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Analysis and design of ring-resonator integrated hemi-elliptical lens antenna at terahertz frequency

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ABSTRACT

In this paper, a novel lens integrated ring-resonator microstrip antenna is analyzed and simulated at 600 GHz. A mathematical model to compute the directivity of this kind of the antenna has been developed and the directivity of the antenna has been computed which is 18 dBi. The proposed model has been simulated by using CST Microwave Studio a commercially available simulator based on finite integral technique and similar result has been obtained. Further, the directivity of the antenna has also been computed by using the techniques reported in the literature and in this case also we have obtained the similar result. Later, a probe-fed patch integrated lens antenna has also been investigated to validate the correctness of the numerical method. To find the potential advantages of this kind of the structure, the −10 dB impedance bandwidth of the antenna has been compared to a lens-integrated probe-fed microstrip patch antenna and a significant enhancement in the bandwidth has been observed.

1. Introduction

The growing demand of high data rate in the wireless communication system has invited the attention of scientists and researchers to explore the terahertz band-gap extending from 100 GHz to 10 THz of the electromagnetic spectrum [1,2]. However, with the increase in operating frequency above 100 GHz, the signal path-loss is excessive except in a few low-atmospheric windows [3]. To overcome the path-loss in order to realize a practical terahertz communication system, it is necessary to improve the directivity of an antenna used in the wireless communication [4]. Due to the demand of the high directivity, various variant of the dielectric lens antenna has remained a favorable choice of the scientific community. This kind of the antenna has extensively been used in the time domain spectroscopy at terahertz frequency [5,6]. Apart from this, in several communication systems at high frequency, the high directivity requirements are also met with the use of the reflector antennas working in tandem to the primary feed. However, the fabrication constraint of this kind of the antenna increases with the increase in the operating frequency and mechanical perfection is reduced. In place of this, at high frequency like quasi-optics, the dielectric lens antenna is preferred and it is used to correct the phase error of the horn antenna and to collimate the wave. Further, due to the collimating property, the dielectric lens also increases the directivity of the overall antenna system. The directivity of the lens antenna depends on relative dielectric permittivity of the material and size of the lens [7]. With the increase in relative dielectric permittivity and size of the lens, the directivity is increased. The increase in the size makes it unsuitable for the microwave applications but it is frequently used in the terahertz domain due to the high directivity. On this way, in the terahertz domain as well as in millimeter wavelength range, a number of lens antennas have been studied theoretically and numerically in [8–15]. The study of these antennas reveals that any primary source can be integrated with the dielectric lens to enhance the overall directivity of the antenna system.

To the best of author's knowledge, this study has been confined to the analysis of the waveguide integrated [16,17], microstrip patch integrated [18], rectangular and circular slot integrated [19], hybrid [20], bowtie integrated [5], and proximity coupled [21] dielectric lens antennas. All these antenna configurations have their own merits and demerits. The ring-resonator antenna has not been used as the primary source. However, due to the variation in the size of the central conducting portion of the patch conductor, the resonance frequency of the antenna can be changed and it may work as the additional tuning parameter for the antenna [23].

In this contribution, we have proposed a hemi-elliptical dielectric lens integrated square ring-resonator-microstrip antenna at 600 GHz. The proposed antenna structure is fed by a narrow microstrip transmission-line. A simple analytical model has been developed to predict the directivity of this antenna. To validate the analytical model, the structure has been simulated by using the CST Microwave Studio and comparable results have been found. Moreover, the probe-fed patch integrated lens antenna has also been analyzed by using the proposed analytical model and its analytical directivity is also comparable with the simulated result. The organization of the paper is as follow. The Section 2 of the manuscript describes the geometrical parameters of the lens integrated ring-resonator antenna. In the

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Section 3, the theory of operation of the proposed antenna is presented. In the Section 4, the numerical analysis of the antenna is discussed. The comparison of analysis with simulation obtained by using CST Microwave studio is presented in the Section 5. The Section 6 explores the comparison of the analysis with other reported literature. In the Section 7, the performance of the lens integrated ring-resonator and a lens integrated probe-fed microstrip patch antenna is compared. Finally, the Section 8 concludes the work.

2. Antenna configuration

A ring-resonator, collimating lens and the lens integrated ring-resonator antenna are shown in Fig. 1 (a), Fig. 1(b) and (c), respectively.

In Fig. 1 (a), a ring-resonator microstrip antenna is shown. The square-ring-resonator's outer edge (W_1) and inner edge (W_2) are 320 μm and 300 μm long, respectively and it is fed by a microstrip transmission-line of length (L_f) and width (W_f) 1180 μm and 20 μm, respectively. The width (d) of the ground plane and substrate are 2400 μm each. The thickness of substrate is 50 μm. The ground plane is made of perfectly electric conductor (PEC) whose length (G) is 900 μm. The substrate of the ring-resonator antenna and the dielectric lens as shown in Fig. 1(a) and (b) is a low dielectric permittivity material (PTFE, $\varepsilon_r = 2.08$, $\tan\delta = 0.0004$). The lens is a truncated hemi-elliptical in nature and it has been extended as a rectangular block whose length is equal to 'L'. The thickness (d) of the extended rectangular block is 2400 μm. Other geometrical parameters of the hemi-elliptical lens are governed by the following Equations [22].

$$b = \frac{a}{\sqrt{1-1/\mu^2}} \tag{1}$$

$$c = b/n \tag{2}$$

$$\mu = \sqrt{\varepsilon_r} \tag{3}$$

In Equations (1), (2), and (3), a, b, and c are semi-minor axis, semi-major axis and focal point of the ellipse, respectively. Further, μ is the refractive index of the material. The values of the other parameters except L are calculated numerically for an elliptical lens. However, the value of L is determined by the parametric study. The structure as shown in Fig. 1 (c) is the proposed lens-integrated ring-resonator antenna which consists of two parts: a) ring structure and b) collimating lens as have shown in Fig. 1(a) and (b), respectively.

3. Theory of operation

From Fig. 1(c), it is revealed that the antenna consists of two parts (a) ring-resonator and (b) the collimating lens as discussed in Section 2. To analyze this kind of the antenna, it is necessary to study the behavior of the primary source (ring-resonator) and (b) the collimating lens.

3.1. Ring-resonator

Fig. 1 (a) depicts that ring-resonator is a primary source, which is used to excite the dielectric lens. The directivity of the antenna system depends on the directivity of the primary source and lens. To estimate the total directivity, it is necessary to analyze the directivity of the ring-resonator antenna. The behavior of ring-resonator antenna has been studied in detail in [23]. The directivity of this kind of the antenna depends on the ratio of inner edge (W_2) to the outer edge (W_1) of the loop and it is calculated by using the following Equation.

$$D_{0Ring} = \frac{4\pi}{{\lambda_0}^2} A_{em} \tag{4}$$

where D_{0Ring}, λ_0 and A_{em} are the directivity of the ring-resonator, free-space wavelength, and the effective area of the ring, respectively. The effective area A_{em} of the square ring-resonator antenna is related to the solid square patch (without removing inner conductor of the patch) by the following Equation.

$$A_{em} = A_{P1} \times \left(\frac{W_2}{W_1}\right)^2 \tag{5}$$

In Eq. (5),A_{P1}, $W_1$and $W_2$are physical area of the outer edge length of square ring-resonator and inner edge length of the solid square patch, respectively.

3.2. Analysis of the hemi-elliptical dielectric lens antenna

The front and side view of a rotationally asymmetric lens is shown in Fig. 2(a) and (b), respectively. From Fig. 2 (a), it is revealed that the collimating property of the hemi-elliptical lens is governed by the extended length (L), semi-major axis, semi-minor axis, and the thickness of the rectangular extended block of the slab (d), respectively.

Further, it is also revealed that the phase front of the wave at vertex of the lens is rectangular in nature and its area is equal to the area of bottom surface of the rectangular extension. The projection area at the vertex is equal to the area as shown in Fig. 2(b). On this way, due to the rotational asymmetric nature of the structure, the semi-minor-axis, thickness of the rectangular substrate (d) and total distance between source to the curved surface of the lens ($b+L$) are related by the following equations.

$$\theta_1 = \tan^{-1}\frac{a}{b+L} \tag{6}$$

$$\theta_2 = \tan^{-1}\frac{d/2}{b+L} \tag{7}$$

In Equation (6) and (7), θ_1 and θ_2 are angles between a, $b+L$ and $d/2$, $b+L$, *in* xz- and yz-planes, respectively. Just outside the curved surface

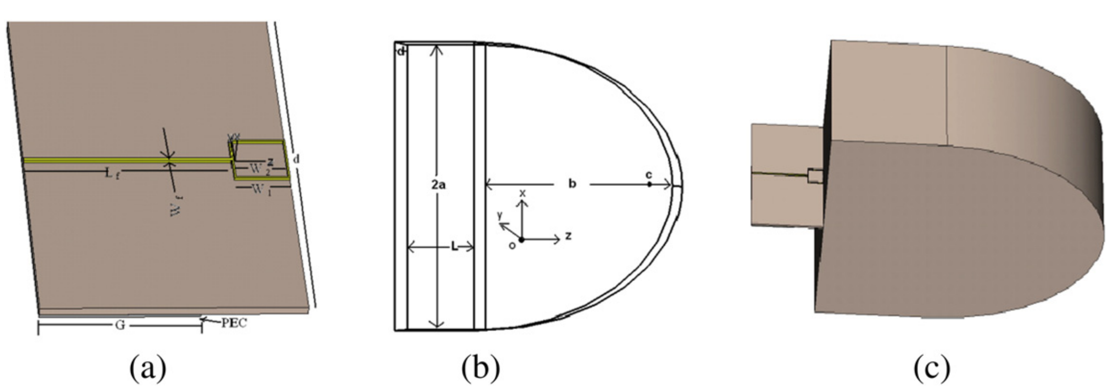

Fig. 1. The proposed (a) ring-resonator (b) collimating lens and (c) lens integrated-ring-resonator antenna.