Helmet Antenna Design Using Characteristic Mode Analysis

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Abstract **—** The helmet antenna is required to achieve hands-free operation for disaster prevention. The helmet antenna is not only low profile with a small configuration, but it also suppresses radiation toward the human head. This paper presents the characteristic mode analysis of the helmet, which is a hemispherical conductor shell to achieve the omnidirectional pattern in the horizontal plane. By deleting the weak part of the electric current on the hemispherical conductor shell, the shape of the folded dipole was obtained with a low resonant frequency. The folded dipole antenna with a slit-loaded copper ring structure with high radiation efficiency and a low SAR value was designed.

Index Terms **—** Characteristic mode analysis, folded dipole antenna, hemispherical shell, helmet antennas, omnidirectional pattern.

I. INTRODUCTION

For safety, a person must wear a helmet and use a transceiver in a one-hand operation. The helmet antenna is required to achieve hands-free operation. In the disaster radio systems operating at 150 MHz in Japan, the transceiver needs to be combined with the helmet for rescue operations. Helmet antennas are suitable for this purpose. In this case, the interaction between the antenna and the human body is essential [1], [2].

Helmet antennas have been investigated for various applications such as military, construction, and disaster prevention. The broadband [3] and omnidirectional radiation [4] are required for helmet antennas. In previous studies, the implementation of the antenna inside a helmet is also investigated. In various applications, the high-frequency antennas can be implemented efficiently in a helmet. However, it is challenging to implement low-frequency helmet antennas at 150 MHz in proximity to the human head.

For a radio system operated at a low frequency, the half-wavelength circular loop antenna [5] and the folded dipole antenna [6] have been proposed. The inverted-F antenna on a hemispherical ground plane has been proposed to enhance the antenna gain [7]. However, the inverted-F antenna has a narrow bandwidth. Since these antennas are arranged in proximity to the human head, the radiation efficiency is reduced, and the value of the specific absorption rate (SAR) increases. The installation of a conductor ring with the slit is effective [8] in reducing the unwanted radiation toward the human head.

The characteristics mode analysis (CMA) has been considered as the systematic design of the antenna shape [9], [10]. The design procedure using CMA has been adapted to the dual-mode antenna with orthogonal radiation patterns [11] and the ultra-wideband patch antenna [12]. However, to achieve the helmet antenna for low-frequency operation, low-profile and small antennas are required to be installed on a small platform. This paper presents the characteristic mode analysis of the helmet, which is a hemispherical conductor shell to achieve an omni-directional pattern in the horizontal plane.

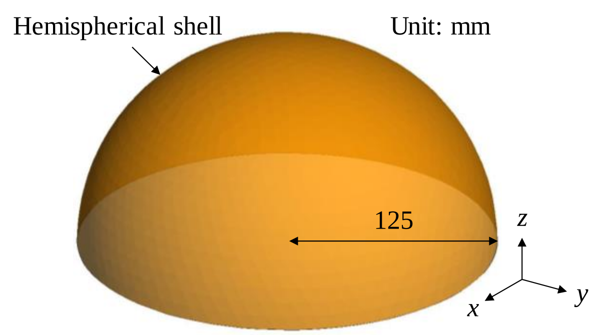

Fig. 1. Configuration of hemispherical conductor shell.

II. CHARACTERISTIC MODES ANALYSIS OF THE HEMISPHERICAL CONDUCTOR SHELL3

Figure 1 shows the simulation models of the hemispherical conductor shell with a radius of 125 mm. The antenna is assumed to be installed on the helmet formed from a dielectric material with ε_r = 3.0 and tanδ = 0.005. However, the characteristic modes are analyzed without the dielectric material, and by using Altair

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The modal significance [10] is defined as:

$$S_n = \left|\frac{1}{1+j\lambda_n}\right|. \qquad (1)$$

Harrington and Mautz [9] obtained the eigenvalue equation as follows:

$$X(J_n) = \lambda_n R(J_n), \qquad (2)$$

where λ_n are the eigenvalues, and J_n are eigenfunctions. R and X are the real and imaginary parts of the impedance matrix obtained from the moment method. Modes with a high modal significance are the current resonances of the structure. When the value of s_n is close to 1, the mode significantly contributes to radiation.

Figure 2 shows the modal significance characteristics of the hemispherical conductor shell. The resonant frequencies of J_1 and J_2 are over 600 MHz. The eigenvalue of J_1 becomes 0.02. Figure 3 shows the modal current distributions of J_1, J_2, J_3, and J_4. As shown in Figs. 3 (a) and (b), the current intensities become strong at the edge of the hemispherical shell. The resonant mode corresponds to a one-wavelength loop current. Furthermore, J_1 and J_2 are orthogonal to each other. Similarly, J_3 and J_4 are orthogonal to each other, as shown in Figs. 3 (c) and (d). In mode J_3, the edge current becomes strong. The current in the middle part of the shell becomes strong in the mode J_4.

Figure 4 shows the radiation patterns of each mode at 150 MHz. As shown in Figs. 4 (a) and (b), the radiation patterns of each polarization on the *xy* plane are shaped like the figure eight. The omnidirectional patterns of the horizontal and vertical polarization are obtained in mode J_3 and J_4, respectively. However, the resonance cannot be achieved easily because these modal significances are extremely low.

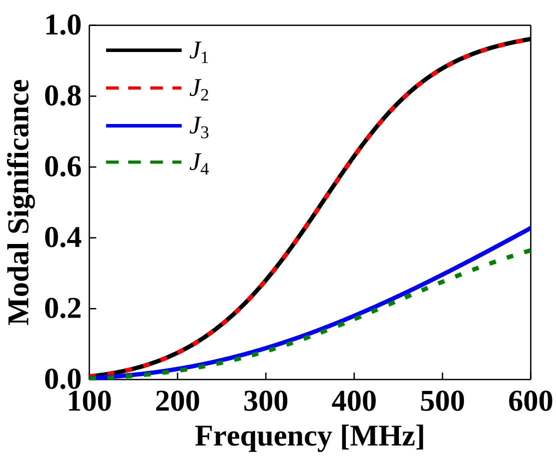


Fig. 2. Modal significance.

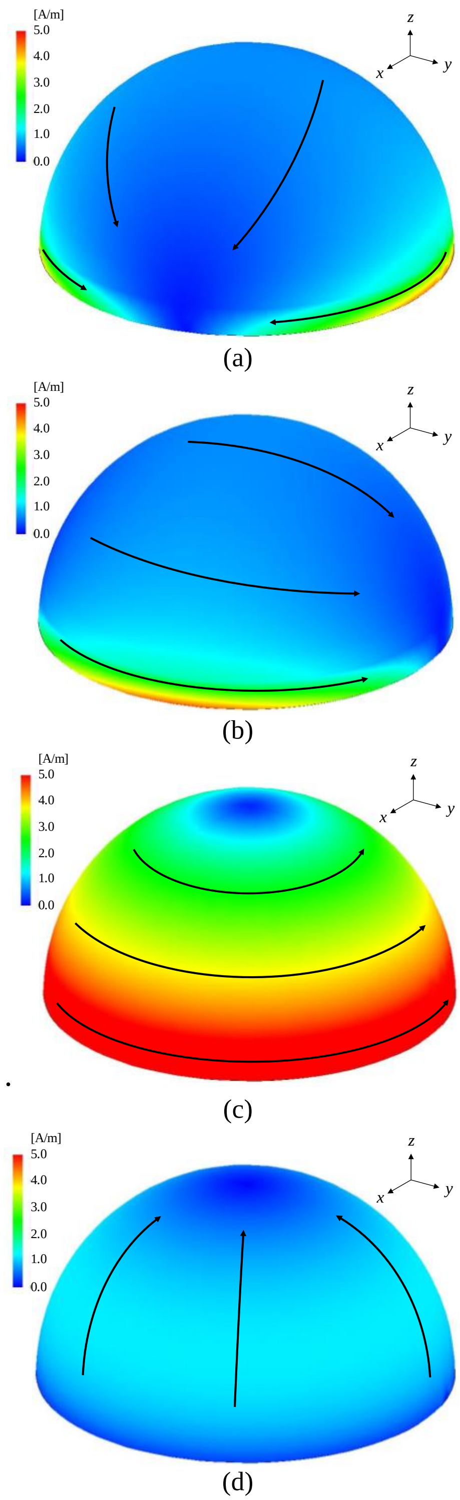


Fig. 3. Modal current distributions of: (a) J_1, (b) J_2, (c) J_3, and (d) J_4 on hemispherical shell.

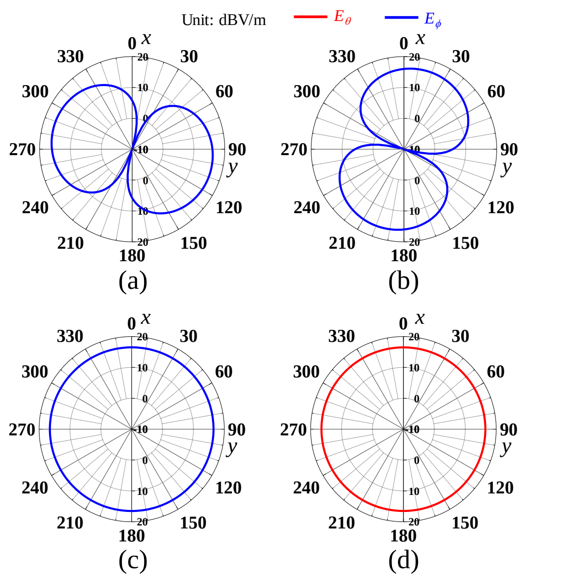
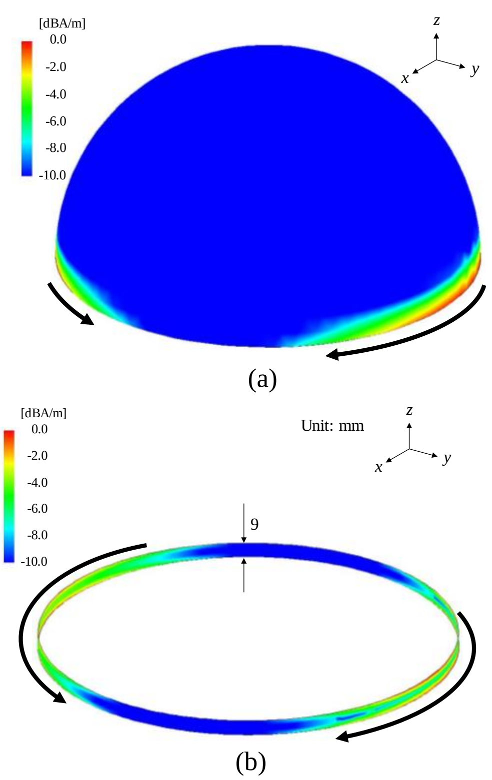


Fig. 4. Radiation patterns of: (a) J_1, (b) J_2, (c) J_3, and (d) J_4.

III. ANTENNA DESIGN BASED ON MODAL CURRENT DISTRIBUTIONS

Figure 5 shows the normalized modal current distribution of J_1. As shown in Fig. 5 (a), the strong electric current is distributed at the edge of the shell. The contour length of the edge of the shell corresponds to one wavelength loop.



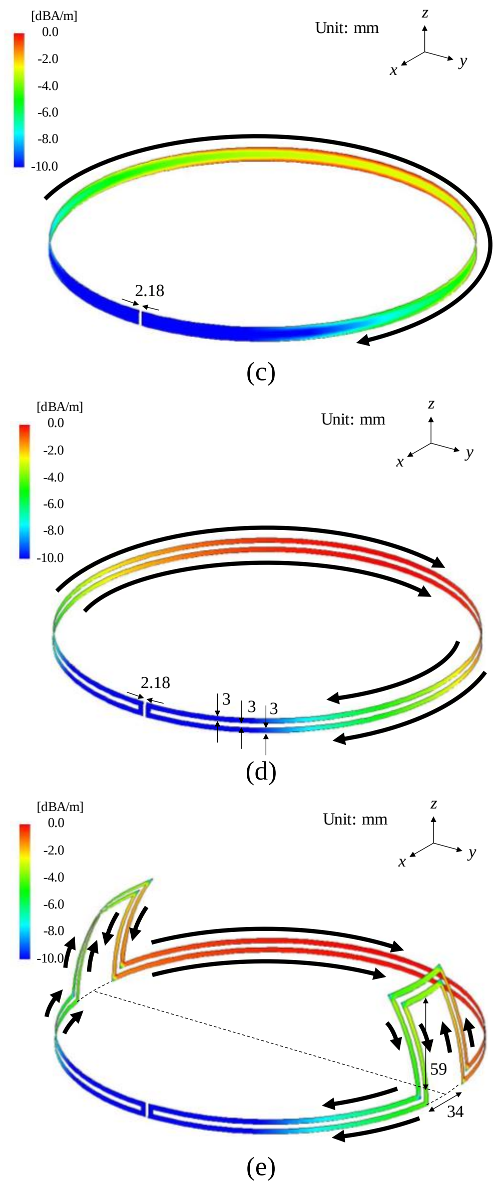


Fig. 5. Normalized modal current distributions of J_1 of: (a) model1, (b) model2, upper part of hemispherical shell is deleted, (c) model 3, slit is arranged, (d) model 4, middle part of conductor is deleted, and (e) model 5, crank structure is added.

Therefore, the upper part of the hemispherical shell is deleted as shown in Fig. 5 (b). The width of the conductor becomes 9 mm. The current flows widely on the conductor because of the narrow conductor.

To change the characteristic modes from the one-wavelength loop to the half-wavelength loop, the conductor is split, shown in Fig. 5 (c). The slit with 2.18 mm width is arranged in the weak part of the electric current in the conductor in Fig. 5 (b). As a result, the electric current flows in one direction.

The current in the middle part of the conductor in Fig. 5 (c) becomes weak in comparison with that at the edge of the conductor. Therefore, the middle part of the conductor is deleted, as shown in Fig. 5 (d). The space between the two conductors is 3 mm. The current intensity of the two strips on the conductor increases. As a result, the configuration of the conductor takes the shape of a folded dipole.

Finally, two crank structures are added at the positions of the strong currents on the conductor in Fig. 5 (a) to adjust the resonant frequency, as shown in Fig. 5 (e).

IV. DESIGN RESULTS

Figure 6 shows the modal significance characteristics of each model, as shown in Fig. 5. The resonant frequency in model 2 becomes 408 MHz, and the resonant frequency of 173 MHz is confirmed by arranging the slit on the conductor in models 3 and 4. For the final design, the resonant frequency of 150 MHz can be achieved by installing the crank structures in model 5.

Figure 7 shows the radiation patterns on the *xy* plane of each model. In comparison with Fig. 4 (a), the radiation patterns of models 1 and 2 are almost the same, as shown in Fig. 7 (a). The radiation patterns with the slit on the conductor become omni-directional on *xy* plane as shown in Figs. 7 (b) and (c). The deviation in the *xy* plane is 4.5 dB in model 5 because of loading the crank structures.

The feed port is arranged at the center of the bottom conductor on the final configuration in Fig. 5 (e) to verify the validity of the characteristic mode analysis. Figure 8 shows the VSWR characteristics of the simulation and measurement. The measured result agrees with the simulated result. Therefore, the validity of the characteristic mode analysis is verified. Moreover, the antenna is attached to the dielectric material with ε_r = 3.0, tanδ = 0.005, and a thickness of 2 mm. The resonant frequency shifts from 150 MHz to 136 MHz. Therefore, the dimension of the antenna should be adjusted during installation on the helmet.

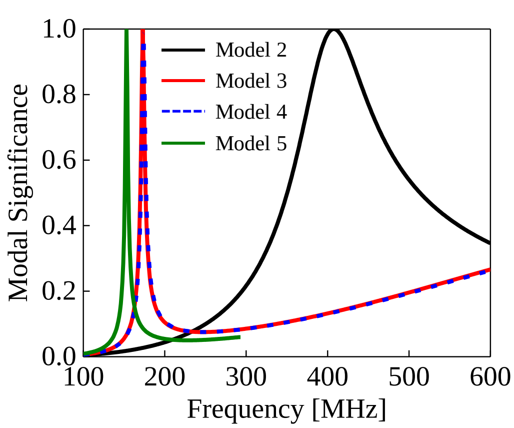


Fig. 6. Modal significance of J_1.

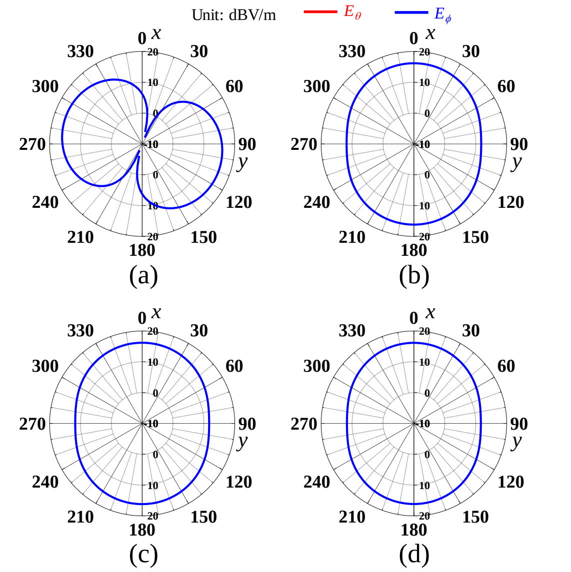


Fig. 7. Radiation patterns on *xy* plane of: (a) model 2, (b) model 3, (c) model 4, and (d) model 5.

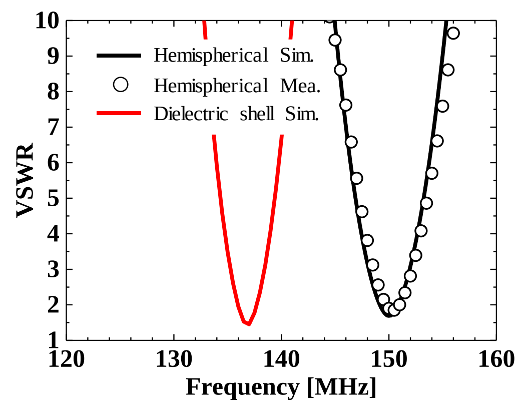


Fig. 8. VSWR characteristics.

V. FOLDED DIPOLE ANTENNA WITH SLIT-LOADED COPPER RING STRUCTURE

Figure 9 shows the simulation models of the folded dipole antenna with a human head with ε_r = 52.3 and a conductivity of 0.76 S/m. The antenna element is arranged on the hemispherical dielectric shell with ε_r = 3.0, tanδ = 0.005, a radius of 125 mm, and a thickness of 2 mm. To achieve the impedance matching, the widths of the feed and non-fed arms of the dipole are 3 mm and 12 mm, respectively. Based on the previous results in [6], the additional conductor ring inside the helmet is effective for reducing the unwanted radiation towards the human head. Figure 9 (b) shows the slit-loaded copper ring structure to reduce the unwanted radiation toward the human head. The finite element method is employed for electromagnetic simulation.

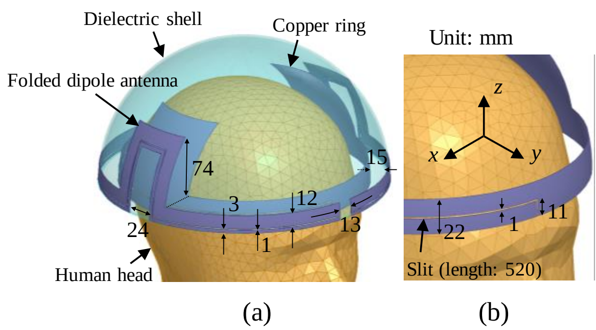


Fig. 9. (a) Configuration of folded dipole antenna with slit-loaded copper ring structure. (b) Detailed view.

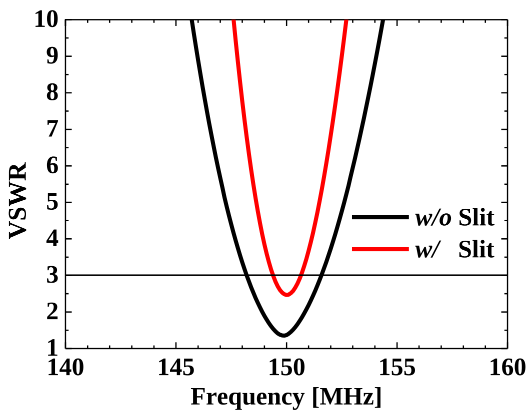


Fig. 10. VSWR characteristics.

Figure 10 shows the simulated VSWR characteristics. The relative bandwidth at VSWR = 3 becomes 2.1 % and 0.9 % with and without the slit, respectively. Figure 11 shows the radiation patterns. The radiation efficiency of 55 % can be achieved by loading the slit. As a result, the realized gain becomes −2.7 dBi. Figure 12 shows the simulated 10 g average local SAR distributions. The unwanted radiation toward the human head can be suppressed, and the maximum SAR value becomes 0.67 W/kg, which is lower than the specified value of 2 W/kg in the IEC 62209-1 standard.

VII. CONCLUSION

This paper presents the characteristic mode analysis of helmet antenna design. By deleting the weak part of the modal current on the hemispherical conductor shell, the shape of the folded dipole was obtained with a low resonant frequency of 150 MHz. The omnidirectional pattern can be achieved in the horizontal plane. A folded dipole antenna with slit-loaded copper ring structure, with a high radiation efficiency and a low SAR value, was designed.

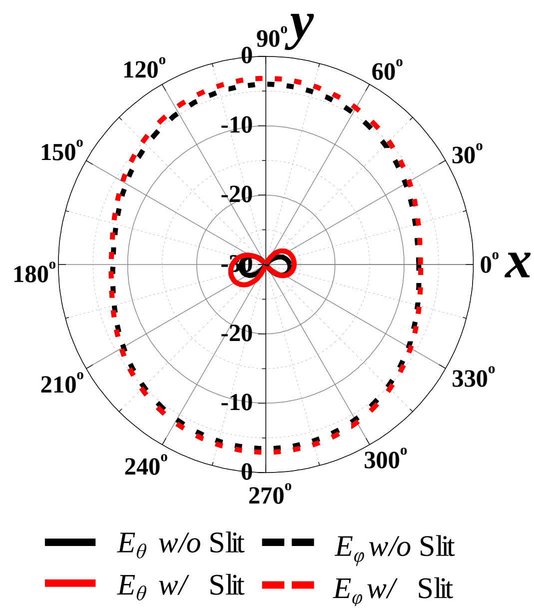


Fig. 11. Radiation patterns.

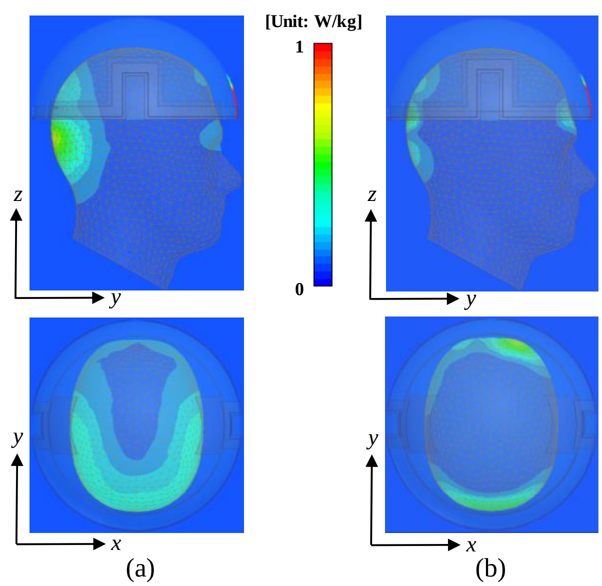


Fig. 12. 10 g average local SAR distributions: (a) without and (b) with slit.

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