influence of ratio R on input reactance

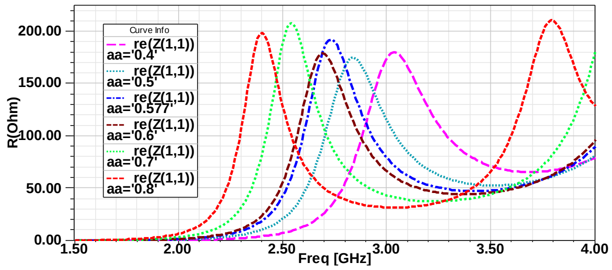


Fig. (13). Influence of ratio R on input resistance

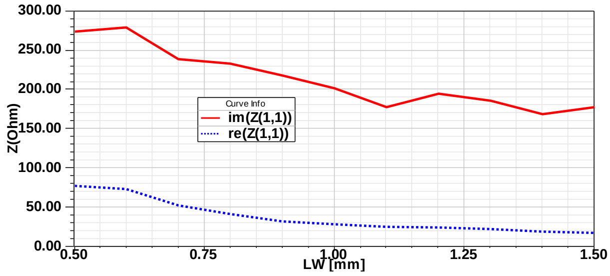


Fig. (14). Effect of parameter LW on input impedance

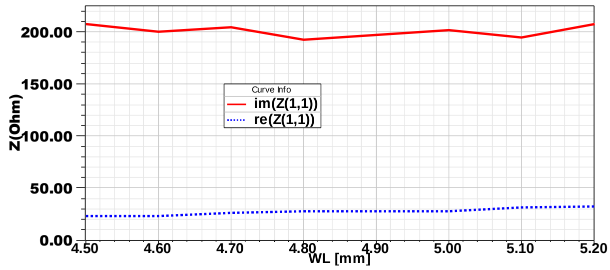


Fig. (15). Influence of parameter WL on input impedance

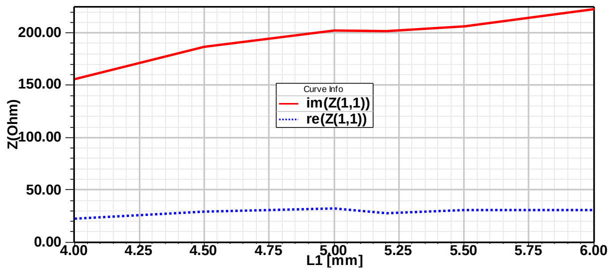


Fig. (16). Effect of parameter L1 on input impedance

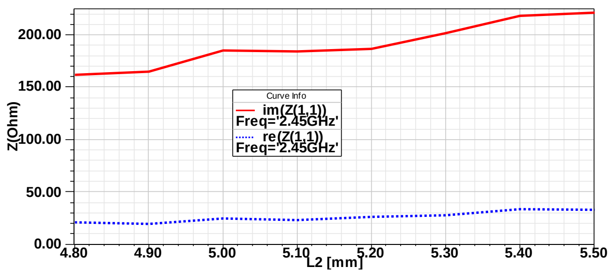


Fig. (17). Influence of parameter L2 on input impedance

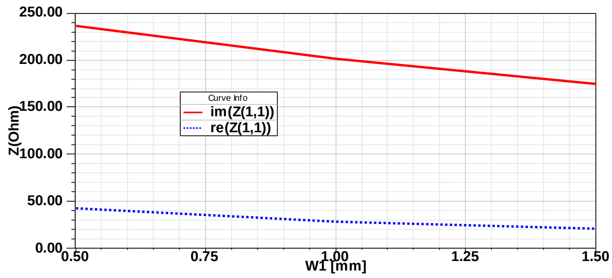


Fig. (18). Effect of parameter W1 on input impedance

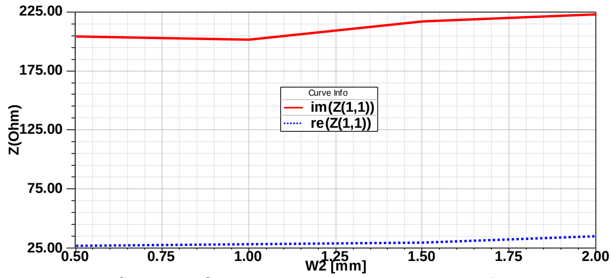


Fig. (19). Influence of parameter W2 on input impedance

3. SUMMARY

In the present paper, we have successfully designed a RFID tag antenna operating frequency of 2.45 GHz. The Sierpinski fractal and mirror image technologies are employed to miniaturize the sizes of tag antenna. Additionally a loaded inductive loop is introduced to achieve impedance conjugate matching between tag antenna and IC chip. It is known through the above analyses that the loaded inductive loop has a great influence on input resistance and input reactance. Consequently, by tuning the parameters of match loop, the input impedance of the proposed SFMA can be adjusted flexibly and broadly to conjugate match with the different IC chips. The designed SFMA can find its applications in logistics and electronic toll collection.

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