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Review:

Research progress on Fabry-Perot resonator antenna*

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Abstract: The Fabry-Perot resonator (FPR) antenna has found wide applications in microwave and millimeter waves and recently attracted considerable interest. In this paper, a summary of planar and cylindrical structures, analytic models and research development is presented, and a comparison between these structures and analytic models is made, showing that such analytic models as the FP cavity mode, electromagnetic band gap (EBG) defect mode, transmission line mode, and leaky-wave mode are consistent when applied to analyze this type of resonator antenna. Some interesting topics under recent research, including dual or multi-band, improvement of gain bandwidth, low profile and beam control, are surveyed.

Key words: Fabry-Perot resonator (FPR) antenna, Electromagnetic band gap (EBG) resonator antenna, Leaky-wave antenna, Defect mode, Artificial magnetic conductor (AMC), Frequency selective surface (FSS)

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INTRODUCTION

A Fabry-Perot resonator (FPR) antenna generally consists of a primary radiator backed with a metal ground plate and a partially reflective covered plate (Trentini, 1956). When the spacing between these plates is about an integer multiple of $\lambda/2$, the forward radiation can be enhanced remarkably by means of in-phase bouncing. The single-feed system allows the gain to be increased with low complexity, as compared to the feeding networks used in conventional antenna arrays, and has drawn more and more attention. Various configurations have been designed in the past years and produced high directivities at broadside. Here we provide a historical overview of such configurations, then show the fundamental principles of analytic modes from different viewpoints, and also make a comparison of these configurations. Additionally, some interesting topics that have been researched recently are surveyed in detail.

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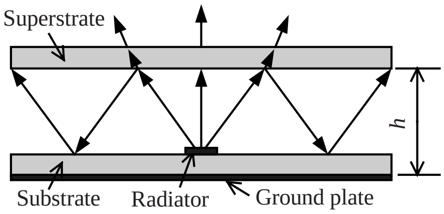
COMPARISON OF ANALYTIC MODELS

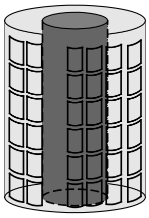
Trentini (1956) first used FPR structure excited by a single source to produce a high directivity at broadside. Successively, other fundamental studies were carried out in (Jackson and Alexopoulos, 1984; Jackson and Oliner, 1988). Recently, more attention has been paid to this type of resonator antenna. This strand of research has been, though different in starting points and focuses, mainly based on the following four analytic models.

FP cavity model

Fig.1a shows the geometry of the proposed FPR, which consists of a primary radiator backed with a metal ground plate and a leaky reflective covered plate. The distance between two parallel plates, with reflective coefficient phases φ_1 and φ_2 respectively, is h. From the ray viewpoint, an electromagnetic (EM) wave excited by the source is bounced in the FP cavity. In order to superpose in phase, the phase shift of the EM waves each return is an integer multiple of 2π, which can be written as



(a)



(b)

Fig.1 Geometry of the Fabry-Perot resonator antenna
(a) Planar type; (b) Cylindrical type

$$-4\pi h/\lambda+\varphi_1+\varphi_2=N\cdot 2\pi,\quad N=0,1,2,\cdots \tag{1}$$

The resonant frequency is determined by

$$f=[(\varphi_1+\varphi_2)/(2\pi)-N]\cdot c/(2h),\ \ N=0,1,2,\cdots, \tag{2}$$

where c is the velocity of light in vacuum (Trentini, 1956; Feresidis and Vardaxoglou, 2001). The minimum of the half power beamwidth of the FPR antenna, achieved near the resonant frequency, can be expressed as

$$\Delta\theta_{3\text{dB,min}}\approx\sqrt{Q/2}, \tag{3}$$

where Q is the quality factor and can be expressed as a function of the magnitude and phase of the reflection coefficient (Boutayeb *et al.*, 2006a).

EBG defect model

The concept of electromagnetic band gap (EBG) resonator antenna was proposed in (Thévenot *et al.*, 1999; Cheype *et al.*, 2002). In fact, the FPR antenna can be regarded as a kind of EBG resonator antenna with defect mode. When the periodicity is broken up due to some defects in EBG materials by inserting irregular components in the periodic structure, the EBG materials display localized frequency windows within the forbidden frequency band. This property is very useful for improving the directivity of an antenna when an EBG structure is used as a superstrate of the antenna. At the defect frequency, the superstrate alters the distribution of the EM fields along specific directions, and also serves to increase the aperture to one much larger than that of the original antenna, thus enhancing the directivity of the antenna in the process (Lee *et al.*2004a). The classic FPR antenna is a particularly interesting case of the EBG resonator antenna when only one slab dielectric superstrate, metamaterials, or a frequency selective surface (FSS) is considered (Liu, 2008). Two multilayer dielectric structures are shown in Fig.2: one is a uniform stack (Fig.2a) and the other contains a defect resonator (Fig.2b). The FPR antenna of Fig.1 exploits the symmetry of the structure in Fig.2b by positioning a ground plate at the image plane of the device. This forces the radiation into the half-space above the ground plane, and allows the placement of a feed antenna on the ground plane.

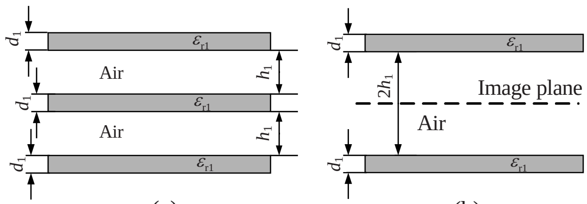


Fig.2 Structure of multi-layer EBG material with defect
(a) Three-layer; (b) Two-layer

Transmission line model

The transmission line model can also be used to analyze the FPR antenna (Jackson and Alexopoulos, 1985; Yang and Alexopoulos, 1987; Jackson *et al.*, 1993; Zhao *et al.*, 2005a; 2005b; Gardelli *et al.*, 2006). It can act as a cascade model of transmission lines with different characteristic impedances when the EM wave propagates in FPR. Jackson and Alexopoulos (1985) established the resonant conditions and the simple asymptotic formulae of resonance gain, beamwidth, and bandwidth for substrate-superstrate antenna geometry by this model. The asymptotic formulae of gain, beamwidth, and bandwidth have been presented for the cases of broadside radiation and for scanning to an arbitrary angle. The resonance conditions derived from the transmission line model are consistent with those derived from the FP cavity model. In (Boutayeb and Tarot, 2006), the normalized transmission coefficient, derived by using a transmission line model and considering the available power from the source, was proposed to analyze the FPR antenna.

Leaky-wave model

The leaky-wave radiation of the microstrip antenna with a superstrate has been examined in (Alexopoulos and Jackson, 1984; Jackson and Oliner, 1988). Starting from the spectral Green's function, the field can be calculated by contour integration. When deforming into the steepest-descent path that passes through the saddle point, the integral contour may cross not only the surface wave poles (the proper Riemann sheet), but also the leaky-wave poles (the improper Riemann sheet). A proper choice of substrate and superstrate thicknesses can generate a resonance condition, whereby the leaky-wave poles become a dominant contribution to the far field and determine the radiation pattern. It can be validated that the resonance condition obtained by the leaky-wave model is the same as that by the transmission line model. Some interesting features can be observed as the leaky-wave pole positions are traced as a function of frequency in the steepest-descent plane.

The four analytic models mentioned above have different purposes. For example, the FP cavity model from the ray viewpoint and the transmission line model from the circuit viewpoint provide quick initial design guidelines, whereas the leaky-wave model generates accurate results and the EBG defect model offers a novel mechanism. They nevertheless can be validated by each other and thus are in essence consistent in analyzing the FPR antenna.

RESEARCH DYNAMICS AND DIRECTIONS

The first way of producing a high directivity antenna excited by a single source was introduced in (Trentini, 1956). Successively, other fundamental studies were conductd in (Alexopoulos and Jackson, 1984; Jackson and Oliner, 1988), where the reflective surface was substituted by a dense dielectric. Alexopoulos and Jackson (1984) first proposed the important idea that the excitation of a leaky wave contributes to the high directivity. A high directivity patch antenna using an EBG cover together with an EBG substrate was designed in (Qiu and He, 2001; Zhu *et al*., 2003), which is very efficient for the improvement of the radiation directivity. However, the EBG superstrate made of dielectric rod layers (Lee *et al.*, 2005a; Weily *et al.*, 2005b) or plates (Wu and Guan, 2004; Weily *et al.*, 2005a) is difficult to fabricate in practice. FSSs can be good candidates to dielectric rod layers and plates (Lee *et al.*, 2004b; Thévenot *et al.*, 2007). Various configurations of the FPR antenna have been designed in the past years, which can be categorized into the following four types according to their research directions.

Dual band or multi-band

Based on the defect model, Lee *et al.*(2004a) proposed a novel design by introducing the second defect to control the defect frequencies of an EBG superstrate with the objective of enhancing the directivity of a patch antenna at two frequencies (Fig.3). Successively, in the newly proposed design (Lee *et al.*, 2005b), two strip-dipole arrays acted as FSSs with the same periodicity but different alignments. The two strip-dipole arrays were placed above and below a thin dielectric layer to achieve a dual band operation (Fig.4a). Pirhadi and Hakkak (2007) proposed a compact and dual band FPR antenna, only one layer superstrate with an appropriate FSS structure (Fig.4b). By incorporating more defects or designing an appropriate FSS structure, this type of antenna with multi-band operation can be achieved.

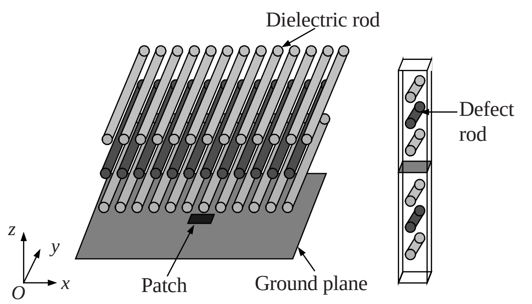


Fig.3 Geometry of a patch antenna with defect EBG superstrate

Improvement of gain bandwidth

The cavity resonance, though increasing the directivity of simple radiating sources, narrows the operational bandwidth significantly. Then the gain enhancement and the bandwidth broadening become a severe challenge. Incorporating EBG and FSS structures, Ge *et al.*(2006) proposed a broadband FPR antenna. Liu *et al.*(2008) presented a new method for obtaining broadband FPR antennae while maintaining

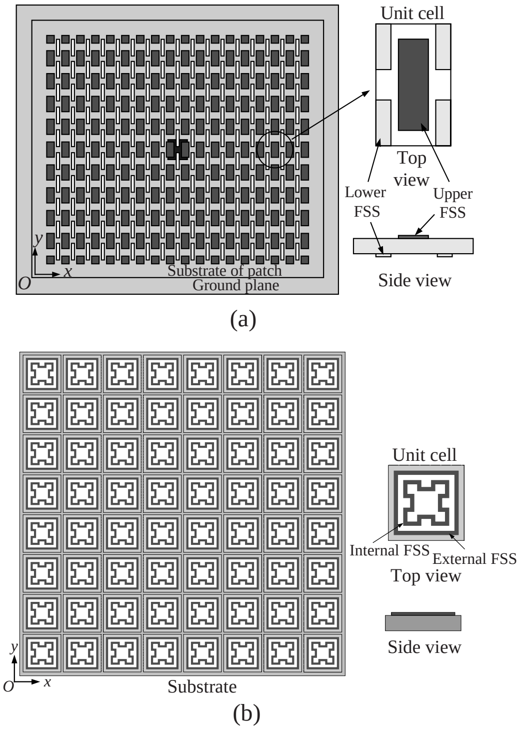


Fig.4 Geometry of the FPR antenna with FSS superstrate
(a) Two-layer FSS; (b) Single-layer FSS

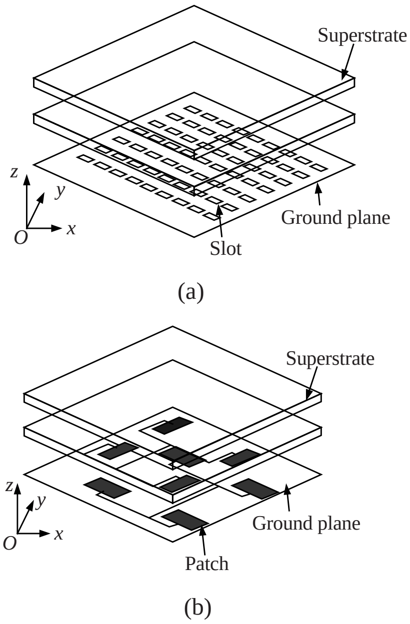


Fig.6 Geometry of the FPR antenna with array feed
(a) Slot array; (b) Dual polarized sparse microstrip array

the high-gain performance. They used a single-layer FSS superstrate with a tapered size element as the reflective covered plate to compensate the phase shift caused by different path lengths (Fig.5). The total reflect field can then be made in-phase superposition in wide bandwidth. Another method to achieve a broadband operation is to replace the simple feed by the array feed (Gardelli *et al*., 2006; Weily *et al*., 2007) (Fig.6), making the field distribution of the aperture more uniform and hence attaining a wide bandwidth of gain.

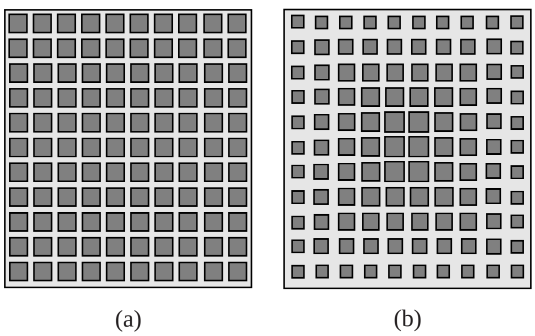


Fig.5 Structure of the FSS cover as a partially reflecting surface. (a) Uniform FSS; (b) Tapered FSS

Low profile

According to the resonant condition Eq.(1), the thickness of an FPR antenna is determined by

$$h=(\varphi_1+\varphi_2-2N\pi)\lambda/(4\pi),\ \ N=0,1,2,\cdots \tag{4}$$

Generally, the antenna profile has always been close to $\lambda/2$ due to $\varphi_1=\varphi_2=\pi$, but able to be reduced by changing the reflection phase. If we replace one plate by a metamaterial reflector that does not reflect with $\varphi=\pi$, the half wavelength restriction can be lifted. For instance, artificial magnetic conductor (AMC) reflectors reflect with $\varphi=0$ at some particular frequencies (Wang *et al.*, 2004; Feresidis *et al.*, 2005; Zhou *et al.*, 2005). Working at these frequencies, a cavity requires only a thickness $h=\lambda/4$. This idea can be pushed even further. If we select an appropriate reflection phase and let $\varphi_1=-\varphi_2$, the theoretical thickness value can be reduced to zero. Since all metamaterials are dispersive, such reflectors can reflect with arbitrary phases depending on *f*, which can in principle remove the lower limit on the cavity thickness.

Beam control

In many current communication systems, the feature of beam forming is required. Hao *et al.*(2004) have demonstrated that an antenna beam can be shaped by shifting the patch antennae from the centers of the cavities (Fig.7). Ourir *et al.*(2007a) proposed a compact steerable directive FPR antenna, as shown in Fig.8a. The phase-varying behaviour was obtained with a regular adjustment of the spacing between each unit cell of the capacitive grid, which forms the phase-varying partial reflecting surface. A ±20° deflection of the antenna beam was obtained. Ourir *et al.*(2007b) further considered the modeling and characterization of an electronically controllable metamaterial partially reflecting surface to an FPR antenna by the insertion of active electronic components, as shown in Fig.8b.

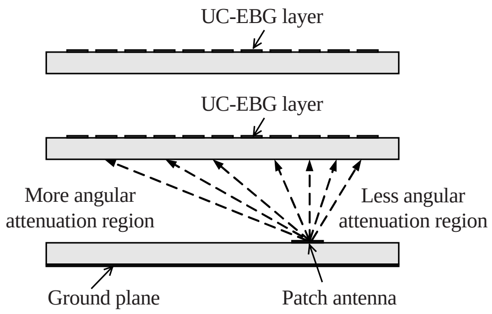


Fig.7 Side view of the layered FPR antenna proposed for antenna beam shaping

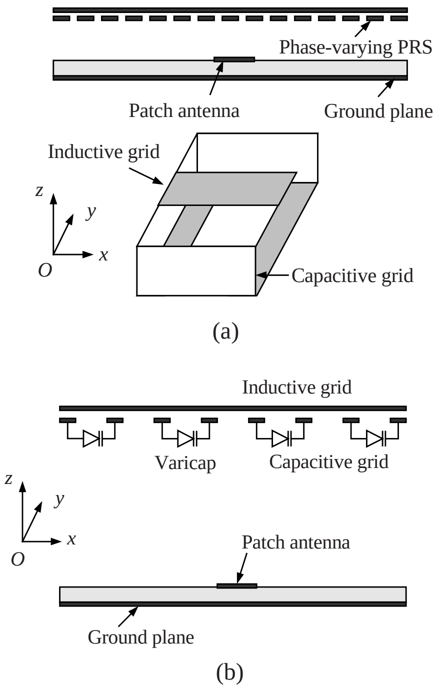


Fig.8 Schematic view of a steerable directive FPR antenna
(a) Mechanical control; (b) Electrical control

To realize an omnidirectional radiation pattern azimuthally, the basic structure presented in Fig.1a has been modified to introduce a revolutionary symmetry. In addition to a simple dipole source, a metallic cylinder acts as ground, and a cylindrical cover comprises a periodic array of FSSs (Palikaras *et al.*, 2004; Boutayeb *et al.*, 2006b; Feresidis *et al.*, 2007) (Fig.1b).

CONCLUSION

A detailed overview of the technology and analytic models for Fabry-Perot resonator antennae has been presented in this paper. It is indicated that the four analytic models, FP cavity, EBG defect, transmission line, and leaky-wave, are consistent in analyzing this type of resonator antenna, since these models can be validated by each other. The advantage of the FPR antenna is high directivity with only one or a few radiating elements, whereas the main disadvantage lies in the reduction of bandwidth. In view of this tension, making use of metamaterials to increase the antenna bandwidth can be further researched.

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