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REVIEW

High gain planar resonant cavity antennas based on metamaterial and frequency selective surfaces

Swati Vaid*, Ashok Mittal

Ambedkar Institute of Advanced Communication Technologies and Research, Dept of Electronics and Communication Engineering, Geeta Colony, Delhi 110031, India

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ABSTRACT

Resonant cavity antenna (RCA) consisting of frequency selective surfaces (FSS) or metamaterial surfaces, provides a low cost alternative to highly directive horn aperture antennas. In addition to this, quasi planar structure of RCA provides reduction in weight & size. Prior research in this field has shown that artificial surface based RCAs have interesting features which are not limited to highly directional radiation. Major research directions in this area are presented in this paper. Earlier research revealed that RCAs could be configured for low profile antennas, reconfigurable antennas, antennas with wide bandwidth, antennas for multiband or antennas for circularly polarized radiation. A comprehensive summary of the pre-published research results is furnished here to indicate the lacunae along with the scope of future development in this area.

1. Introduction

In the year 1956, the concept of resonant cavity antenna based on partially reflecting superstrate was introduced by Trentini [1]. Since then, it had attracted significant attention because of the interesting features like light weight and highly directive properties of these antennas needed for high speed wireless and satellite applications. The basic configuration of RCA is shown in Fig. 1. It consists of a primary source, most commonly a planar antenna (e.g. a microstrip printed circuit antenna) which feeds the cavity formed by the antenna ground plane & the superstrate. This structure is addressed by different names in the literature, like "Reflex cavity antenna", "Fabry–Perot cavity antenna", "electromagnetic band gap (EBG) antenna", "planar leaky-wave antenna", and many other variations of these names [2–9].

Fundamental principle behind the operation of RCA can be explained as: the electromagnetic waves originating from the primary source experience multiple reflections within the cavity. Certain part of their energy is transmitted out from the superstrate during reflection. Height of the cavity is opted (typical) so that the reflected waves in the cavity sum up constructively and the directivity of the primary source get enhanced. So this antenna composite obviates the need for a complex feed network to realize high directivity. Apart from the height of the cavity, the radiation properties of RCA also depends on the reflection characteristics of ground plane and superstrate. Therefore besides the design flexibility in the primary antenna, configurability of superstrate and ground plane provides an additional flexibility in the design of RCA.

Various artificial surfaces are used in RCA for configuring the ground plane characteristics artificially or as superstrate. Few examples of the artificial surfaces are metamaterial surfaces such as high impedance surface, artificial magnetic conductor, near zero refractive index media and frequency selective surfaces. These artificial surfaces, i.e. frequency selective surfaces and metasurfaces, consist of periodic 2-dimensional array of metallic or dielectric scatterers. Here, the term 2-dimensional array suggests that the thickness of the scatterers is kept small as compared to the wavelength of operation. Metamaterial surface or metasurface is a surface formed by the distribution of electrically small scatterers chosen to achieve desired behaviour [10–12] whereas FSS is a composite material [13]. Both these surfaces are conceptually different. The difference between the two comes mainly from the periodicity and size of the scatterers. In the case of metasurface, the periodicity is kept smaller than the wavelength and scatterers are arranged in such a manner that these can resonate. This complete material behaves as an effective homogeneous medium which can be characterized by the electric and magnetic polarizabilities of its constituent scatterers or surface susceptibilities. Whereas in FSS, scatterers have period larger or comparable with the wavelength

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* Corresponding author. Tel.: +91 9654809600.
E-mail addresses: vaid2006@gmail.com (S. Vaid), ashok.mittal@ieee.org (A. Mittal).

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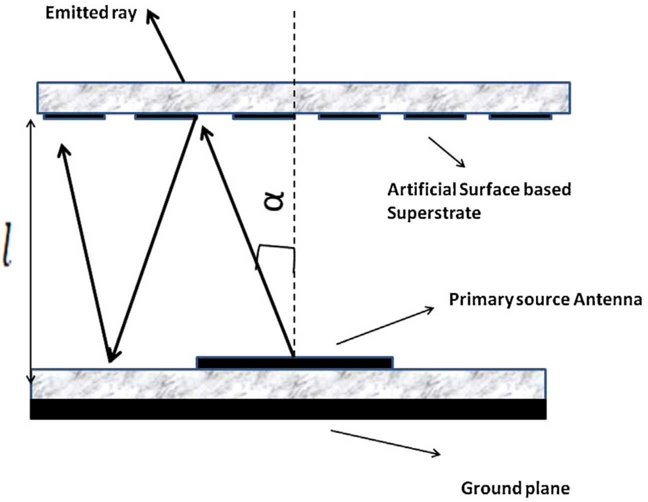

Fig. 1. Basic configuration of artificial surface based resonant cavity antenna.

and the material no longer behaves as an effective medium. FSS exhibits lattice dispersion and is characterized by reflectivity and transmittivity.

Metamaterial and FSS based low profile multiband or tunable RCAs show immense scope for emerging high speed wireless applications such as next generation mobile networks (5G), software defined or cognitive radio, etc. This adds to the motivation to review the progress in research in this area. This paper has summarized the interesting capabilities of RCAs after the inclusion of Metasurface and(or) FSS. Further to the introduction above, Subsequent sections of this paper discuss the basic principle and the research progress in RCA.

2. Literature review

RCA has been analyzed in the past using different analysis models i.e. ray optic model [1], EBG defect model [3], leaky wave model [5,6], transverse equivalent network model [14–18]. Out of these models, the ray optic model gives a simpler conceptual picture of the working mechanism of RCA. So, ray optic model is discussed here, specifically in the context of the prevailing research. However, this model has its own shortcomings. For example, it does give an insight about the pattern bandwidth but it is unable to explain the impedance bandwidth of a RCA, i.e. whether it can be enhanced or not be enhanced [19,20].

It is important to note here that the explanation for the operation of metasurfaces based highly directive RCA needs a greater detail because metasurface is characterized by surface susceptibilities rather than reflectivity and transmittivity. To find the detailed explanation of metasurface based RCA, papers discussed here may be referred.

Assuming the reflection coefficient of the superstrate is $\rho e^{j\varphi}$ and of the ground is $\rho_g e^{j\varphi g}$, this configuration can produce boresight ($\alpha = 0$ degrees) directivity D relative to that of primary antenna at the far field at a particular frequency f (α is the direction from the normal to the superstrate)

$$D = \left(\frac{(1 + |\rho(f, \alpha = 0)|)}{(1 - |\rho(f, \alpha = 0)|)} \right). \tag{1}$$

If the following condition is satisfied for $\alpha = 0$:

$$\varphi + \varphi_g - (2\boldsymbol{\pi} 2l)\cos\alpha/\boldsymbol{\lambda} = 2N\boldsymbol{\pi}. \tag{2}$$

$N = 0, \pm 1, \pm 2, \pm 3$ represent the resonances in the cavity.

The half-power fractional bandwidth (HPBW or pattern bandwidth) of highly reflecting superstrate with frequency independent reflection characteristics can be calculated by using the below mentioned formula

$$\mathrm{HPBW} = \left(\frac{(1 - \rho)}{(2\boldsymbol{\pi} l\, \rho^{0.5})} \right). \tag{3}$$

As one can see from Eq. (1), the directivity or gain depends on the reflectivity ρ of the superstrate and it increases considerably with ρ. So, high gain can be obtained with a highly reflective screen. However, Eq. (3) shows that higher reflectivity results in narrower HPBW of the antenna. It was also mentioned by Feresidis et al. [21], that narrower bandwidth is expected for antenna heights beyond the first one obtained from Eq. (3). In addition, as $\boldsymbol{N}$ increases the side lobes in the radiation pattern become higher.

The recent research directions in RCA based on metasurfaces and FSS can be broadly divided into four main categories namely low profile, improved bandwidth or multiband, circularly polarized and reconfigurable RCA.

2.1. Low profile RCA

The phase of the reflection coefficient of ideal ground (PEC) is $\varphi_g = \boldsymbol{\pi}$, so if a superstrate is used above PEC ground which has a reflection phase of $\varphi = \boldsymbol{\pi}$, the cavity height (i.e. the antenna profile) for higher boresight directivity comes out to be half a wavelength (for $N = 1$) using Eq. (2) but if the phases of the reflection coefficients of ground and superstrate are manipulated such that $\varphi = -\varphi_g$, the theoretical antenna profile can be reduced to zero (for $N = 1$). Using this concept, reduced profile RCA has been reported in the literature.

In 2001, A.P. Feresidis and J.C. Vardaxoglou [21] investigated the effect of using FSS on top of waveguide aperture antennas. Then in 2004-2006 [22–24] the same group proposed a low profile RCA by using AMC ground plane with FSS superstrate. And the profile of the antenna is reduced up to $\boldsymbol{\lambda}/4$ to $\boldsymbol{\lambda}/6$ with 12 dB enhancement in the gain of primary source. At the same time Ourir et al. [25] reduced the profile up to $\boldsymbol{\lambda}/30$ to $\boldsymbol{\lambda}/60$ with approx. 15 dB enhancement in directivity of primary source by using a 2-D composite metamaterial, made of capacitive and inductive grids for applications to ultra-thin RCA. Much recently, the profile of the RCA has been reduced to $\boldsymbol{\lambda}/125$ [30] with 6.4 dB gain enhancement by using fishnet superstrate and mushroom type EBG ground plane. Instead of single source, ultra thin RCA's (profile $\approx \boldsymbol{\lambda}/17$ to $\boldsymbol{\lambda}/22$) are also fed with multiple sources or array antenna [26,28], which resulted in array thinning and side lobe reduction. An important point to note here is that there is an extent up to which we can reduce the profile of the RCA because the more the profile gets reduced lesser would be the impedance bandwidth of the RCA as the quality factor will increase. A detailed survey is tabulated in Table 1.

In addition to the papers mentioned above and in Table 1, there are some low profile RCA designs using meta-surfaces exhibiting near zero permeability [31] and artificial magnetic superstrates [32].

2.2. Improved bandwidth or multiband RCA

The literature reported in this category can be subdivided in two sub-categories. This is done because an antenna bandwidth can be defined in two different ways i.e. pattern bandwidth (Half power bandwidth) and impedance bandwidth:

2.2.1. RCA with wide pattern BW (or multiband)

The studies in the literature show that the pattern bandwidth of RCA depends primarily on the characteristics of superstrate or its ground plane. The various techniques used for improving pattern bandwidth are mentioned below: