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Analysis and design of optically transparent antenna on photonic band gap structures

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ABSTRACT

An optically transparent microstrip patch antenna is designed on photonic bandgap structures and its radiation characteristics are computed and analyzed in the visible spectrum region. The proposed antenna consists of indium tin oxide, a transparent conducting material used both as a radiating patch and a ground plane separated by the 5 μm thin glass substrate. The introduction of periodic cylindrical air cavity structures in the glass substrate leads to the formation of photonic band gap. The patch thickness is carefully selected based on the analysis of the optical transmission coefficient with respect to patch thickness. The effective dielectric constant of the photonic band gap loaded glass substrate is computed using the effective medium approach. The refractive index of the proposed antenna is presented and discussed. The radiation efficiency of the antenna is shown to improve significantly due to insertion of proposed photonic band gap structures. The proposed design has yielded a bandwidth of 2–2.3 THz for a return loss (S_{11}) of less than −15dB and achieved a peak gain of 4.97dB at 2.27 THz.

1. Introduction

Recently transparent conducting material (TCM) has emerged as a critical ingredient for developing optically transparent electronic components such as organic light emitting diodes (OLED) [1], liquid crystal displays (LCD) [2], solar cells [3] and optical antennas [4–6]. This role has been well served by Indium tin oxide (ITO) materials [7]. Microstrip patch antennas are widely used in aircraft, satellite and commercial applications due to its attractive features such as low profile and robust structure. It can be fabricated using modern printed circuit technology. It is a decent applicant for miniaturization in terahertz frequency applications. It consists of a pair of parallel electrically conducting layers separated by a dielectric material. Low dielectric constant substrates are essential for maximum radiation in the desired direction. The microstrip line feed configuration is used to feed the antenna. The radiating patch and the microstrip feed lines are usually photo etched on the dielectric substrate using photolithography technique. Terahertz operating frequency antennas are widely used in satellite systems for short distance communications [8]. Previous researchers of this topic expressed the difficulty in achieving high gain (>2dB) for microstrip patch antenna [9].

The optical transmission can be controlled in photonic band gap (PBG) devices, by creating two-dimensional periodic structures in a transparent dielectric material [10,11]. The photonic crystals as a substrate are used to enhance the electrical performance of the microstrip antenna at the terahertz frequency regime [12]. The two dimensional photonic crystals are essentially used for miniaturization, also to overcome the microstrip patch antenna limitations such as low efficiency, gain (≤2dB) and narrow bandwidth [13]. The introduction of PBG unit cells in the dielectric substrate volume reduces the effective dielectric constant, refractive index and also improves the gain and radiating efficiency of the antenna [14]. In recent years, the electromagnetic periodic crystals have been used in several microwave and optical applications [15,16]. The effective dielectric constant and refractive index of the PBG material would depend on dimension and periodicity of the PBG unit cell. There are several techniques used to extract the effective dielectric constant of the PBG material [17,18]. The finite element method (FEM) is primarily used to analyze the PBG structures for terahertz antenna applications.

The present work discusses the designing of an optically transparent microstrip antenna over a thin glass substrate with PBG unit cells in the visible spectrum region. The organization of the paper is as follows. Sections 2 and 3 discusses about the microstrip patch antenna with PBG configuration. In Section 4 analysis of proposed antenna model is done. Section 5 investigates the results of

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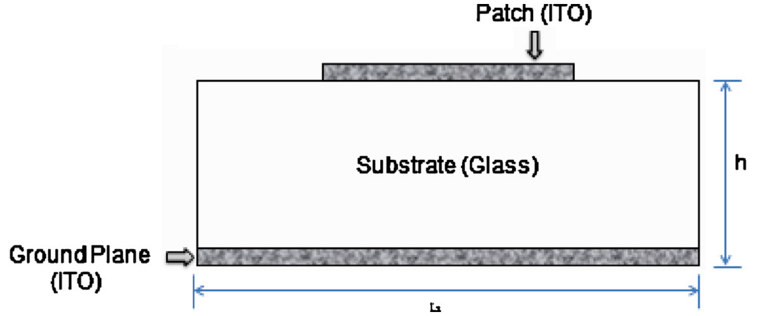

Fig. 1. Optically transparent microstrip patch antenna basic structure.

the optical transmission, refractive index, radiation efficiency and gain of the PBG loaded antenna. Finally, section 6 concludes with an improved peak gain and radiation efficiency of the PBG loaded antenna.

2. Microstrip patch antenna design

The proposed microstrip patch antenna basic structure consists of a transparent conducting patch and a ground plane separated by 5 μm thin glass substrate. The radiating patch in square and rectangular shapes is preferred because of easy analysis and fabrication. As indicated in the Fig. 1, the transparent conducting rectangular radiating patch consists of a thin (patch thickness (t) is very much less than the free space wavelength) transparent conducting material (TCM) such as ITO. The patch is placed on one side of the dielectric substrate with its other plane grounded. The thickness of the substrate material (h) should be less than the free space wavelength ($0.003\ \lambda_0 \le h \le 0.05\ \lambda_0$).

In a microstrip patch antenna, fringing fields are the main sources of electromagnetic radiation. The excited fields at the edges of the patch undergo fringing. The amount of fringing field purely depends on the patch dimensions, effective dielectric constant and thickness of the substrate material [19]. So low dielectric constant of the substrate material is preferred, because it enhances the fringing fields. Terahertz antennas usually have thin substrates with high dielectric constants, which results in tightly bound fields within the dielectric material. So it has a lesser radiation efficiency, smaller bandwidths and greater losses. The substrate having a low dielectric constant is desirable for getting better radiation characteristics of the antenna in the desired direction [20]. The microstrip feed line is connected between the rectangular patch and coaxial line for impedance transition. The antenna input impedance can be matched by tuning the width, position and length of the microstrip feed line.

3. Photonic bandgap structure

The electromagnetic periodic crystals have attracted a lot of attention as a substrate for high frequency antenna applications. The introduction of periodic cylindrical air cavity unit cells into the substrate volume, leads to the formation of PBG in the dielectric substrate [21]. The creation of PBG structures is principally used to reduce the accumulation of fields in the dielectric substrate; also it enhances the fringing fields at the edge of the antenna patch. This in turn decreases the effective dielectric constant and the refractive index of the dielectric material. The lowering of the effective dielectric constant of glass substrate improves the radiation efficiency of the PBG loaded antenna in the desired direction with high directivity [22].

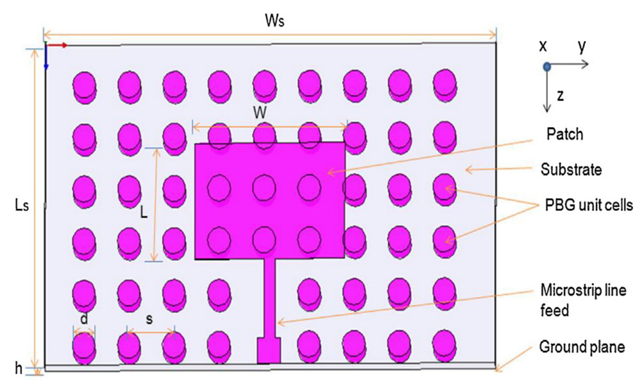

Fig. 2. PBG unit cells on the glass substrate.

The PBG is widely used to control the refractive index of the substrate material to be less than 1. The refractive index of the PBG material depends on the lattice factor (k), where k is the ratio of the radius of cylindrical air cavity unit cells (d) to the PBG unit cell interspacing distance (s) [23]. In [23], one dimensional PBG structures have been designed and the dielectric characterization is done using an effective medium approach in the (0.5–0.7) THz band. This can be fabricated using custom designed lithographic mask [24,25]. The PBG loaded antenna is shown in Fig. 2. The dimensions of the optically transparent patch antenna are given in Table 1.

4. Optical antenna model analysis

The general equation for calculating the resonant frequency of the rectangular microstrip patch antenna is given by [26],

$$f_r = \frac{c}{2(L + 2\Delta L)\sqrt{\varepsilon_{\text{eff}}}} \quad (1)$$

Table 1
Design parameters of optically transparent antenna.

Parameters	Symbol	Value
Operating wavelength	λ_{visible}	$400\ \text{nm} \le \lambda_{\text{visible}} \le 700\ \text{nm}$
Operating frequency	f	(2–2.3) THz
Patch length, width and thickness	$L \times W \times t$	95 μm × 147 μm × 0.2 μm
Dielectric substrate length, width and thickness	$L_s \times W_S \times h$	250 μm × 400 μm × 5 μm
Dielectric constant (glass)	ε_r	6
PBG unit cell size (diameter)	d	25 μm
PBG unit cell inter spacing distance	s	30 μm