A Study of Resonant Antennas on Semi-infinite Substrates at Terahertz Frequency

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Abstract

This paper is concerned with four different types of resonant antennas on semi-infinite substrates made of high-permittivity dielectric materials. Full-wavelength single-dipole, full-wavelength dual-dipole, half-wavelength single-slot, and full-wavelength four-leaf-clover-shaped dipole antennas are studied at a frequency of around 1.0 THz. The overall performance of four resonant antennas in terms of input impedance and radiation characteristics have been investigated and compared using the moment simulator FEKO

Keywords : Resonant antenna, semi-infinite substrate, THz photomixer, high input resistance.

1. Introduction

The idea of using a planar antenna that has been lithographically integrated on the surface of a dielectric lens to couple electromagnetic radiation to active semiconductor devices is attractive because of its potential for eliminating substrate modes and increasing the Gaussian coupling efficiency (Gaussicity). In addition, the fabrication procedures are well suited to monolithic or hybrid integrated circuit technology, and offer greater dimensional accuracy and durability, and reduced cost. Since the lens is electrically large compared to the antenna, the antenna elements act as if they are at the interface of an air–dielectric half-space. Moreover, aside from the radiation patterns, an antenna exhibits similar resonant characteristics on both a lens substrate and a semi-infinite substrate [1]. Hence, an antenna fabricated on a semi-infinite substrate can be used in the initial investigation of its resonant characteristics, which saves a significant amount of computational time.

A comparison of dipole, bow-tie, spiral, and log-periodic antennas on a thin substrate at infrared frequencies has recently been reported [2]. However, planar antennas built on a substrate are quite different from ordinary antennas in free space or on a thin substrate, primarily because antennas tend to radiate most of their energy on the substrate side, especially on high-permittivity substrates at high frequencies. The properties of antennas on semi-infinite substrates have been studied extensively for many years, from substrates made of lossy dielectrics (such as water or earth) [3-5] to substrates made of lossless dielectrics (such as GaAs or Si) [1, 5–9]. However, there have been no detailed studies comparing several types of resonant antenna on high-permittivity lossless semi-infinite substrate at terahertz (THz) frequency.

In this paper, we examine and compare the overall performance of several types of resonant antenna in terms of input impedance, radiation patterns, and radiation efficiency. The four antenna types selected for this research are full-wavelength single-dipole, full-wavelength dual-dipole, half-wavelength single-slot, and full-wavelength four-leaf-clover-shaped dipole, all designed on a semi-infinite Si substrate ($\varepsilon_r = 11.7$) and to resonate at around 1.0 THz.

2. Antenna Geometry and Characteristics

Figure 1 shows the four types of antenna under consideration. The antennas were all designed to resonate at around 1.0 THz for the sake of comparison. The metal layer had a conductivity of 1.6×10^7 S/m and a thickness of 0.35 μm. The single-dipole, dual-dipole, and four-leaf-clover-shaped antennas all had a total length of approximately 1 λ at about 1.0 THz on the Si substrate, in order to provide maximum input resistance. However, the single-slot antenna provided maximum input resistance at a total length of approximately λ/2, since a slot antenna is complementary to a dipole antenna (in accordance with Babinet's principle). Accordingly, these four resonant antennas exhibited high input resistance characteristics suitable for THz photomixer designs. The initial dimensions of the antennas were as follows: L_D = 94 μm and w_D = 3 μm for the single-dipole antenna (Fig. 1a); A = 70 μm, B = 49 μm, C = 3 μm, D = 1 μm, and E = 5 μm for the dual-dipole antenna (Fig. 1b); L_S = 46 μm and w_S = 3 μm for the single-slot antenna (Fig. 1c); $D_x = D_y$ = 37 μm, $G_x = G_y$ = 2 μm, and w = 3 μm for the four-leaf-clover-shaped antenna (Fig. 1d). Note that the right and left halves of the four-leaf-clover-shaped antenna each formed a full-wavelength dipole with a total length of approximately $2[(Dx + Dy) - (Gx + Gy) - 1.5w]$, corresponding to 1 λ at about 1.0 THz on the Si substrate [10].

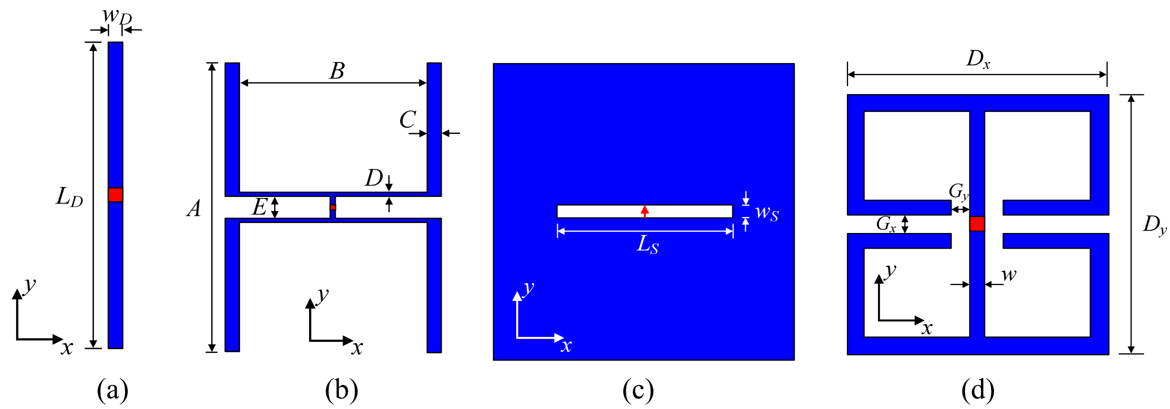

Fig. 1. Geometries of the four resonant antennas: (a) full-wavelength single-dipole, (b) full-wavelength dual-dipole, (c) half-wavelength single-slot, and (d) full-wavelength four-leaf-clover-shaped antennas.

The four antennas were simulated via the FEKO software package featuring the method of moments (MoM), the Si substrate being approximated with a semi-infinite Green's function layer. The single-slot antenna was fed by a wire port, while the single-dipole, dual-dipole, and four-leaf-clover-shaped antennas were all fed by an edge port with the same voltage source (of magnitude 1 V). The single-slot antenna was oriented in the x-direction, whereas the other three antennas were oriented in the y-direction, in order to provide a clear comparison of the antenna radiation patterns.

The input impedance characteristics of the single-dipole, dual-dipole, single-slot, and four-leaf-clover-shaped antennas are shown in Fig. 2 (a–d), respectively. The single- and dual-dipole antennas resonated at around 1.0 THz, and had input resistances of 302 Ω and 220 Ω, respectively. The single-slot antenna exhibited a slightly lower input resistance than the two dipole antennas, and had an input resistance of 170 Ω at the resonant frequency of 1.0 THz. The highly resonant four-leaf-clover-shaped antenna had a high input resistance of about 1800 Ω at the resonant frequency of 1.0 THz. The high input resistance of this antenna was due to the high Q and narrow band characteristics of the design.

Figure 3 (a–d) show the radiation patterns of the four antennas plotted in the *E*- and *H*-planes, which respectively correspond to the *yz*- and *xz*-planes of the antennas' orientation. As the figure indicates, all of the antennas exhibited radiation patterns with a minimum in the *E*-plane and a maximum in the *H*-plane at the critical angle $\theta_c = \pi - \sin^{-1}[(\varepsilon_r)^{-1/2}]$ on the dielectric side, which is about 163° for the Si substrate (ε_r = 11.7). Both the *E*- and *H*-plane patterns of the four antennas had a null value at the air–dielectric interface. For the single-dipole antenna, the *E*-plane beam pattern was narrower than the *H*-plane beam pattern, due to the nature of current dipole radiation. However, for the dual-dipole antenna, the *E*-plane beam pattern was wider than the *H*-plane beam pattern because of the array effect. Hence, a small side lobe appeared near the interface in the *H*-plane pattern of the dual-dipole antenna. For the four-leaf-clover-shaped antenna, the *E*-plane and *H*-plane patterns were almost identical to those of the single-dipole antenna, but the *E*-plane beam pattern was wider than the *H*-plane pattern. This beam angle behavior was similar to that of the dual-dipole antenna. The radiation patterns on the air sides of the single-dipole, dual-dipole, and four-leaf-clover-shaped antennas were almost identical. However, the *E*-plane and *H*-plane radiation patterns of the single-slot antenna were quite different from those of the other three antennas, as can be seen in Fig. 3(c). Since the patch was modeled to be infinite in extent, the two media (air and dielectric) were effectively isolated. Minimum and maximum values did not occur at the critical angle for the single-slot antenna. The *E*-plane had no null value at the air–dielectric interface, but the *H*-plane did, as noted in [5].

From the radiation efficiency and directivity perspectives, the four antennas behaved differently. The radiation efficiencies of the single-dipole, dual-dipole, and four-leaf-clover-shaped antennas were 95%, 82.5%, and 51%, respectively. The maximum directivities at the critical angle were 9.9, 9.8, and 8.9 dBi for the single-dipole, dual-dipole, and four-leaf-clover-shaped antennas, respectively. The directivities at θ = 180° were 7.7, 8.7, and 7.9 dBi, corresponding to directivity differences (compared to the maximum values at the critical angles) of 2.2, 1.1, and 1.0 dBi for the single-dipole, dual-dipole, and four-leaf-clover-shaped antennas, respectively. For the single slot antenna, the radiation efficiency was 78.8% and the directivity at θ = 180° was only 1.2 dBi. This behavior variation was also noted in [5], in which it was reported that the radiation of a slot in an infinite ground does not concentrate in a cone, as with a current dipole.

3. Conclusions

We have investigated and compared the overall performances of four resonant antennas designed on a semi-infinite Si substrate in terms of input impedance and radiation characteristics. The input impedances of the four antennas exhibited similar behaviors, but the radiation characteristics varied, especially in the case of the single-slot antenna. The four-leaf-clover-shaped antenna had the highest input resistance among the four antennas, and the single-dipole antenna had good overall radiation characteristics (radiation efficiency, clean main beam, and directivity). The study can be used in the initial investigation of the antenna resonant characteristics, which saves a significant amount of computational time, prior to using with an integrated lens substrate for terahertz receivers.

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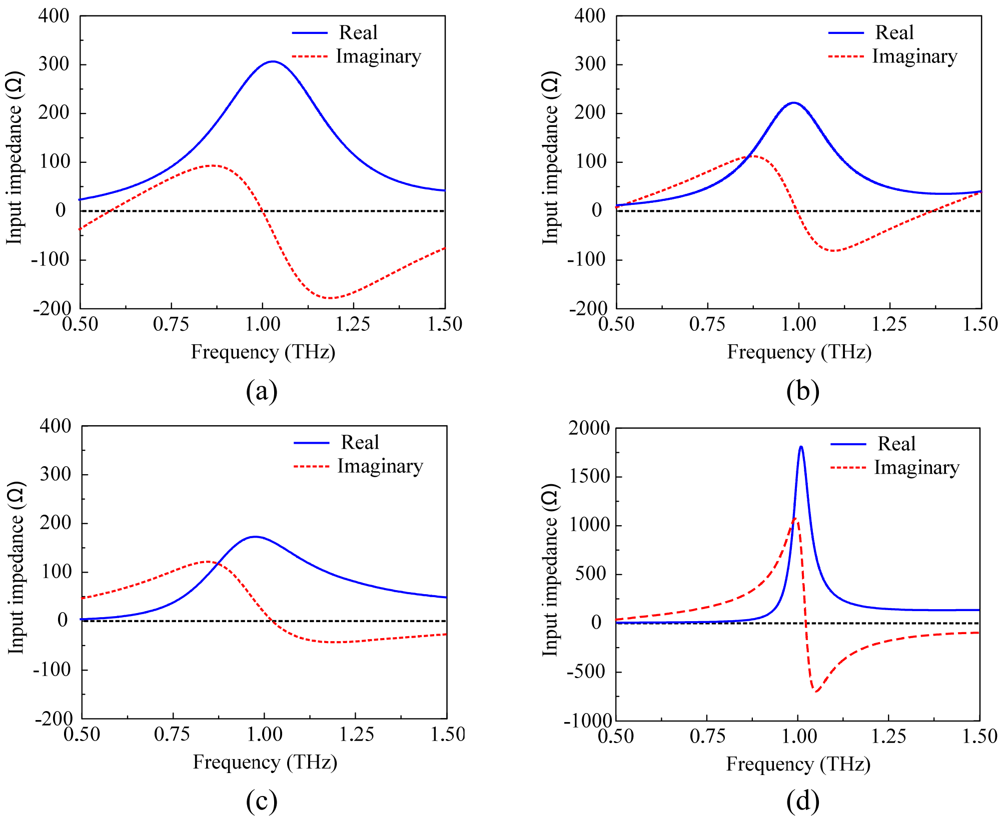

Fig. 2. Input impedance characteristics versus frequency of the (a) single-dipole, (b) dual-dipole, (c) single-slot, and (d) four-leaf-clover-shaped antennas.

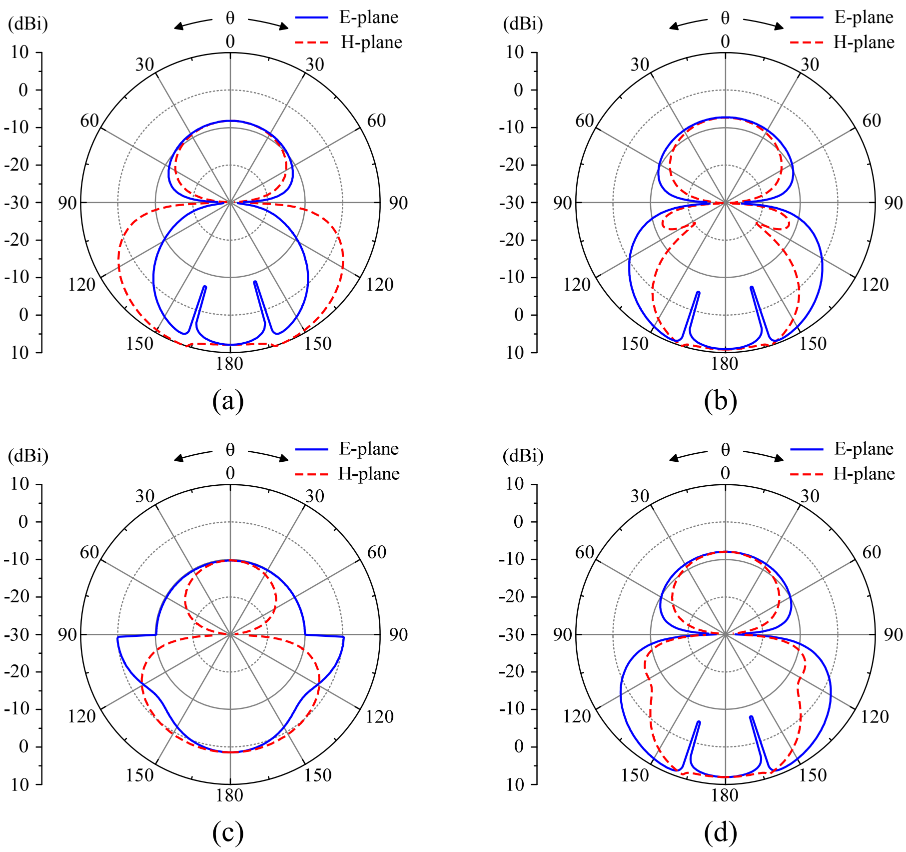

Fig. 3. Radiation patterns of the antennas at the resonant frequency of around 1.0 THz: (a) single-dipole, (b) dual-dipole, (c) single-slot, and (d) four-leaf-clover-shaped antennas.