Omni-directional small planar antenna composed of folded slots spanning over both sides

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Abstract:
A small planar antenna composed of folded slots is proposed for mobile communications, especially for being mounted on unmanned aerial vehicles (UAVs). Bending slits are made rotationally symmetrically on top and bottom sides of a printed circuit board. The slits are joined in pairs via open edges of the printed board to form slots spanning over both the sides. The directivity is omni-directional and the polarization is dominantly horizontal. The antenna can be controllably miniaturized by being made of a thinner substrate because the resonant frequency decreases as the substrate thickness decreases. Influence of an adjacent conductor plate is examined for the actual usages of being mounted on UAVs and mobile terminals.

Keywords: small antenna, planar antenna, omni-directional, horizontal polarization, symmetry structure, unmanned aerial vehicle (UAV), drone

Classification: Antennas and propagation

References

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1 Introduction

Various applications using unmanned aerial vehicles (UAVs) or drones have been proposed and are expected to make our life easier [1]. Since UAV uses are increasing, the frequencies in 169 MHz band were newly allocated for UAV control in Japan. For wireless remote control of a freely-movable UAV, an omni-directional antenna is required. Since the wavelength of 169 MHz is approximately 1.8 m, compactness is also required for the antenna to be mounted on UAVs [2][3]. Thus, we proposed a small planar omni-directional antenna. The planar antenna was chosen because it can be mounted inside of or under a UAV. In order to reduce interference with the wireless systems using adjacent frequency bands, the frequency bandwidth in which $|S_{11}| < -10$ dB was set to 400 kHz (the fractional bandwidth is 0.24%) in this paper since the channel bandwidth allocated to 169 MHz band is 400 kHz.

2 Antenna structure

Fig. 1 shows the design of proposed antenna when the number $n$ of slots is four. Bending slits are made rotationally symmetrically on top and bottom sides of a printed circuit board. The slits on both sides are the same with each other, and the slits are united in pairs to form slots spanning over both the sides. Such the method of spanning slots is effective for making slots long [4]. In the previous proposal [5], the slit pairs on both sides are shortly joined via a small open edge, thus the edge of the board is mostly closed. In this proposal, to make slots longer with keeping the antenna size, the edge of the board is mostly opened and each open edge is employed as a part of the spanning slot. The spanning folded slot is indicated by an arrow in Fig. 1(a). Up to approximately one-third of the slot can be consist of the open edge. The slots are fed from the center of the antenna plate by a coaxial cable, for example.

Fig. 1(b)-1 and -2 show the top view of the proposed antenna when $n = 4$ and $n = 2$, respectively and the definition of size parameters. Fig. 1(c) shows the values of size parameters with which impedance matching is attained, where $f_{res}$ denotes the lowest resonant frequency and $\lambda_{res}$ denotes the wavelength at the frequency. A moment method software IE3D and a finite element method software Ansys HFSS were used for optimizing and calculating the antenna characteristics. Type 1 and Type 2 were designed for parametric study with the dielectric substrate thickness $h$ set to 16 mm, and Type 3 was designed for prototype in 169 MHz band with $h$ set to 1.588 mm. It is found that all the designs of $n = 4$ and 2 optimized to attain impedance matching have the common characteristic that slot parts are positioned outer of the antenna plate as the parts are nearer to the slot ends.

3 Parametric study and experimental examination

3.1 Influence of symmetrically arranged slot number $n$

It is found from the table in Fig. 1(c) that $f_{res}$ decreases from 117.6 MHz to 69 MHz when $n$ decreases from 4 to 2. The slot length is 784 mm when $n = 4$ and $\lambda_{res}$ is 2551 mm, thus the slot length is approximately $0.31 \lambda_{res}$. The slot length is 1587
When $n = 2$ and $\lambda_{\text{res}}$ is 4348 mm, thus the slot length is approximately $0.36 \lambda_{\text{res}}$.

Therefore, the approximately half reduction of the resonant frequency should be caused by the approximately doubling of the slot length when $n$ decreases from 4 to 2. The area, the volume and the weight can be decreased to approximately one fourth when $n$ decreases to the half because the antenna width $W$ is decreased to approximately the half in order not to change $f_{\text{res}}$. Thus, it is effective for making the antenna small and light weight to select $n$ as a small number.
3.2 Influence of substrate thickness $h$

Fig. 2(a) shows the antenna characteristics of Type 1 when $h$ is varied. Fig. 2(a)-1 shows the frequency responses of $|S_{11}|$ and $\eta_{\text{rad}}$. The frequency resonance is kept to exist even when $h$ is varied whereas $f_{\text{res}}$ varies. The frequency $f_{\eta}$ also varies equally with $f_{\text{res}}$. It is found that $f_{\text{res}}$ becomes lower as $h$ becomes smaller. This implies that the antenna can be designed smaller when it is made of a thinner substrate.

Fig. 2(a)-2 shows the dependences of $f_{\text{res}}, f_{\eta}$ and $\eta_{\text{max}}$ on $h$. The resonant frequency $f_{\text{res}}$ is 117.6 MHz when $h$ is 16 mm, thus $W = 300$ mm is 0.118 times of $\lambda_{\text{res}} = 2551$ mm and $\eta_{\text{rad}}$ is -1.6 dB. The total slot length is 784 mm and is approximately 0.31 $\lambda_{\text{res}}$. When $h$ decreases to the half, 8 mm, $f_{\text{res}}$ decreases to 0.82 times, 96.3 MHz, and the ratio of $W$ to $\lambda_{\text{res}}$ decreases to approximately 0.096 whereas $\eta_{\text{max}}$ decreases to -3.0 dB.

The frequency bandwidth $f_w$ in which $|S_{11}|$ is below -10 dB is 0.42 % when $h = 16$ mm. Thus, the target bandwidth 0.24 % is covered by Type 1. Fig. 2(a)-3 shows $h$ dependence of $f_w$. It is found that $f_w$ becomes narrower as $h$ becomes smaller.

Fig. 2(a)-4 shows the directivity of the absolute gain $G_a$ in the $zx$ plane. The horizontal polarization is approximately 10 dB higher than the vertical polarization, and the gain decreases and the cross-polarization discrimination increases with decreasing $h$. 

![Graphs showing antenna characteristics and dependencies](image-url)
Conductor plate inserted in the center between top and bottom sides of the antenna (Cu, thickness is 0.02 mm)

Frequency response of $|S_{11}|$ using $L_O$ as a parameter when $h = 8$ mm, $W = 300$ mm, $L_I = 170$ mm (Type 1)

Simulation and measurement results of frequency response of $|S_{11}|$ (Type 3)

Simulated horizontal pattern of absolute gain $G_a$ at 169.7 MHz (Type 3)

Measured horizontal pattern of relative gain $G_r$ at 170.5 MHz (Type 3)

Fig. 2. Influence of $h$, conductor plate insertion, and experimental result.
3.3 Influence of inserting a conductor plate between surfaces
We investigated the influence of inserting a ring-shaped conductor plate shown in the Fig. 2(b)-1 in the center between the top and bottom surface conductors. Fig. 2(b)-2 shows the frequency response of $|S_{11}|$ when the outer size $L_O$ is varied with the inner size $L_I$ of the ring-shaped plate fixed to 170 mm. The investigated antenna is Type 1 but $h$ is 8 mm. It is found that $f_{\text{res}}$ increases when the inserted plate becomes larger. The resonant frequency $f_{\text{res}}$ increases also when the thickness $h$, which is equal to the distance between surface conductors, increases as shown in Fig. 2(a)-1 and -2. Because electrical interaction between the slot parts on the top and bottom sides decreases in both the cases, the interaction is considered to cause the reduction of $f_{\text{res}}$.

3.4 Experimental examination
The antenna width $W$ of Type 3 is 120 mm which is 0.068 $\lambda_{\text{res}}$, thus Type 3 is electrically small compared with Type 1. Fig. 2(c)-1 shows the frequency responses of $|S_{11}|$ simulated by HFSS and measured. The simulation and measurement results agree well each other. The fractional bandwidth is 0.25% in the measurement result, thus 400 kHz can be covered by the prototype.

The simulated and measured patterns are shown in Fig. 2(c)-2 and -3, respectively. The absolute gain $G_a$ at $f_{\text{res}}$ of 169.7 MHz is shown for the simulated pattern and the relative gain $G_r$ at $f_{\text{res}}$ of 170.5 MHz is shown for the measured pattern. It is demonstrated that the omni-directional directivity is attained by the proposed antenna. The measurement result agrees with the calculation result in that the horizontal polarization is higher than the vertical polarization. Whereas the cross-polarization cancellation of simulation result is 19.3 dB, that of the measurement is 8.2 dB. The low cancellation of the measurement result should be caused by insufficient electromagnetic wave absorption of the anechoic chamber and electrical influence of feed cables due to the low measurement frequency.

4 Influence of adjacent conductor plate
Whereas the proposed antenna can be set inside of a UAV thanks to its planar shape, antennas are put on some objects in many cases. Therefore, the electrical influence when the antenna is located closely to a plate as shown in Fig. 1(a) was investigated. Whereas UAVs are not generally made of conductor, the case where the plane is made of copper is investigated as the worst case.

The influence of distance $H'$ from a conductor plate was examined in the condition that the conductor plate is infinite. Fig. 3 (a) shows the frequency response of $|S_{11}|$ of Type 1 when $H'$ is varied. It is found that $|S_{11}|_{\text{res}}$ at $f_{\text{res}}$ first increases, then $f_{\text{res}}$ shifts to higher when $H'$ decreases. It is found that even when $H'$ is decreased to 400 mm (approximately 0.16 $\lambda_{\text{res}}$), the impedance matching of $|S_{11}|$ being less than -6 dB is kept at 117.6 MHz which is $f_{\text{res}}$ of the isolated state. Fig. 3(b) shows $H'$ dependences of $f_{\text{res}}$ and $|S_{11}|_{\text{res}}$, and Fig. 3(c) shows $H'$ dependences of $f_h$ and $\eta_{\text{max}}$. It is found that not only $|S_{11}|$ but also $\eta_{\text{rad}}$ deteriorates when $H'$ decreases and $\eta_{\text{max}}$ reduces to -4.7 dB when $H'$ is 200 mm. When $H'$ decreases less than 200 mm, $f_{\text{res}}$, and $f_h$ steeply increases.
5 Conclusion

An omni-directional antenna was proposed to be mounted in or under UAV for remote control and its basic performance was experimentally demonstrated. The antenna is planar and small of approximately 0.1 wavelengths of the resonant frequency. The compactness is achieved by spanning folded slots over both sides of the antenna plate. Its polarization is dominantly horizontal. The resonant frequency decreases when the thickness $h$ becomes small whereas the radiation efficiency and the frequency bandwidth decrease. Thus, the proposed antenna can be designed smaller when it is made of a thinner substrate.

It was found that the impedance matching of $|S_{11}| < -6$ dB can be maintained even when the antenna is located closely to a conductor plate up to approximately 0.16 wavelengths of the resonant frequency. Because the dominant cause of the degradation of impedance matching is the increase of the resonant frequency, it is effective to design the resonant frequency lower to cancel the increase.

The electrical interaction between slot parts on the top and bottom sides is considered to be the cause of the resonant frequency decrease. Clarification of its mechanism is a future work. The enhancement of the impedance matching frequency bandwidth is regarded as an important subject of investigation to extend the application scope.