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Investigation of Antenna-Integrated Transparent Socket Panel

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ABSTRACT This paper presents the first antenna-integrated socket that can be used in place of the commercial socket. The socket panel is made of K9 glass for the aesthetic purpose. It serves as the dielectric resonator (DR) loading for the integrated slot antenna fabricated in the ground plane. The socket (DR)-loaded slot antenna is directly fed by a coaxial cable at the slot center. Considering the practical scenarios, the antenna is investigated in three different cases, namely the socket panel, socket panel with plug, and socket panel with the plug and cable. For demonstration, the socket-loaded antenna is designed in 2.4-GHz WLAN band (2.40–2.48 GHz). The reflection coefficient, radiation pattern, antenna gain, and efficiency in each case are measured. Measured results show that the impedance bandwidth can cover the entire frequency band. The antenna can be potentially used as a camouflaged antenna or an attractive home or office decoration.

INDEX TERMS Integrated antenna, slot antenna, socket panel, transparent antenna.

I. INTRODUCTION Transparent antennas have been extensively investigated. They have been incorporated in the automobile/aircraft [1]–[5], solar module [6], [7], mirror [8], and even wearable glasses [9] by using transparent conductive materials (TCMs). Recently, water has been implemented for transparent antenna designs due to the high transparency and easy availability [10], [11]. In general, planar transparent antennas are used for ease of integration, but the utilized materials (TCMs/water) usually reduce the efficiencies of the antennas significantly. To circumvent the efficiency problem, a 3-D transparent dielectric resonator (DR) antenna (DRA) was investigated [12]. The transparent DRA is made of K9 glass, which is economical and widely available in the market. Its antenna gain and efficiency are comparable with those of conventional ceramic DRAs fabricated. The glass DRA has been used as a multi-function element such as a focusing lens [12], [13], decorative glassware [14], light cover [15], [16], and mirror [17].

In this paper, the first antenna-integrated transparent socket panel is investigated. The functional socket panel is made of K9 glass for aesthetic appearance. It is attached to a ground plane where a slot antenna is fabricated. In other words, the glass socket serves as a DR loading for a slot antenna. It should be mentioned that the antenna-integrated socket panel is compatible with commercial socket panels.

The antenna is studied in three different application scenarios, namely the socket panel, socket panel with plug, and socket panel with plug and connection cable. The socket panel is investigated first and compared with that without a power box. It was found that the plug broadens the impedance bandwidth but slightly reduces the antenna gain and efficiency. Finally, to mimic the real situation, the socket panel was measured in the presence of the plug along with a long cable. It was found that the long cable can reduce the antenna gain and efficiency, but it has only little effects on the reflection coefficient across our frequency range. For demonstration, the socket (DR)-loaded slot was designed at ~2.4GHz for WLAN applications. For each application scenario, the measured impedance bandwidth can completely cover the 2.4-GHz WLAN band.
II. ANTENNA-INTEGRATED SOCKET PANEL WITHOUT PLUG

A. CONFIGURATION

Figure 1 shows the configuration of our antenna-integrated socket panel without any plugs. The socket panel consists of a panel and a power box, which are modeled according to the practical size. The square panel is made of K9 glass with a dielectric constant of 6.85. Its height and side length are designed as \( h = 8 \text{ mm} \), and \( a = 87 \text{ mm} \), respectively. The ground plane is obtained by sticking an adhesive copper tape to the glass panel. Its size is the same as the panel size. It should be mentioned that the copper tape is just used for demonstration which can be replaced by a transparent conductive material for better appearance. A rectangular slot antenna was fabricated in the ground plane. It has a slot length of \( L = 42 \text{ mm} \) and slot width of \( W = 12 \text{ mm} \). To reduce the influence of the plug on the slot antenna, the slot is displaced from the panel center by an offset of \( x_0 = 32.5 \text{ mm} \). Although one off-center located slot will result in the asymmetric radiation, it relaxes the requirement for the feeding network. The slot can be directly fed by a coaxial cable at the center of the slot [18]. Three rectangular holes were drilled in the panel and ground plane for the insertion of the plug, which has dimensions of \( l_1 = 9 \text{ mm} \), \( l_2 = 7 \text{ mm} \), and \( w = 5 \text{ mm} \). In practical applications, the three rectangular holes on the ground plane can be designed larger than the given dimensions to avoid the potential danger caused by short circuit. Two elliptical holes are reserved for fixing the panel on an object.

![Figure 1. Configuration of our antenna-integrated socket panel.](image)

B. MEASURED AND SIMULATED RESULTS

To show the effects of the power box located behind the panel, two cases with and without the power box are investigated and compared with each other. The simulation is carried out by using ANSYS HFSS. Agilent network analyzer PNA 8753 was used for measuring the reflection coefficients, whereas Satimo StarLab system was deployed for the far field measurement. Figure 2 shows the photos of the socket panel prototype without any plugs.

![Figure 2. Photos of antenna-integrated socket panel without any plugs.](image)

(a) Top view showing dismantled socket panel and power box. (b) Side view showing socket panel with power box.

Figure 3 gives the measured and simulated reflection coefficients of the panel with and without the power box. The bare panel case is considered first. With reference to the figure, both the measured and simulated resonant frequencies (min. \( |S11| \)) are 2.44 GHz. The measured 10-dB impedance bandwidth (\( |S11| \leq -10\text{dB} \)) is 7.8\% (2.35–2.54 GHz), reasonably agreeing with the simulated impedance bandwidth of 6.5\% (2.37–2.53 GHz). Both the measured and simulated impedance bandwidths cover the 2.4-GHz WLAN

![Figure 3. Measured and simulated reflection coefficients of antenna-integrated panels with/without power box: \( h = 8 \text{ mm}, a = 87 \text{ mm}, l_1 = 9 \text{ mm}, l_2 = 7 \text{ mm}, w = 5 \text{ mm}, x_0 = 32.5 \text{ mm}, L = 42 \text{ mm}, \) and \( W = 12 \text{ mm} \).](image)
band (3.3%). Next, the panel with the power box is investigated. In the measurement, the power box is obtained directly from a commercial socket panel. The measured and simulated reflection coefficients are also shown in Fig. 3 for ease of comparison. Again, reasonable agreement between the measured and simulated results is observed. Referring to the figure, the panel with the power box resonates at 2.4 GHz in both the measurement and simulation. The measured and simulated impedance bandwidths are 8.7% (2.31–2.52 GHz) and 8.3% (2.31–2.51 GHz), respectively. As can be observed from the figure, the effect of the power box on the reflection coefficient is negligible.

Figure 4 shows the measured and simulated radiation patterns of the panels with/without the power box at 2.4 GHz. The two cases have the same simulated maximum gain direction at $\phi = 0^\circ$, $\theta = 35^\circ$ and also the same measured maximum gain direction at $\phi = 0^\circ$, $\theta = 49^\circ$. The difference between the measured and simulated results is due to experimental tolerances.

Figure 5 shows the measured and simulated gains of the panels with/without the power box in maximum-gain directions. The parameters of bare panel are the same as those in Fig.3.

![Figure 4](image_url)

**Figure 4.** Measured and simulated radiation patterns of antenna-integrated panels with/without power box at 2.4 GHz. (a) Elevation ($xz$-) plane of bare panel. (b) Elevation ($yz$-) plane of bare panel. (c) Elevation ($xz$-) plane of panel with power box. (d) Elevation ($yz$-) plane of panel with power box. The parameters of bare panel are the same as those in Fig.3.

Figure 4 shows the measured and simulated radiation patterns of the bare panel (Fig. 4(a) and (b)) and panel with the power box (Fig. 4(c) and (d)) at 2.4 GHz. With reference to the figure, the measured result reasonably agrees with the simulated result in each case. The asymmetry of the $xz$-plane radiation patterns is caused by the asymmetric position of the slot. It can also be seen from the figure that the radiation patterns of the two cases are very similar to each other, showing that the power box has negligible effects on the radiation patterns. The two cases have the same simulated maximum gain direction at $\phi = 0^\circ$, $\theta = 35^\circ$ and also the same measured maximum gain direction at $\phi = 0^\circ$, $\theta = 49^\circ$.

C. PARAMETRIC STUDY

A parametric study was carried out to investigate the effects of the slot and panel dimensions on the antenna performance. Since the power box has only little effects on the antenna, it was removed and only the bare panel was considered in
the parametric study. The slot length \((L)\) and panel height \((h)\) are investigated. Figure 7(a) shows the simulated reflection coefficient with \(L\) altered from 40 mm to 44 mm. As can be observed from the figure, the resonance shifts to a higher frequency as \(L\) decreases, showing that the resonance is due to the slot. Figure 7(b) shows the simulated reflection coefficient with \(h\) increased from 7.5 mm to 8.5 mm. With reference to the figure, the resonant frequency also increases as \(h\) decreases. It can be found from the figure that the resonant frequency increases by only 3.6% (from 2.40 GHz to 2.49 GHz) when \(h\) decreases by 13.3% (from 8.5 mm to 7.5 mm). In contrast, when \(L\) decreases by 10% (from 44 mm to 40 mm), the resonant frequency increases by 6.3% (from 2.37 GHz to 2.53 GHz). It shows that the resonance is more sensitive to the slot length \(L\) than to the panel height \(h\). It verifies that the resonance is caused by the socket (DR)-loaded slot.

It should be mentioned that the proposed panel antenna can be designed radiating as a DRA, when a transparent material with a higher dielectric constant is used, for example zirconia.

### III. ANTENNA-INTEGRATED SOCKET PANEL WITH PLUG

In this part, both the power plug and power box are connected to the panel to mimic the real situation. Figure 8(a) shows the configuration. The model of the plug is based on a commercial plug with wires and fuse, as shown in Fig.8 (b). The parameters of the bare panel and power box are the same as those in Fig.3.

Figure 9 shows photos of the antenna-integrated socket panel with the plug and power box. Figure 10 shows the measured and simulated reflection coefficients of the socket panel with the plug and power box. With reference to the figure, reasonable agreement is observed between the measured and simulated results. The measured and simulated impedance bandwidths are 15.1% (2.27–2.64 GHz) and 13.1% (2.29–2.61 GHz), respectively, with same resonant frequency of 2.44 GHz for both the measured and simulated results.

Both bandwidths entirely cover the 2.4-GHz WLAN band (3.3%). It can be found that this configuration has a broader measured impedance bandwidth (15.1%) than that (8.7%).
FIGURE 9. Photos of antenna-integrated socket panel with plug and power box. (a) Top view showing the assembled structure and dismantled components. (b) Side view showing the assembled structure.

FIGURE 10. Measured and simulated reflection coefficients of antenna-integrated socket panel with the plug and power box. The parameters of bare panel are the same as those in Fig. 3.

For ease of comparison, the measured reflection coefficients of these two cases are shown in Fig. 12, along with the measured reflection coefficient of the basic socket panel configuration (Fig. 9). With reference to the figure, the reflection coefficients of the three cases are similar to one another. The socket panel with the plug and cable has a measured resonant frequency of 2.45 GHz. The resonant frequency shifts to 2.47 GHz when the cable is connected to a monitor. These two cases have measured impedance bandwidths of 13.65% (2.32–2.66 GHz) and 13.71% (2.31–2.65 GHz), respectively, showing that the monitor has negligible effects on the reflection coefficient.

Figure 13(a) and (b) shows the measured and simulated radiation patterns of the antenna-integrated socket panel with
FIGURE 13. Measured and simulated radiation patterns of the antenna-integrated socket panel with the plug and power box at 2.4 GHz. (a) Elevation x-z plane. (b) Elevation y-z plane. The parameters of bare panel are the same as those in Fig. 3.

FIGURE 14. Measured radiation patterns of antenna-integrated socket panel with the plug and connection cable. (c) Elevation x-z plane. (d) Elevation y-z plane. The parameters of bare panel are the same as those in Fig. 3.

the plug (Fig. 9) at 2.4 GHz. As can be observed from the figure, the measured results reasonably agree with the simulated results. The measured and simulated maximum gain directions are along $\phi = 0^\circ$, $\theta = 49^\circ$ and $\phi = 0^\circ$, $\theta = 35^\circ$ respectively, which are the same as those of the panel without the plug. Figure 14(a) and (b) shows the measured radiation patterns of the socket panel with the plug and connection cable (Fig. 11) at 2.4 GHz. As compared with the case without the cable, the radiation patterns in Fig. 13 have similar shapes, except that there are ripples caused by the cable.

Figure 15 shows the measured and simulated maximum realized antenna gains of the socket panel with the plug (Fig. 9). With reference to the figure, the measured and simulated peak values are 4.58 dBi and 4.72 dBi, respectively. For ease of comparison, the measured maximum realized gain after adding the connection cable is also shown in Fig.15. It can be observed from the figure that the peak gain is 4.14 dBi across the measured impedance passband (2.32–2.66 GHz). The antenna gain is degraded because the long cable introduces loss. Figure 16 shows the measured total antenna efficiencies (mismatch included) of the socket panels with and without the connection cable. Without the cable, the panel has the maximum and minimum total efficiencies of 78.2% and 42.9% across the measured impedance passband (2.27–2.64 GHz), respectively, whereas the maximum and minimum total efficiencies in the WLAN band (2.4–2.48 GHz) are 71.8% and 66.0%, respectively. After adding the cable, the socket panel has the maximum and minimum efficiencies of 71.6% and 48% in the measured impedance passband (2.32–2.66 GHz), respectively. In the WLAN band (2.4–2.48 GHz), the maximum and minimum efficiencies becomes 63.2% and 56.8%, respectively. It can be expected that a lower efficiency is obtained when there is a connection cable due to the loss caused by the cable. The result is consistent with the finding of the antenna gains in Fig.15.
IV. CONCLUSION
An antenna-integrated transparent socket panel has been investigated. The socket panel is made of K9 glass for aesthetic appearance, being compatible with the commercial socket panel. A piece of adhesive copper tape has been stuck at the back of the panel to form the ground plane. A rectangular slot antenna was fabricated in the ground plane, giving the socket (DR)-loaded slot antenna. The slot has been designed off the panel center to reduce the influence of the plug on the antenna performance. For demonstration, the panel antenna was designed for 2.4-GHz WLAN (2.40–2.48 GHz) applications. Prototypes were fabricated to verify the simulations. It has been found that the slot antenna can radiate effectively. Also, virtually the power box has no effects on the antenna performance due to the isolation of the ground plane.

The practical application scenarios have been considered by studying the effects of the plug and connection cable. Three different cases have been investigated, namely the socket panel without any plugs, socket panel with a plug, and socket panel with a plug having a connection cable. The prototype was measured in each case. Measured 10-dB impedance bandwidths of 8.7%, 15.1%, and 13.65% have been obtained for the first, second, and third cases, respectively. It has been found that without the plug, the measured realized antenna gain and total efficiency are 5.68 dBi and 76.4%, respectively in the designed frequency band. When the plug is inserted into the panel, a higher impedance bandwidth can be obtained due to the coupling of the plug and the loss introduced by the plug. It has led to a slightly lower antenna gain (4.58 dBi) and efficiency (71.8%). It has been found that the antenna gain (4.14 dBi) and efficiency (63.2%) will further be reduced after adding the cable due to the loss introduced by the cable. For the reflection coefficient, similar results have been obtained for the three cases.

The panel antenna can be used as a camouflaged antenna. Finally, it should be mentioned that by integrating LEDs with the panel, the design will become a very attractive home or office decoration.

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REFERENCES

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