Low-Profile Wideband Antenna by Loading Oblique Short Elements to Trapezoidal Plate with Capacitance Disk

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Abstract. This paper proposes a low-profile wideband antenna composed of a capacitance disk, trapezoidal plate, and four oblique short elements. The characteristics of the proposed antenna are analyzed through simulation. The results demonstrate that the proposed antenna offers a low-profile and wideband performance. In addition, its radiation patterns are omnidirectional in horizontal plane. This antenna is prototyped, and the validity of the simulation is verified through measurements.

Keywords: Low-profile, Wideband, Antenna

1. Introduction

The monopole antenna is widely used because its radiation pattern is omnidirectional with vertically polarized waves. However, the height of the conventional monopole antenna is a quarter-wavelength of the operational frequency [1]. It becomes a protrusion in limited space. In addition, the conventional monopole antenna only operates at around the frequency where the antenna height is a quarter-wavelength. In this paper, we focus on indoor antennas installed in dead zones where broadcasting waves of digital terrestrial television, and communication waves of mobile communication systems etc. are difficult to reach. Particularly, there are many vertically polarized wave antennas installed as indoor antennas on the ceilings of underground shopping areas and buildings, etc. Because these antennas are installed in a small space, low-profile antennas are required. In addition, these antennas require wideband characteristics to cover the operational bands of several communication systems. However, the antenna height and the relative bandwidth are in a trade-off relationship. The antenna height increases as the...
relative bandwidth increases, and the relative bandwidth decreases as the antenna height decreases. Therefore, it has been important challenge to achieve both low-profile and wideband characteristics.

In many underground areas and buildings, the large total floor areas are large, while the height of the ceilings are low. Therefore, the antennas with monopole-type radiation patterns, the omnidirectional characteristics in horizontal direction, are used as antennas on ceiling in underground areas and buildings [2, 3]. Much research has been done on the low-profile wideband antenna with monopole-type radiation patterns. Monocone antennas with a flat plate element and several short elements have been reported [4, 5, 6, 7, 8]. Additionally, a low-profile and wideband antenna composed of an exponentially shaped element, a flat plate element, and several short elements has been reported [9, 10]. These antennas have a relative bandwidth (voltage standing wave ratio (VSWR) ≤ 2 or |S11| ≤ –10 dB) of more than 100%. However, they are higher than 0.055λ₀ (λ₀ : the wavelength of the lowest operational frequency). The relative bandwidth and antenna height of the antennas in [11] are 157.8%, and 0.046λ₀, respectively. However, the antenna in [11] is designed on a VSWR ≤ 2.7 criterion. Furthermore, the radiation patterns in the horizontal plane deteriorate at several frequencies. Although the relative bandwidth of the antenna in [12] is 148% the antenna height is 0.053λ₀. A low-profile and wideband antenna consisting of a triangular radiation element, capacitance disk placed on the triangular radiation element, oblique short elements, and folded rim has been reported [13]. Antenna heights of 0.03λ₀, 0.04λ₀, and 0.05λ₀ are studied, with relative bandwidths of 18.6%, 29.3%, and 42.8%, respectively. The antenna in [14] consists of a circular patch and shorting vias. The relative bandwidth is 18.6% for a height of 0.024λ₀. In [15], a monopolar circular patch antenna loaded with shorting vias and a coupled annular ring has been proposed. The relative bandwidth is 27.4%, and antenna height is 0.029λ₀.

This paper presents a low-profile wideband antenna which has monopole-type radiation patterns. The low-profile and wideband antenna is achieved by loading oblique short elements to a trapezoidal plate with a capacitance disk.

2. Configuration of antenna

Figure 1 shows the configuration of the proposed antenna placed on a ground plane. The proposed antenna consists of a trapezoidal plate, capacitance disk and oblique short elements, and is fed from the trapezoidal plate, with a 1 mm high feed point (h_feed). In addition, d_short and α_short are the diameter and oblique angle of the short elements, respectively. d_plate and h_plate are the diameter and thickness of the capacitance disk, respectively; here, h_plate is 0.5 mm. Finally, h_all, w_top, and w_feed are the height of the proposed antenna, the upper part and base line of the trapezoidal element, respectively. Here, the thickness of the trapezoidal plate is 1 mm.
3. Determining an initial model

In this chapter, the initial model of the proposed antenna is considered, and the analysis is performed using the finite-difference time-domain (FDTD CST STUDIO SUITE 2019). The ground plane is considered as infinite. In this study, a low-profile and wideband antenna is considered by changing the shape of the antenna in [13] without a folded rim. The initial model is composed of the capacitance disk, triangular element ($w_{feed} = 0 \text{ mm}$) and vertical short elements ($\alpha_{short} = 0^\circ$ and $d_{short} = 1 \text{ mm}$). For the initial model, the width of the triangular plate $w_{top}$ is considered as a parameter when $h_{all} = 22.5 \text{ mm}$. In this case, 22.5 mm is equivalent to $0.045\lambda_0$ at 600 MHz. Here, $d_{plate}$ is defined as $(w_{top} + d_{short})$. Figure 2 (a) shows VSWR characteristics of the proposed antenna when $w_{top}$ is varied. It can be confirmed that the VSWR is not less than or equal to 2 below 600 MHz at any case. The input impedance characteristics of the proposed antenna are shown at Fig. 2 (b). The frequency as well as resistance of the serial resonance decreases as $w_{top}$ increases. Therefore, impedance matching cannot be achieved below 600 MHz. Because the VSWR is close to 2 at around 600 MHz when $w_{top} = 160 \text{ mm}$, the initial model is determined as $w_{top} = 160 \text{ mm}$. 
4. Optimization

In this chapter, improvement of the initial model of the proposed antenna is considered. The analysis is performed using FDTD (CST STUDIO SUITE 2019), and the ground plane is considered as infinite. Here, optimization is performed using $d_{plate}$, $d_{short}$, $w_{feed}$ and $\alpha_{short}$ as parameters. First, impedance matching at around 600 MHz is considered by expanding the diameter of the capacitance disk ($d_{plate}$). Next, enhancement of the relative bandwidth is studied by changing the shape of the triangular element to a trapezoidal element ($w_{feed}$), and adjusting the diameter of the short elements ($d_{short}$). Finally, further reduction of the antenna height is considered by adding an oblique angle ($\alpha_{short}$) to the short elements.

4.1. Impedance matching by expanding the capacitance disk

In this section, improvement of the VSWR characteristics at around 600 MHz is considered by expanding the diameter of the capacitance disk. The characteristics are simulated using $d_{plate}$ as a parameter. Here, $w_{top}$, $\alpha_{short}$ and $d_{short}$ are kept as 160 mm, 0°, and 1 mm, respectively. Figure 3 shows VSWR and input impedance characteristics of the proposed antenna when $d_{plate}$ is varied. From Fig. 3 (a), it is confirmed that the VSWR characteristics are less than 2 below 600 MHz when $d_{plate} = 200$ mm and 238 mm. In addition, the kink in the smith chart is close to the circle with $\text{VSWR} \leq 2$ when $d_{plate} = 200$ mm in Fig. 3 (b). Therefore, $d_{plate}$ is determined to be 200 mm. Expanding the relative bandwidth by adjusting the kink will be examined in the next section.
4.2. Relative bandwidth enhancement by changing shape of the triangular element and adjusting the diameter of the short elements

In this section, to enhance the relative bandwidth of the proposed antenna while maintaining a low-profile, the shape of the triangular element is changed to a trapezoidal element and the diameter of the short elements is adjusted. Figure 4 shows the antenna height and relative bandwidth (VSWR ≤ 2) diagrams of the proposed antenna for various $w_{feed}$ and $d_{short}$ at $w_{top} = 160$ mm and $d_{plate} = 200$ mm. In Fig. 4 (a), the antenna height of the proposed antenna is shown to be almost greater than $0.050\lambda_0$ when $d_{short} \geq 6$ mm. The antenna height is lower than $0.050\lambda_0$ at $d_{short} = 4$ mm to $d_{short} = 5$ mm. There is a region in which the height of the proposed antenna is lower than $0.045\lambda_0$ at $d_{short} \leq 3$ mm. On the other hand, the relative bandwidth characteristics differ from the antenna height characteristics. Figure 4 (b) shows that the relative bandwidth is large around $d_{short} = 5$ mm to $d_{short} = 6$ mm and $w_{feed} = 40$ mm to $w_{feed} = 80$ mm. The relative bandwidth is less than 40% when $d_{short} \leq 3$ mm. From the above, it can be confirmed that the antenna height is low and the relative bandwidth is wide when $d_{short} = 5$ mm and $w_{feed} = 80$ mm. The antenna height is $0.048\lambda_0$ and the relative bandwidth is 73.0% at $d_{short} = 5$ mm and $w_{feed} = 80$ mm.
The reason for the low antenna height and wide relative bandwidth at $d_{\text{short}} = 5$ mm and $w_{\text{feed}} = 80$ mm is considered. Figure 5 shows input impedance characteristics of the proposed antenna when $w_{\text{feed}}$ is varied at $d_{\text{short}} = 1$ mm and when $d_{\text{short}}$ is varied at $w_{\text{feed}} = 80$ mm. From Fig. 5 (a), by changing the shape of the triangular element to a trapezoidal element, the serial resonance resistance reduces at a low frequency and the parallel resonance resistance reduces largely at a high frequency. Furthermore, as it can be seen from Fig. 5 (b), the serial resonance resistance increases largely at a low frequency and the parallel resonance resistance reduces at a high frequency by adjusting the diameter of the short elements. Thus, kink due to double resonance can be adjusted to the circle with VSWR $\leq 2$ by changing $w_{\text{feed}}$ and $d_{\text{short}}$. Therefore, it is considered that the height of the proposed antenna is low and the relative bandwidth is wide at $w_{\text{feed}} = 80$ mm and $d_{\text{short}} = 5$ mm.
4.3. Reduction of the antenna height using the oblique short elements

It is confirmed that the antenna height is low and the relative bandwidth is wide when the variables are $w_{top} = 160$ mm, $d_{plate} = 200$ mm, $w_{feed} = 80$ mm and $d_{short} = 5$ mm. In this section, we considered further reduction of the height of the proposed antenna by adding an oblique angle to the short elements. Figure 6 (a) shows the antenna height and relative bandwidth when $\alpha_{short}$ is varied. From Fig. 6 (a), it can be confirmed that the antenna height reduces as $\alpha_{short}$ decreases. On the other hand, the relative bandwidth is more than 70% between $\alpha_{short} = -30^\circ$ and $\alpha_{short} = 0^\circ$, and is less than 40% when $\alpha_{short} \leq -40^\circ$ and $\alpha_{short} \geq 10^\circ$. At $\alpha_{short} = -30^\circ$, the proposed antenna has a relative bandwidth of 71.4%, and the height is 0.046 $\lambda_0$. The reason for the low antenna height and wide relative bandwidth at $\alpha_{short} = -30^\circ$ is considered. Figure 6 (b) shows the input impedance characteristics of the proposed antenna when $\alpha_{short} = -30^\circ$ and $\alpha_{short} = 0^\circ$. By changing $\alpha_{short}$, the parallel resonance resistance at a lower frequency decreases, and the triple resonances are in a circle with VSWR $\leq 2$. Therefore, the antenna height is low and the relative bandwidth is wide when $\alpha_{short} = -30^\circ$. 

![Figure 6: Simulation results (when $\alpha_{short}$ is varied)](image_url)

Figure 7 shows radiation patterns at 600 MHz and 1200 MHz when $\alpha_{short} = -30^\circ$. It can be confirmed that the proposed antenna has monopole-type radiation patterns, and they are almost omnidirectional in the $xy$ plane at both frequencies.

![Figure 7: Radiation patterns ($\alpha_{short} = -30^\circ$)](image_url)
5. Loading on a finite ground plane

To confirm the radiation patterns when the proposed antenna is loaded on a finite ground plane, the proposed antenna is loaded on the $450 \times 450$ mm ground plane and is compared with the top-loaded triangular antenna (TLTA) with folded rim [13]. In [13], the antenna heights of $0.03\lambda_0$, $0.04\lambda_0$, and $0.05\lambda_0$ are studied, with the relative bandwidths ($\text{VSWR} \leq 2$) of 18.6%, 29.3%, and 42.8%, respectively. Here, the antenna with antenna height of $0.05\lambda_0$ is considered. The lowest frequency ($\text{VSWR} \leq 2$) of the TLTA with folded rim is redesigned the same as the lowest frequency of the proposed antenna. The lowest frequencies of the TLTA with folded rim and the proposed antenna are both 610 MHz.

5.1. Radiation patterns

Figure 8 shows radiation patterns of the TLTA with folded rim and the proposed antenna at 600 MHz and 1200 MHz. At 600 MHz, it can be confirmed that both the TLTA with folded rim and the proposed antenna have monopole-type radiation patterns. In $xy$ plane, there is no significant difference between the radiation pattern of the TLTA with folded rim and the radiation pattern of the proposed antenna. The differences between the radiations of the proposed antenna and the radiations of the TLTA with folded rim are 0.9 to 1.0 dB. In $yz$ plane and $zx$ plane, although the radiations for the downward direction of the proposed antenna are weaker than those of the TLTA with folded rim, the radiations for the upward direction of the proposed antenna are stronger than those of the TLTA with folded rim. The gain of the proposed antenna is 3.7 dBi, and the gain of the TLTA with folded rim is 1.1 dBi. At 1200 MHz, both the TLTA with folded rim and the proposed antenna also have monopole-type radiation patterns. However, the radiation patterns of the proposed antenna are different from the those of the TLTA with folded rim in that the intensities of the radiations are strong. Because the proposed antenna has the wider relative bandwidth than the TLTA with folded rim, the radiations of the proposed antenna are stronger than those of the TLTA with folded rim in high frequency. In $xy$ plane, the radiations of the proposed antenna are 5.6 to 7.3 dB stronger than the radiations of the TLTA with folded rim. Similarly, in $yz$ plane and $zx$ plane, the radiations of the proposed antenna are stronger than the radiation of the TLTA with folded rim in most of the directions. The gain of the proposed antenna is 5.5 dBi, and the gain of the TLTA with folded rim is $-6.8$ dBi.

From the above, it can be confirmed that the proposed antenna has monopole-type radiation patterns, and the radiation patterns are omnidirectional in the $xy$ plane at both frequencies. In addition, the radiations of the proposed antenna are stronger than the radiations of the TLTA with folded rim in most of the directions at 1200 MHz. Here, the cross-polarizations ($E_\phi$) are observed in $xy$ plane at the proposed antenna. This reason will be examined in the next section.
As mentioned above, it is confirmed that the radiation patterns of the proposed antenna in the $xy$ plane are omnidirectional. To analyze the reason that the radiation patterns are omnidirectional in the $xy$ plane, current distributions are confirmed. Figure 9 shows current distributions of the proposed antenna at 600 and 1200 MHz. In Fig. 9, the arrows represent current flows. From Fig. 9, because the current flows to the short elements, it is strongly distributed on the short elements. Therefore, radiations occur strongly from the short elements. Furthermore, each short element is arranged at a small distance with respect to the wavelength. The distance of the feed point from the short elements is $0.13\lambda_0$ at 600 MHz and $0.27\lambda_0$ at 1200 MHz, respectively. Hence, the radiation patterns of the proposed antenna in the $xy$ plane are omnidirectional.

Next, we consider the reason that cross-polarizations ($E_{\phi}$) are observed in $xy$ plane at the proposed antenna. From Fig. 9, because the proposed antenna has a rectangular ground plane, currents flow for horizontal direction on the edges of the ground plane. Therefore, the cross-polarizations ($E_{\phi}$) are radiated from the edges of the ground plane at the proposed antenna. At 600 MHz, because the length of the ground plane is close to one wavelength, the cross-
polarization at 600 MHz is stronger than that at 1200 MHz. On the other hand, the TLTA with folded rim has a circular ground plane, and the cross-polarization ($E_\phi$) is not observed. From the above, it is considered that cross-polarization ($E_\phi$) is observed at the proposed antenna.

![Current Distributions](image1)

Figure 9: Current distributions of the proposed antenna

6. Experimental results

A prototype of the proposed antenna is shown in Fig. 10. The proposed antenna is loaded on a 450 × 450 mm ground plane. Figure 11 shows simulated and measured results of the VSWR characteristics of the proposed antenna. The measured results are in good agreement with the simulated results. The measured relative bandwidth of the VSWR $\leq 2$ is 77.7% (from 610 MHz to 1385 MHz). The height of the proposed antenna is $0.046\lambda_0$.

![Prototype](image2)

Figure 10: Prototype of the proposed antenna on 450 × 450 mm ground plane
Figure 11: Simulated and measured VSWR characteristics

Figure 12 shows the measured and simulated radiation patterns of the proposed antenna. The measured results are in good agreement with the simulated results. The frequencies are 600 and 1200 MHz, respectively. The proposed antenna has monopole-type radiation patterns, and they are almost omnidirectional in the xy plane at any frequency. At 600 and 1200 MHz, the measured gains are 2.3 and 5.7 dBi, respectively.

Figure 12: Simulated and measured radiation patterns
Figure 13 shows the relationship between the relative bandwidth and the antenna height of the proposed antenna and the reference antennas. Here, the proposed antenna is compared with [12, 13, 14, 15]. All values shown in Fig. 13 are measured values. To the best of our knowledge, from the perspective of achieving both the low-profile and the wideband characteristics, the antennas in [12, 13, 14, 15] have the maximum performance among the reported antennas with monopole-type radiation patterns. From Fig. 13, it can be seen that the antenna height increases as the relative bandwidth increases, and the relative bandwidth decreases as the antenna height decreases. Although the relative bandwidth (VSWR ≤ 2) of the antenna in [12] is 148%, the antenna height exceeds 0.05λ₀. In [13], the antenna heights of 0.03λ₀, 0.04λ₀, and 0.05λ₀ are studied, with the relative bandwidths (VSWR ≤ 2) of 18.6%, 29.3%, and 42.8%, respectively. The antenna in [14] has the relative bandwidth (|S₁₁| ≤ –10 dB) of 18.6% and the antenna height of 0.024λ₀. The relative bandwidth (|S₁₁| ≤ –10 dB) of the antenna in [15] is 27.4%, and the antenna height is 0.029λ₀. On the other hand, the relative bandwidth (VSWR ≤ 2) of the proposed antenna is 77.7%, and the antenna height is 0.046λ₀. The painted areas in Fig. 13 summarize the area reported in previous studies and the area pioneered in this paper. The area painted in purple indicates the reported area by previous studies, and the area painted in red indicates pioneered area by the proposed antenna. From Fig. 13, it can be confirmed that both the low-profile and the wideband characteristics are achieved in the proposed antenna, and the proposed antenna has pioneered non-reported area in previous studies.

7. Conclusion

In this paper, a low-profile and wideband antenna is proposed. The low-profile and wideband antenna was achieved by loading a circular plate and four oblique short elements to a trapezoidal element. As a result, the measured antenna height and relative bandwidth of the proposed antenna was 0.046λ₀ and 77.7%, respectively. In addition, the radiation patterns were almost omnidirectional in horizontal plane. Achieving the low-profile and wideband antenna with useful radiation pattern for the facilities with high ceilings is future work.
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