A 3D printed metallized Fabry–Perot cavity antenna with improved bandwidth and low side-lobe levels

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Introduction: Due to high directivity and simple configuration, Fabry–Perot cavity antennas (FPCAs) have attracted many studies [1–3]. Most of the proposed FPCAs are designed with print circuit boards (PCBs), which have the advantages of easy fabrication and lightweight [1–3]. However, the PCB substrate adversely affects the radiation efficiency and power-handling capability of the FPCA [4, 5]. The application scenarios of the FPCA are limited. Therefore, the metallic FPCA draws great attention [6–9].

A metallic FPCA usually consists of a surrounding enclosed cavity, a waveguide feed, and a grid superstrate. Due to the strong resonance, high-order parasitic modes and surface waves caused by the nearly enclosed cavity [7–9], the metallic FPCA suffers from high side lobes and narrow bandwidth. To decrease the side lobes and improve the radiation performance, the research [8] studied several techniques to suppress the parasitic mode inside the metallic Fabry–Perot cavity. Another research [9] stacked two cavities with different sizes as an FPCA and obtained a bandwidth of approximately 10%. However, the design procedure of the stacked cavities is complicated and time-consuming.

On the other hand, the metallic FPCA suffers from a heavy weight, which also limits its application scenarios. Nowadays, 3D printing technology has become increasingly popular in the fabrication of microwave devices [10], which features significantly reduced weight without sacrificing attributes of its electric properties. In the typical fabrication process, the antenna is firstly 3D printed by plastic materials; then the conductive layer on the printed antenna is created by utilizing the surface metallization.

In this letter, a 3D printed metallized FPCA is designed with an operating frequency of 5.8 GHz. To improve the bandwidth and reduce the side-lobe levels (SLLs), a non-uniform grid superstrate and a choke groove are utilized in the FPCA. The designed FPCA is fabricated and measured for verification, whose weight is only 13% of the one fabricated with copper. The measured result agrees well with the simulated one.

Antenna Design: The configuration of the proposed FPCA is shown in Figure 1. A non-uniform grid superstrate, a ground plane with a choke groove, surrounding walls, and a wideguide feed. For easy measurement, a wideguide-coaxial converter is connected to the antenna directly. The operating frequency of the antenna is selected to 5.8 GHz. The antenna aperture is square and the side length is 125 mm. The thicknesses of the surrounding walls and the ground plane are 2 and 3 mm, respectively.

For a conventional FPCA without surrounding walls, the resonant frequency can be expressed as [3]

\[ f_r = \frac{c}{2\pi} \left( \frac{\phi_x + \phi_y}{2\pi} + n \right) \]  

(1)

where \( c \) is the speed of light in free space, \( h_c \) is the distance between the superstrate and the ground plane, \( \phi_x \) and \( \phi_y \) are the reflection phases of the superstrate and the ground plane, respectively, and \( n \) is an integer. Due to the nearly enclosed cavity with surrounding walls, the resonant frequency of the proposed FPCA is changed to

\[ f_r = \frac{c}{2\pi} \sqrt{\left( \frac{\phi_x}{L_c} \right)^2 + \left( \frac{\phi_y}{L_c} \right)^2 + \left( \frac{2\pi f_c}{L_c} \right)^2} \]  

(2)

where \( L_c \) and \( L_s \) are the lengths of the cavity along \( x \) and \( y \) axes, and \( p \) and \( m \) are integers. The basic mode of the FPCA is TE011 mode [9], which means \( p, m, \) and \( n \) are 0, 1, and 1, respectively.

As demonstrated by Equations (1) and (2), the resonant frequency of the FPCA is strongly related to the reflection phase of the superstrate. Therefore, a non-uniform superstrate with variable reflection phase distribution can lead to multiple resonances, and therefore, broaden the bandwidth. In this work, a single-layer metal grid is adopted as the non-uniform superstrate. The thickness of the metal superstrate is 2 mm. The length of the unit cell \( L_u \) is set to 15 mm (approximately 0.29\( \lambda \)). Different reflection phases could be achieved by changing the length of the square slot \( S \).

Through full-wave simulations, an optimized non-uniform grid is obtained for the FPCA, which is symmetrical about \( x \) and \( y \) axes. The lengths of the slots only change with the position along the \( y \) axis, which are 12.50, 12.75, 13.00, 13.25, and 13.50 mm from the centre to border, respectively. The distance between the superstrate and ground plane is 26.7 mm. The feed wideguide adopts the BJ-70 with an inner length of 34.85 mm and an inner width of 15.80 mm. The open slot on the ground plane of the feed has a length of 23.79 mm and a width of 1.86 mm. A gradient configuration with a height of 13.50 mm is adopted for the transformation from the wideguide to the open slot, as shown in Figure 1(c). Figure 2 shows the simulated input reflection coefficients of the
FPCA employing the non-uniform grid superstrate or a uniform grid superstrate with a length of slots of 13 mm, where a significantly improved bandwidth is observed. In comparison with the uniform superstrate, the non-uniform superstrate enhances the input bandwidth from 1.21% to 6.24%.

Furthermore, some surface waves can be excited in the FPCA by the waveguide feed. They can propagate along the cavity and radiate to undesired directions, adversely affecting the radiation performances and leading to high side lobes. Some previous researches [11, 12] revealed that the choke groove is able to suppress the surface waves and reduce the side and back lobes. Therefore, a choke groove is utilized in this work and its dimensions are obtained by the optimization with full-wave simulations. The choke groove is located at 24.25 mm from the centre with a depth $h_g$ of 15 mm and a width $D_g$ of 3 mm. The simulated current amplitude distributions and radiation patterns of the FPCA with or without the choke groove are obtained and shown in Figures 3 and 4, respectively.

As depicted in the red circle of Figure 3, the current amplitude with the groove is smaller than that without the groove, demonstrating that the current propagating from the feed to the surrounding walls is depressed by the choke groove. As shown in Figure 4, the simulated SLLs on E and H plane are both below $-15$ dB, while the broadside directivities are nearly the same.

Moreover, the effects of the non-uniform grid superstrate and choke groove on the FPCA’s directivity are also investigated. Figure 5 shows the simulated directivities versus the frequency, where it is observed that the non-uniform superstrate and choke groove do not significantly affect the directivity. The difference is only around 0.2 dB at 5.8 GHz.

**Fabrication and Measurement:** The designed FPCA was fabricated and the prototype is shown in Figure 6. The fabrication process involves two steps. First, the antenna was printed with mixtures of nylon and resin by an SLA printer; and then a 20-$\mu$m thick copper layer was plated on the 3D printed antenna. The copper layer may need to be taken into consideration during the design, depending on the frequency and antenna dimensions. As shown in Figure 6, there are some small holes on the waveguide, which aim to facilitate the electroplating process, as the plating solution can flow into the antenna without the need of splitting the antenna. Moreover, the holes also have the ability to further reduce the weight of the FPCA. With properly selected positions, these holes do not affect the electric properties of the FPCA. The weight of the prototype is 190 g, which is only 13% of the one fabricated with copper.

The fabricated FPCA was measured for verification. The reflection coefficient of the prototype was measured by an Agilent E8362B network analyser, as shown in Figure 7. As depicted, the measured and simulated input reflection coefficients $|S_{11}|$ agree well, with a very slight frequency shift. The measured $|S_{11}| \leq 10$ dB bandwidth of the FPCA is approximately 6.4% (from 5.65 to 6.02 GHz).
Fig 9  Directivity and gain of the FPCA versus the frequency plane at 5.8 GHz

Fig 8  Radiation patterns of the FPCA on. (a) E plane at 5.8 GHz. (b) H plane at 5.8 GHz

The radiation performance of the FPCA was measured in an anechoic chamber. Figures 8 and 9 show the simulated and measured radiation patterns on E and H planes at the operating frequency of 5.8 GHz and the gain versus the frequency, respectively, which are also in good agreement. The directivity of the FPCA is 17.21 dB at 5.8 GHz, corresponding to the gain versus the frequency due to that the broadside beam is splitted. Moreover, the measured 10 dB bandwidth is 2.3% (from 5.63 to 5.90 GHz). The gain decreases at high frequency due to that the broadside beam is splitted. The measured SLLs on E and H plane are approximately 6.4% (from 5.65 to 6.02 GHz). The SLLs on E and H plane are −14.03 and −21.62 dB, respectively.

Conclusion: A lightweight 3D printed metallized FPCA has been presented in this letter. Different from other metallic FPCA, a non-uniform grid superstrate and a choke groove have been used to enhance the bandwidth and reduce the SLLs. The fabricated FPCA is merely 190 g in weight, which is only 13% of a same FPCA made of copper. An excellent agreement between the measured and simulated results has been observed, which demonstrates a high fabrication accuracy. The measured $|S_{11}|$ = 10 dB bandwidth of the FPCA has been improved to approximately 6.4% (from 5.65 to 6.02 GHz). The SLLs on E and H plane are −14.03 and −21.62 dB, respectively.

Acknowledgments: This work was supported by Civil Aerospace Technology Research Project (D010201).

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Received: 31 January 2021  Accepted: 2 March 2021

doi: 10.1049/ell2.12147

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Table 1. Comparison between our proposed design and others in the literature

| Ref. | Structure | Size (λ) | $|S_{11}|$ (10 dB bandwidth) | Gain and SLL (dB) | Other features |
|------|-----------|----------|-----------------------------|------------------|---------------|
| [3]  | PCB       | (1.75)$^2$ $\times$ 0.95 | 4.7%                         | 19.4/−18         |               |
| [7]  | Metal     | $11 \times 11 \times 0.43$ | −                               | 27.8/−          |               |
| [8]  | Metal     | $1 \times 1 \times 0.34$  | 14.7%                         | 12/−15          |               |
| [9]  | Metal     | $1.85 \times 1.85 \times 1.0$ | 10%                           | 15.9/−20        | Stacked cavity |
|      |           |          |                              |                  |               |

This work 3D print 2.4 $\times$ 2.4 $\times$ 0.8 6.4% 16.1/−14 Low weight

*Feed structure is not included in the height, which is flexible and depends on the application scenarios.