A Study on Antenna with Characteristics of Insensitive to Metal for Installation in Proximity to Two Metal Walls

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Abstract. In order to achieve a near-metal-insensitive antenna for closed space wireless communications, the impedance characteristics of folded monopole antennas (FMA) are of intense interest. The characteristics of a near-metal-insensitive antenna are basically not influenced by proximate objects, especially metal. This paper investigates the antenna characteristics when the antenna approaches metal plates in multiple directions to replicate an actual use environment. The results allow us to develop a higher impedance model that yields greater antenna performance than the conventional middle impedance model.

Keywords: Antenna, Metal plate, Folded monopole antenna

1. Introduction

The research and development of wireless communication technologies are advancing rapidly, not only for open space applications, but also for closed space applications [1, 2, 3]. Radio wave propagation and electric field distributions are more complicated in closed spaces than in open spaces, and further research is needed to achieve novel applications in the latter. Of particular note, antenna characteristics are a significant issue in closed space wireless communication. It is known that the antenna characteristics are strongly influenced by proximate objects (especially metal), so near-metal-insensitive antennas are essential for closed space wireless communications [4]. This problem was targeted in a previous study that examined multiple antennas and switched among the antenna elements in an effort to increase robustness against proximate objects[5]. In [6], external circuits were considered as a means of changing the antenna characteristics to offset the influence of proximate objects. In [7], the radiation pattern is controlled so as to be less susceptible to the influence of a proximate ob-
ject from a specific direction. However, these methods create problems with antenna size, cost, and radiation pattern. Therefore, we design antennas using the high impedance method, which avoids these problems. We have already investigated the impedance characteristics when a metal plate approaches a folded monopole antenna (FMA) from one direction [8]. Moreover, we have proposed a higher impedance model (HIM) whose step up ratio is changed to improve robustness against proximate metal plates [9, 10]. In this paper, we confirm the effectiveness of the proposed method in the actual use environment shown in Fig. 1. The metal plate is taken to approach the antenna from multiple directions. This paper proceeds as follows. Section 2 discusses the antenna structure of FMA. Section 3 discusses the impedance characteristics and the optimum value of step up ratio in HIM. Section 4 discuss the characteristics of the FMA when metal plates approach from two directions. Finally, Section 5 summarizes this paper.

Figure 1: Two assumed installation scenarios

2. Antennas structures

The structure of the FMA investigated here is shown in Fig. 2. The antenna element consists of two parallel metal strips with widths $w_1$ and $w_2$. The two strips are short connected by metal strips with width $w_3$ and length $s$, on the same side. At the other side, one strip with width $w_1$ is connected to the ground plane and the other strip with width $w_2$ is connected to the feed point. Both metal joining strips have total length of $l + h$, and they are folded to realize a low profile antenna with height $h$. The antenna element is placed on the ground plane to replicate the expected construction arrangement. Therefore, considering the mounting space and the layout flexibility of electronic components, the placement of the antenna elements is preferably at the edge of the ground plane. The simulation assumes the antenna material is copper. The infinite plane of Fig. 2, which models a metal wall, is located parallel to the ground plane.
The distance between the ground plane and the infinite plane is defined as $d_z$. We examined the optimum mesh size for designing the antenna. Using the simulation model shown in Fig. 2, the mesh size was varied from $\lambda / 10$ to $\lambda / 30$, and the influence on the simulation result was confirmed. At this time, $d_z$ value was fixed to 0.01$\lambda$. As $\lambda / 10$ yielded different VSWR characteristics values from $\lambda / 20$ and $\lambda / 30$, and the mesh size does not affect antenna characteristics for sizes of $\lambda / 20$ or less, the mesh size was set to $\lambda / 20$ in this study.

**Figure 2: Structure of FMA**

3. **Impedance characteristics**

The impedance characteristics of the FMA are investigated in this chapter. We studied the models in which the metal plate approaches from one direction, the $-z$ direction. All calculations were performed on the electromagnetic simulator (Hyper Works FEKO 2017. 02). The antenna impedance can be changed by altering the step up ratio\[9\]. The input impedance of the FMA $Z$ is expressed by equation (1).

$$Z = (1 + a)^2 Z_m,$$

where $Z_m$ is impedance of the monopole antenna, and $(1+a)^2$ is the step up ratio. The $a$ value is given by (2) and (3).

$$a = \frac{\ln \left\{\frac{4c + 2\sqrt{2c^2 - \left(\frac{W_2}{2}\right)^2}}{2c^2 - \left(\frac{W_2}{2}\right)^2}\right\} - \ln(w_2)}{\ln \left\{\frac{4c + 2\sqrt{2c^2 - \left(\frac{W_1}{2}\right)^2}}{2c^2 - \left(\frac{W_1}{2}\right)^2}\right\} - \ln(w_1)}$$

$$c = \frac{\frac{w_1 + w_2}{2} + s}{2}, \quad (3)$$
where \( w_1, w_2, \) and \( s \) are as indicated in Fig. 2. The step up ratio is determined by \( w_1, w_2, \) and \( s \).

The simulation model is shown in Fig. 2. We define the model of step up ratio 4 as the middle impedance model (MIM). MIM yields a VSWR of 1.3 and input impedance of 37 Ω at 2.4 GHz, when there is no infinite plane. The high impedance model (HIM), on the other hand, makes the impedance increase with the step up ratio, see Table 1. We examined the optimal step up ratio value for HIM, which is defined as the one that minimizes \( d_z \) while achieving VSWR of 3 or less. The three stage design process is as follows. First, four step up ratio values about 2 to 5 times compared to the middle impedance model are designed. Second, the sum of \( w_1, w_2, \) and \( s \) is fixed to 3 mm. Third, the minimum value of \( w_2 \) is set to 0.2 mm. The parameters of the designed antennas are shown in Table 1. In the simulations, the \( d_z \) value was varied from 0.01\( \lambda \) to 1\( \lambda \), and the antenna characteristics were confirmed. The simulation results are shown in Fig. 3. The step up ratio of 12.7 yielded smaller VSWR value for \( d_z \geq 0.03\lambda \) than the ratio of 15.1. However, the minimum value of \( d_z \) that satisfies VSWR \( \leq 3 \) is smaller in step up ratio 15.1. The step up ratio of 21.5 attained the minimum value of \( d_z \) that satisfies VSWR \( \leq 3 \) for all HIM, but VSWR \( \geq 3 \) in the range of 0.04\( \lambda \) to 0.08\( \lambda \). Therefore, the step up ratio of 15.1 was chosen as the optimum value. The antenna with step up ratio of 15.1 has a VSWR of 2.4 and input impedance of 120 Ω at 2.4 GHz, when there is no infinite plane. The impedance characteristics of this antenna were investigated assuming that metal plates approached from two directions.

Table 1: Optimum antenna parameters for each step up ratio

<table>
<thead>
<tr>
<th>Step up ratio</th>
<th>4</th>
<th>7.8</th>
<th>12.7</th>
<th>15.1</th>
<th>21.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( w_1 ) [mm]</td>
<td>1</td>
<td>1.1</td>
<td>1.8</td>
<td>2</td>
<td>2.3</td>
</tr>
<tr>
<td>( w_2 ) [mm]</td>
<td>1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>( w_3 ) [mm]</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( l ) [mm]</td>
<td>27</td>
<td>26.8</td>
<td>26.8</td>
<td>26.8</td>
<td>26.8</td>
</tr>
<tr>
<td>( s ) [mm]</td>
<td>1</td>
<td>1.7</td>
<td>1</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>( h ) [mm]</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
4. Proximity effect of metal plates on multiple directions

The antenna characteristics of the FMA with optimized step up ratio of 15.1 when metal plates approach from two directions are determined. The simulation model assumes the following three patterns. First model assumes that the metal plates approach from the $-z$ direction and $-x$ direction. Second model has the metal plates approach from $-z$ direction and $-y$ direction. Third model has the metal walls approach from $-x$ direction and $-y$ direction. The simulations examine two models of MIM and HIM. The distance between the antenna and the metal plate is defined in the $x$ direction as $d_x$, in the $y$ direction as $d_y$, and in the $z$ direction is $d_z$, and the distance varies in the range of $0.01\lambda$ to $1\lambda$. Each metal plate is square with edge length of $2\lambda$.

The simulation results are presented as a two dimensional distribution map of VSWR value at each antenna position. The color of the distribution map represents the VSWR value. VSWR values of 3 or less in white, VSWR values larger than 3 in red. Hereafter we replaced the infinite plane with a finite metal plate. For that reason, prior to simulating the proximity effect of the metal plate, we determined the optimum mesh size of the metal plate using values from $\lambda/10$ to $\lambda/30$. Based on the results, the $d_z$ value was fixed to $0.01\lambda$. We confirmed that the mesh size does not affect antenna characteristics for $d_z$ values of $\lambda/20$ or less. Accordingly, the mesh size of the metal plate was set to $\lambda/20$ in this study.

4.1. Approach from $-x$ and $-z$ directions

The simulation model is shown Fig. 4. The metal plates approach from $-x$ and $-z$ directions. Installation position of the antenna is assumed to be well away from the $y$ axis plates. The metal $xz$ plane plates were not modeled in the simulation. Figure 5 shows the distribution map of the simulated VSWR values at each antenna position. Figure 5(a) and Fig. 5(b) show the results of MIM and HIM, respectively. Vertical axis is $d_x$, horizontal axis is $d_z$. The distribution maps show that VSWR does not deteriorate with changes in $d_z$. However, HIM yields a
larger area of VSWR values of 3 or less when $d_z$ is changed. The effect of metal plates approaching from the $-x$ direction and $-z$ direction was also investigated. The distance was varied in the range of $0.01\lambda$ to $1\lambda$. When the metal plates approached the antenna from the $-x$ direction, the input impedance decreased when $d_x$ was less than $0.1\lambda$. However, since the change in impedance was small, the VSWR distribution map basically shows no change. When the metal plate approached the antenna from the $-z$ direction, the simulation confirmed that a current opposite to the current flowing through the ground plane of the antenna flowed to the metal plate. Therefore, the VSWR deteriorated due to a decrease in the input resistance of the antenna.

![Figure 4: Simulation model (Approach from $-x$ and $-z$ directions)](image)

![Figure 5: Distribution maps of VSWR value](image)
4.2. Approach from $-y$ and $-z$ directions

Simulation model is shown Fig. 6. The metal plates approach from $-y$ and $-z$ directions. Installation position of the antenna is assumed to be is well away from the $x$ axis direction plates. The metal $yz$ plane plates were not modeled in the simulation. Figure 7 shows the distribution maps of the VSWR values at each antenna position. Figure 7(a) and Fig. 7(b) show the results for MIM and HIM, respectively. Vertical axis is $d_y$, horizontal axis is $d_z$. As a result of comparing distribution maps, HIM yields a smaller area of VSWR values of 3 or less for the change in $d_y$. However, HIM yields a larger area of VSWR values of 3 or less when $d_z$ is changed. Therefore, we investigated in detail the deterioration in VSWR characteristics as $d_y$ decreased. We simulated the metal plate approaching only in the $-y$ direction using $d_y$ values from $0.01\lambda$ to $1\lambda$. The Smith chart of the simulation results is shown in Fig. 8. The input impedance increases for $d_y$ values less than $0.2\lambda$ which is opposite the results predicted. However, we did confirm the increase in the capacitive component and the decrease in the current value. The causes of the impedance increase are considered to be as follows. First, as the metal plate approaches the antenna from the $-y$ direction, the capacitance component of the antenna increases. This increase causes a change in the input impedance of the antenna, and impedance mismatch occurs at the feeding point. Consequently, the power input to the antenna decreases. Furthermore, since the impedance is given as the ratio of voltage to current, the impedance increased due to the decrease in the current value.

Figure 6: Simulation model (Approach from $-y$ and $-z$ directions)
4.3. Approach from $-x$ and $-y$ directions

The simulation model is shown Fig. 9. The metal plates approached from $-x$ and $-y$ directions. Installation position of the antenna is assumed to be well away from $z$ axis plates. The metal $xy$ plane plates were not modeled in the simulation. Figure 10 shows the distribution maps of the VSWR values at each antenna position. Figure 10(a) and Fig. 10(b) show the results of MIM and HIM, respectively. Vertical axis is $d_z$, horizontal axis is $d_y$. VSWR did not deteriorate with the change in $d_y$. HIM yields a smaller area in which the VSWR value is 3 or
less when the \( d_y \) value changes. This deterioration in VSWR is for the same reason as discussed in Section 4.2. Further, deterioration in VSWR is suppressed in the area where \( d_x \) is 0.1\( \lambda \) or less, see Fig. 10(b). The discussion in Section 4.1 confirmed that the impedance decreases at \( d_x \) values of less than 0.1\( \lambda \). Therefore, the increase of impedance due to the change in \( d_y \) is canceled when \( d_x \) is less than 0.1\( \lambda \), which suppresses the deterioration in VSWR.

Figure 9: Simulation model (Approaches from \(-x\) and \(-z\) directions)

![Simulation model](image)

Figure 10: Distribution maps of VSWR value

(a) MIM

(b) HIM

Figure 10: Distribution maps of VSWR value
5. Conclusion

This paper confirmed the effectiveness of an FMA antenna designed using the high impedance method when the antenna approaches metal plates in multiple directions to replicate an actual use environment. The proposed antenna (HIM) offers a greater area in which the VSWR ≤ 3. The HIM is effective even if the metal plate approaches from multiple directions unless the wall is close to the −y direction.

References


