The Use of Reflection and Transmission Models to Design Wideband and Dual-Band Fabry-Perot Cavity Antennas (Invited Paper)

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Abstract—This paper explores how wideband and multi-band performance can be achieved in Fabry-Perot resonant cavity antennas using two design methodologies, one based on a Reflection Model of a unit cell and the other based on a Transmission Model of a unit cell. In particular, two wideband antenna designs and two dual-band designs are considered. They include low-profile planar metallo-dielectric antennas based on one printed dielectric slab and very simple antennas based on two unprinted all-dielectric slabs. Desired wideband or multi-band performance is achieved either by engineering the reflection phase and magnitude of the superstrate using the Reflection Model or by extending the defect-mode bandwidth using the Transmission Model. Key theoretical and experimental results are presented to highlight the advantages of selected antenna designs.

I. INTRODUCTION

A Fabry-Perot cavity antenna (FPCA) usually consists of a primary feed antenna located in a resonant cavity that is formed between a perfect reflector (e.g., a metal ground plane or an artificial magnetic conductor (AMC)) and a partially reflecting superstrate (PRS) structure, which can be one-dimensional (1-D), two-dimensional (2-D), or three-dimensional [1-6]. Typically, to achieve high antenna directivity, strong PRS reflectivity (∼0.6-0.9) is required [3]. Cavities with high quality factors (Q-factor) often lead to antennas with high directivities and narrow bandwidths. To achieve the required operating bandwidth, one can use fewer elements in a sparse array configuration [7] while still avoiding grating lobes.

The radiation phenomenon of such FPCCs can be explained in terms of leaky waves. When the cavity height is approximately half-wavelength, the gain enhancement is achieved as the resonance conditions of a substrate-superstrate assembly are satisfied [8]. A transverse equivalent network (TEN) model has been developed to analyze the radiation characteristics and resonance conditions of this class of antennas with multiple substrate-superstrate structures excited by a horizontal electric dipole [9]. Full-wave numerical methods are often utilized to achieve good overall antenna performance by matching the inputs of FPCCs to standard 50Ω feed lines.

In this paper, we explore the ways of achieving wideband and multi-band operation from FPCCs using two design methodologies. In particular, we focus on two wideband antenna designs and two dual-band antenna designs.

II. DESIGN METHODOLOGY

It is well known that defects or resonant inclusions can be introduced to an EBG structure to form localized transmission windows within the bandgap [2]. EBG structures with defects behave as narrowband transmission filters as well as spatial filters in which the defect restricts the waves to propagate only in certain directions. Therefore, the transmission and reflection analysis of EBG structures give useful insight into how they can guide, filter, reflect or collimate electromagnetic waves. The frequency response of such structures can be easily obtained numerically using FDTD-based or FEM-based electromagnetic solvers. ANSYS HFSS and CST Microwave Studio are two commercially available software packages commonly used for this purpose.

We have employed two methods to design FPCCs. One method is based on the computation of the reflection coefficient of the superstrate structure, shown as Γ in the Reflection Model given in Fig. 1(a). In the other method, the ground plane is removed, the image of the superstrate structure is introduced as shown in Fig. 1(b) and transmission through this Transmission Model is investigated.

A. Transmission Model

Consider a simple FPCA, made out of two unprinted dielectric slabs. Its Reflection Model with the ground is shown in Fig. 1(a) and its Transmission Model without the ground but with the image is shown in Fig. 1(b). The latter can be considered as an air-cavity defect in a truncated EBG structure. The frequency response of such structures is well-established
and is described using the theory of multilayer structures in which each dielectric layer is characterized by its own scattering matrix. The transmission response of one such EBG structure with and without the defect is shown in Fig. 1(c). This EBG structure consists of two dielectric slabs of same permittivity ($\varepsilon_1 = \varepsilon_2 = 9.2$), separated by an air gap. All layers are $\lambda/4$ thick. The narrow bandwidth of the defect mode in Fig. 1(c) indicates that the corresponding antenna would be narrowband. In order to increase the antenna bandwidth, the width of the defect band should be increased, as shown later with an example.

In this section, we reached in the previous section using the Transmission Model. In order to design a wideband antenna, the reflection phase of the superstrate structure should be engineered to follow the ideal curve in the operating bandwidth. Multi-band antennas can be designed by making the two curves to intersect at multiple frequencies. These design approaches are demonstrated with examples in the following sections.

![Reflection Model](image)

**B. Reflection Model**

Reflection phase of the superstrate (i.e., the angle of $\Gamma$ in Fig. 1(a), denoted by $\varphi_{EBG}$ hereafter) reveals interesting information. The reflection phase of a typical superstrate decreases with increasing frequency, as shown in Fig. 2. For a given cavity height, there exists an ideal superstrate phase that makes the cavity to resonate at a given frequency. Fig. 2 also shows this ideal phase. It is possible to form an efficient antenna when $\varphi_{EBG}$ is equal to the ideal superstrate phase. In Fig. 2, this happens only at one frequency hence only a single-band antenna is possible with this superstrate structure. Furthermore, as $\varphi_{EBG}$ curve has a negative gradient and the ideal curve has a positive gradient, the resulting antenna would be narrowband. Note that this is the same conclusion we reached in the previous section using the Transmission Model.

![Reflection Phase vs Frequency](image)

**C. Conditions for Directivity Enhancement**

For efficient antenna operation, the Fabry-Perot resonance condition must be satisfied in the frequency range of interest. Referring to Fig. 1(a), this translates into following three conditions: (i) the phase of $\Gamma$ must be close to the ideal value, (ii) the magnitude of $\Gamma$ must be sufficiently large (typically $> -4$ dB), and (iii) in the Transmission Model (e.g. Fig. 1(b)), the tangential component of the electric field must vanish at the symmetry plane.

![Reflection Phase vs Frequency](image)

**D. Impedance Matching**

To achieve good overall antenna performance including overall efficiency, in addition to good radiation characteristics, the antenna input should be well matched to standard 50Ω feed lines. This often requires designing an appropriate primary-feed antenna to feed the cavity. This has been successfully achieved for all designs presented in the next section through analyses of complete antennas using full-wave numerical methods.

### III. Multi-Band FPCAs

In this section, let us explore two dual-band FPCA designs resulted from the application of the Reflection Model to engineer the phase of the superstrate structure. The first design utilizes a single dielectric superstrate with a 2-D printed pattern on one of its surfaces. The second design needs two simple unprinted all-dielectric slabs. The design methodology is to make the superstrate phase curve meet the ideal phase curve at both operating bands while achieving a sufficiently strong reflection phase magnitude.

**A. Dual-band FPCA with Thin Printed PRS**

A thin single-layer PRS superstrate with a printed pattern on one side can be designed to achieve a dual-band antenna.
Fig. 3 shows an example dual-band antenna designed to operate at 5.2 GHz and 5.8 GHz for Wi-Fi IEEE802.11a/n and HiperLAN2 [10]. Note that only a single array of slots is etched on the lower surface of the 0.8mm-thick FR4 substrate.

Fig. 3. Dual-band FPCA: (a) PRS with slots on lower surface (b) unit cell (c) antenna configuration and printed monopole feed [10]. h = 26.5 mm.

The PRS reflection phase exhibits a sharp positive gradient around its resonance frequency. The PRS resonance frequency is different from the cavity resonance frequency, and is entirely determined by the slots in the PRS. This rapid phase increase has been exploited to satisfy the cavity resonance condition at two distinct frequencies, one below and one above the PRS resonance frequency. A dual-band FPCA, made out of this PRS and excited by a probe-fed printed monopole, has peak directivities of 18.5 dBi and 21 dBi at 5.2 GHz and 5.8 GHz, respectively. The 10dB return-loss bandwidths are 4.3% and 4.8% at the center of the lower and higher frequency bands, respectively.

### B. Dual-band FPCA with Unprinted Dielectric Slabs

The same methodology can be applied to design a simple dual-band FPCA, made out of two plain unprinted all-dielectric slabs. The two slabs have the same thickness and dielectric permittivity and can be made out of low-cost FR4 material [11]. Fig. 4 shows the reflection phase curves of an example EBG structure for different values of inter-slab spacing ‘h1’.

Let us consider the case for h1 = 10 mm. The superstrate reflection phase curve meets the ideal curve at three frequencies. However, the reflection coefficient magnitude is very low and the superstrate is nearly transparent at 15 GHz (f266) because the secondary cavity (between the two slabs) resonates at f266. Hence high directivity is not possible at this frequency but it is possible at the other two crossing points at 13.5 GHz and 16.2 GHz. The reflection magnitude is strong enough at these two frequencies so both the magnitude and phase conditions for Fabry-Perot cavity resonance are fulfilled. The result is a dual-band antenna.

Fig. 4. Reflection phase of the superstrate structure and the desired reflection phase for Fabry-Perot cavity resonance. Material: TMM10 (εr = 9.2), h = 10 mm, slab thickness = 1.6 mm.

A prototype of such a simple high-gain dual-band linearly-polarized FPCA is shown in Fig. 5. With this antenna configuration, peak gains of about 17.5 and 18.5 dBi, and 10dB return-loss bandwidths of 3.8% and 3.4%, have been measured in our lab at 9.5 GHz and 11.5 GHz, respectively. Thus, the design methodology has been validated.

Fig. 5. A dual-band FPCA based on two unprinted 3.2mm-thick TMM10 slabs (εr = 9.2). The slabs are held by nylon spacers.

### IV. WIDEBAND FPCAS

According to the Transmission Model, a wideband FPCA needs a wide defect mode. According to the Reflection Model, the reflection phase of the superstrate should be engineered to follow the ideal phase curve. This often requires inverting the gradient of the phase from negative to positive over a wide operating frequency band. Furthermore, the reflection coefficient magnitude should be sufficiently large (generally greater than −4dB) over the same wide band to ensure cavity resonance. Based on these observations, several wideband FPCAs have been realized. Here we explore two example designs: first based on a thin PRS with printed 2-D patterns on both surfaces and the second made out of two unprinted simple dielectric slabs.

#### A. Wideband FPCA with Thin Printed PRS

Fig. 6 shows a thin PRS composed of single dielectric slab with two-dimensional dipole arrays printed on both surfaces. The advantage is that the antenna is low-profile, with the antenna height only slightly greater than the cavity height. The concept is to control the strength of the PRS composite resonance appropriately and hence the reflection phase gradient and the minimum reflection magnitude. This is
achieved by making dipoles on one side to resonate close to the lower end of the band and those on the other side to resonate around the upper end of the band [12].

The PRS is made from 1.6mm-thick RT/Duriod 5880 material (εr = 2.2), its total thickness is 0.064λ0 and has overall dimensions of 110 × 110 mm², i.e., about 4.5λ × 4.5λ at midband (12 GHz). The two dipole arrays printed on the two sides of PRS include 12×18 dipoles. The antenna has a large 295×295 mm² ground plane. The cavity height is 13.2 mm. The antenna achieves a wide 3-dB gain bandwidth, from about 11.1 GHz to 13 GHz, i.e. a bandwidth of 15.7% with a peak gain of 16.1 dBi at 11.5 GHz. Within the 3-dB bandwidth, fairly good radiation patterns and sidelobe levels are achieved. The antenna is well matched from 11.5 GHz to 16.5 GHz.

B. Wideband FPCA with Two Unprinted Dielectric Slabs

A simple superstrate structure made out of unprinted slabs can be designed to exhibit wideband cavity resonance. We have recently investigated a configuration, similar to the one shown in Fig. 1(a) that utilizes two unprinted dielectric slabs of same thickness. In this case, let us employ the Transmission Model with the image for this investigation. By creating a dielectric contrast between the two slabs and by optimizing the distance h1 between them, an overall EBG structure can be configured to obtain two overlapping defect modes with a wide half-power bandwidth, as shown in Fig. 7.

![Defect-mode transmission of a classical resonator and a wideband resonator](image)

We have recently designed and successfully implemented a wideband FPCA based on this simple superstrate structure. It has small lateral dimensions (1.9λ0×1.9λ0 at 13 GHz) and is fed by single source in the middle. The predicted peak directivity is 17.2 dBi at 13 GHz. The 3-dB directivity bandwidth is extremely wide and extends from 10.65 GHz to 15 GHz (≈35%). The antenna is well matched and its impedance bandwidth extends from 11.0 GHz to 15 GHz.

V. CONCLUSION

It is possible to design a FPCA to operate over a wide band or multiple bands using the methods outlined. The Reflection Model or the Transmission Model of a unit cell can be utilized to design the superstrate but the simulation of the complete antenna is required to match the antenna input to a standard 50Ω feed line to achieve good overall antenna performance. When a low-profile antenna is required, PRS-type single-layer metallo-dielectric printed superstrates can be designed to achieve wideband or dual-band operation. When simplicity is desirable, two or more unprinted all-dielectric slabs can be used to achieve the same.

REFERENCES


