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Microstrip patch array antenna on photonic crystal substrate at terahertz frequency ☆

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ABSTRACT

Recent advancement in the fabrication and packaging technology has led to the micrometer and nanometer-scale device modeling. This technological development and subsequent reduction in the dimension of devices like modulators, detectors and antennas has brought a thought of increasing the operating frequency of the system to the extent of sub-millimeter wavelength. In the view of the technical breakthrough in the area of fabrication and packaging, we have explored a printed antenna array on the photonic crystal in the terahertz spectrum in this paper. An equivalent circuit model of the antenna has been proposed and a methodology to investigate various electrical parameters is discussed. Tunable parameters of the structure have been explored to optimize the electrical performance of the proposed antenna. The analysis is also compared by using two simulators: (a) CST Microwave Studio based on finite integral technique and (b) Ansoft HFSS based on finite element method. The effect of the photonic crystal as substrate to enhance the gain of this kind of the antenna has also been demonstrated. The gain, directivity, front-to-back ratio (F/B ratio), and the radiation efficiency of the proposed antenna at 600 GHz is 16.88 dBi, 17.19 dBi, 14.77 dB and 89.72%, respectively. Finally, the performance of the antenna has been compared with the reported literature.

1. Introduction

Terahertz band gap, which extends from millimeter to far-infrared regime, is the least explored electromagnetic spectrum. Due to the unique properties like less hazardous effect on human being, ability to be used in astrophysics, spectroscopy, explosive detection, medical application and fine image resolution, various researchers are on the way of exploring this band of the electromagnetic spectrum [1–3]. In addition to this, recently we have reported a method of implementing a high gain terahertz microstrip antenna for the surveillance system, which would replace the multi-reflector surveillance system for explosive detection [4]. Apart from this, due to the continuous demand of higher bandwidth and high data-rate for wireless communication as well as the feasibility study of the application of lower terahertz spectrum in the wireless communication is also on progress [5,6]. With the advancement in the semiconductor technology, high frequency sources, modulators and detectors are also being invented [7,8] and it is predicted that within the short span of the time, the terahertz wireless/surveillance system would become reality. However, the power generated by sources in this frequency regime is comparatively low which cannot propagate longer distance. The atmospheric attenuation of the wave at this frequency is also high. It has been predicted that with the atmospheric attenuation of 100 dB/km, transmitted power of 1mW and receiver sensitivity of 1 pW, a communication or surveillance link up to 500 m can be established with the presently available resources [9]. To overcome the limitation of sources and detectors, it is necessary that the gain and directivity of an antenna used in the wireless communication system must be increased to combat the power losses due to reflection, refraction and absorption of the electromagnetic energy in this band of frequency [10].

To increase the gain and directivity of the printed antenna in the microwave frequency regime, various techniques and topologies have been investigated [11–16]. Each topology has its own advantages and disadvantages. Even with the best effort, except in the few cases, in the microwave frequency regime, the gain of the antenna has been increased up to 10–12 dBi only. To increase the gain in the terahertz frequency regime of the spectrum, we have reported a microstrip patch antenna [17], which is designed on the thick substrate. The increase in the thickness of substrate cannot be immune to the surface wave loss which is dominant loss factor at the millimeter and terahertz frequency range [18,19]. To overcome this problem, the photonic crystal is considered as the

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suitable candidate as a substrate material [20–23]. However, the gain requirement cannot meet by the application of the photonic crystal substrate alone. From the early age, it is known that the Yagi-Uda type antenna is blessed with the high gain, directivity and the front-to-back ratio (F/B ratio) [24–28]. Recently, DeJean and Tentzeris [29] have proposed a topology which has shown significant enhancement in the gain apart from increase in the F/B ratio at millimeter and microwave frequency band. However, the implementation of reflector with narrow strip increases the fabrication complexity at THz frequency. To take the advantages of this array, the reflector-less Yagi-Uda type microstrip antenna on the photonic crystal substrate needs to be studied at the terahertz frequency.

In this paper, a new topology of the patch array type printed antenna is proposed at the terahertz frequency regime, which is characterized by its high gain, directivity, and F/B ratio apart from the radiation efficiency. The organization of the paper is as follows. The Section 2 deals with the geometrical configuration of the proposed patch array type printed antenna. A brief review of the substrate and feeding mechanism is described in the Section 3. The equivalent circuit model of the antenna, parametric study of the proposed structure, the effect of the mutual impedance, and the comparison of the result with the reported literature are presented in the Section 4–7, respectively. Finally, the present work is concluded in the Section 8.

2. Geometric configuration

The proposed antenna structure is shown in Fig. 1. It consists of five patches in which D, D1, D2, D3 and D4 are the driven element and directors, respectively. The reflector component of standard Yagi-Uda type printed antenna has been omitted in present design to reduce the fabrication complexity which makes this structure a novel one with reflector-less array. At the high frequency, the width of the reflector element is quite less than the wavelength, so it does not completely reflects the scattered electromagnetic field in the intended direction and reduces the gain of the antenna due to metallic loading on the structure. The feed line has been arranged as the stepped impedance transmission line to provide the better matching between the port and driven element. The antenna is designed on the photonic crystal substrate of host material PTFE ($\varepsilon_r = 2.08, \tan\delta = 0.0004$) of thickness 100 μm in which air–gaps (in cylindrical shape) of radius 10 μm and period 100 μm have been implanted. The antenna and ground metallization of copper of thickness 20 μm has been used. The physical dimension of each element is shown in the Table 1.

Table 1
Geometric parameters of the proposed antenna.

Geometric parameters	Symbol	Dimension (μm)
Feed line length (Lf1)	Lf1	200
Feed line width (Wf1)	Wf2	50
Feed line length (Lf2)	Lf2	200
Feed line width (Wf2)	Wf2	100
Length of driven element(D)	L	154
Width of driven element (D)	W	154
Length of director (D1, D2)	LD1	143
Width of director (D1, D2)	WD1	105
Length of director (D3, D4)	LD2	143
Width of director (D3, D4)	WD2	105
Gap between D and D1, D2	G1	Variable
Gap between D1, D2 and D3, D4	G2	Variable
Separation between D1 and D2	S1	Variable
Separation between D3 and D4	S2	Variable

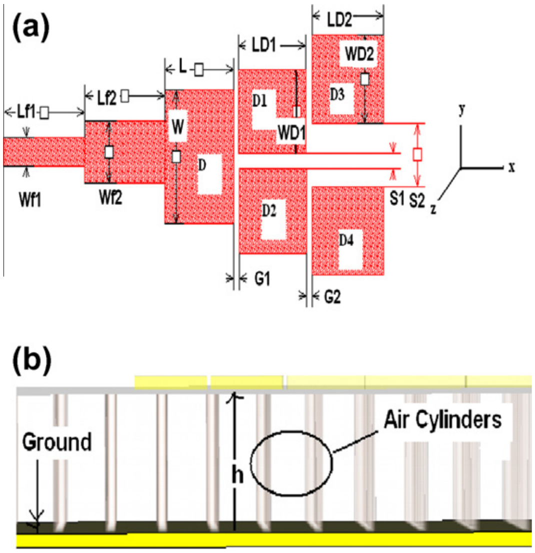

Fig. 1. Geometrical configuration of the patch array printed antenna (a) schematic diagram and (b) side view of the whole structure.

3. Substrate material and feeding mechanism

From the analysis and experimental verification [30,31], it is established that in general except Silicon, with the increase in the operating frequency, the effective permittivity and the loss tangent of the high dielectric permittivity material increases. The dielectric loss is proportional to the loss tangent and it indicates that the loss would increase at the terahertz frequency. In the case of Silicon as the substrate, the loss tangent decreases after 1.0 THz [31] but it is significantly high below this frequency. Apart from this, the application of the high dielectric permittivity material invites another problem known as shock wave which occurs at the air-substrate interface due to the difference in the permittivity of the substrate and the air [32]. In addition to this, there is the high skin-depth loss of the conducting material at this frequency. Despite these facts, the terahertz wave has been successfully transmitted with the help of the oversized metallic waveguides [33,34]. Due to the skin effect, with the increase in the operating frequency, the losses in the microstrip transmission line increases. This fact has been described in [35] where authors indicate that at 300 GHz, the loss in the microstrip transmission line is 150 dB/m and it increases with the factor of $f^{3/2}$ where f is the operating frequency. On this way, the loss in a microstrip transmission line is 4.24×10^{-4} dB/μm at 600 GHz. However, the terahertz devices are in the order of the micrometer and total loss would be insignificant. Further, the propagation of the terahertz wave on the microstrip line designed on the low dielectric permittivity material has been experimentally established in [36,37]. In addition to this, due to the ease of the integration with other device, the use of the planar technology like microstrip is a better choice at high frequency [38]. Aforementioned literatures indicate that the microstrip transmission line may also find its suitable application as a feed line at the terahertz frequency. When the operating frequency is increased, the substrate property also changes. The substrate characteristic for the multilayer homogeneous substrate has been analyzed in [39]. The advantage of using a low dielectric permittivity material in the terahertz antenna design has been explored in [40]. In addition to this, with the use of the photonic crystal, the homogeneous substrate dielectric permittivity is further reduced and it helps in the reduction in the surface wave loss [41–43]. On this way, it is concluded that the low dielectric permittivity