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A Photomixer Driven Terahertz Dipole Antenna with High Input Resistance and Gain

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Abstract—A terahertz (THz) antenna is proposed that offers high input resistance and gain in the presence of an electrically thick GaAs substrate. The antenna is centrally fed using two vertical probes connected to a photomixer on a thin low temperature grown gallium arsenide (LTG-GaAs) film which is supported by the GaAs substrate. An input impedance of $\sim 3.3\,\text{k}\Omega$ has been achieved using a dipole antenna that is printed on a thin dielectric slab, and isolated from the supporting substrate using a metal ground plane. A square aperture has been introduced to facilitate the illumination of the photomixer with two laser beams. Furthermore, a frequency selective surface (FSS) has been incorporated in the configuration, which results in a broadside gain of $\sim 19\,\text{dBi}$ at a resonance frequency of 0.97 THz.

1. INTRODUCTION

Information transmission plays an increasingly important role, which results in a continuous demand for higher data rates. However, it is difficult to afford sufficient free bandwidths in the current frequency plans, which extend to 275 GHz [1]. Although the infrared frequency range may be considered as an option, it is limited by severe reflection losses, receiver sensitivity, as well as eye-safety issues [2]. The terahertz frequency range represents a promising alternative as it fills the gap between the far infrared and millimeter wave bands. Several terahertz applications have been proposed for security, biology, medical and imaging systems [3, 4].

A well-known approach to generate a continuous-wave (CW) THz signal is to employ a photomixer, in which the THz wave is produced by using two laser beams that illuminate a LTG-GaAs photomixer with a typical thickness of $1.5\,\mu\text{m}$. The difference between the frequencies of the laser beams should be in the THz range. As a result a photocurrent will be induced between the photomixer metal electrodes, which can be transferred into a radiated THz wave using a properly designed antenna [5]. However, the photomixer presents a considerably high output impedance that is typically in the order of $10\,\text{k}\Omega$ [5]. In addition, the photomixer is usually grown on a type III-V semiconductor substrate with a considerable thickness and a dielectric constant of $\varepsilon_r \approx 12.9$. Consequently, the input impedance of a THz antenna that lies in the plane of the photomixer will be reduced by a factor of $\sqrt{((\varepsilon_r + 1)/2)}$ [6]. This motivates a challenging task of designing an antenna with a free space input resistance that is in the order of $\sim 25\,\text{k}\Omega$. As a consequence, the pronounced impedance mismatch results in only a marginal fraction of the generated THz power being radiated. Therefore, a special attention needs to be given to design a THz antenna with a high input resistance. Another problem associated with the presence of the thick GaAs substrate is that most of the power will be radiated into the substrate, which necessitates the use of a hemispherical Si lens. Additionally, considerable surface wave modes will be generated that degrades the radiation efficiency and polarization characteristics [7]. It should be noted that for fabrication purposes, a typical GaAs substrate thickness of $\sim 300\,\mu\text{m}$ is used to provide the needed mechanical support as

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well as to optimize the thermal flow. Therefore, using a thin GaAs substrate is not recommended owing to the aforementioned reasons [8], as well as the added complexity of fabricating a GaAs membrane. Although employing a lens results in a considerably higher gain, it is usually associated with a lower input resistance that deteriorates the matching efficiency of a photomixer driven THz antenna, and hence reduces the radiated power significantly. In addition there are applications where a silicon lens is not preferred. For instance, when the alignment of the silicon lens to the device is rather critical and a silicon-lens free design simplifies the setup albeit at the cost of a narrower bandwidth. Furthermore, the absence of the lens provides a much smaller device.

Numerous photomixer based THz antennas have been proposed in the literature with particular emphasis on achieving a higher input resistance. As an example, an input resistance of 270 Ω has been achieved at 0.4 THz using a dipole [9], where it has been suggested that a resonant antenna needs to be utilized in order to improve impedance matching. In a later study, a folded dipole that is printed on a 350 μm GaAs substrate has been reported with a considerably higher input resistance of $\sim 3\,\mathrm{k\Omega}$ [10]. Additionally, a Yagi-Uda antenna has been designed with an input resistance of 4.4 kΩ using an extremely thin 4 μm GaAs substrate [11]. Further, an input resistance of $\sim 1.6\,\mathrm{k\Omega}$ has been reported using a four leaf clover shaped antenna that is backed by an extended hemispherical lens substrate [12]. In addition, an efficient THz dipole has been reported with an input impedance of $\sim 3.88\,\mathrm{k\Omega}$ in conjunction with an enhanced directivity using either a Silicon lens [13], or a FSS [14]. However, in both of these studies a thin $\sim 12\,\mu\mathrm{m}$ grounded GaAs substrate has been used in conjunction with a cavity that has been created underneath the photomixer leaving an unsupported 1.5 μm layer. A number of THz antenna configurations have been reported in [15] with a realized gain of 14.3 dBi assuming a photoconductive switch source impedance of 50 Ω, and using a GaAs substrate thickness range of 56–79 μm. In a recent study, measured and simulated results have been reported for a THz meander dipole with improved radiation and matching efficiencies [16].

Therefore, there is an obvious need to design a THz antenna that considers the existence of the electrically thick GaAs substrate and, at the same time, minimizes the associated performance degrade. This can be achieved by devising a novel configuration in which the THz antenna is electromagnetically decoupled from the supporting GaAs substrate. Such a design is proposed in this article by incorporating reflecting surface such as a conducting ground plane (GP) to achieve a higher input resistance as well as to minimize (ideally eliminate) any radiation towards the GaAs substrate. The presence of a reflecting surface provides a considerably high input resistance in the order of $\sim 3.3\,\mathrm{k\Omega}$. In addition, isolating the THz antenna from the GaAs substrate offers an additional advantage of providing a broadside radiation, which eliminates the need of a lens. Furthermore, the metal ground plane serves another purpose as it facilitates the creation of a Fabry-Perot resonator (FBR) antenna with a pronounced gain enhancement.

2. ANTENNA CONFIGURATION AND EFFICIENCY

The proposed geometry is illustrated in Fig. 1, in which it has been assumed that the photomixer is grown on a $(1800 \times 1800 \times 300)\,\mu\mathrm{m}^3$ GaAs substrate with a relative dielectric constant of $\varepsilon_r = 12.9$. It is well known that a higher input impedance can be achieved using a resonant dipole that is printed on a thin grounded substrate [17]. Therefore, a thin Arlon AD 320 dielectric substrate has been inserted between the Gold dipole and the reflecting surface. This thin substrate thickness and relative permittivity have been chosen as $d = 12\,\mu\mathrm{m}$ and $\varepsilon_{r1} = 3.25$, respectively. However, in order to eliminate any obstruction to the illuminating laser beams, a central illumination cavity opening having a square aperture is considered in the top thin substrate in conjunction with a square slot in the ground plane of identical size. As illustrated in Fig. 1, the dipole has been connected to the photomixer using two vertical probes of length d. The length, thickness, and width of the dipole have been chosen as 105 μm, 0.35 μm and 3 μm, respectively.

Since this is a parallel resonance mode antenna, the impact of ohmic losses can be understood by considering the equivalent circuit shown in Fig. 2, from which an expression for the resonance input resistance can be derived as

$$R_{in} = \frac{X_L^2 R_r}{X_L^2 + R_\ell R_r} \tag{1}$$

where X_L is the inductive reactance at resonance. This equation demonstrates that the presence of ohmic

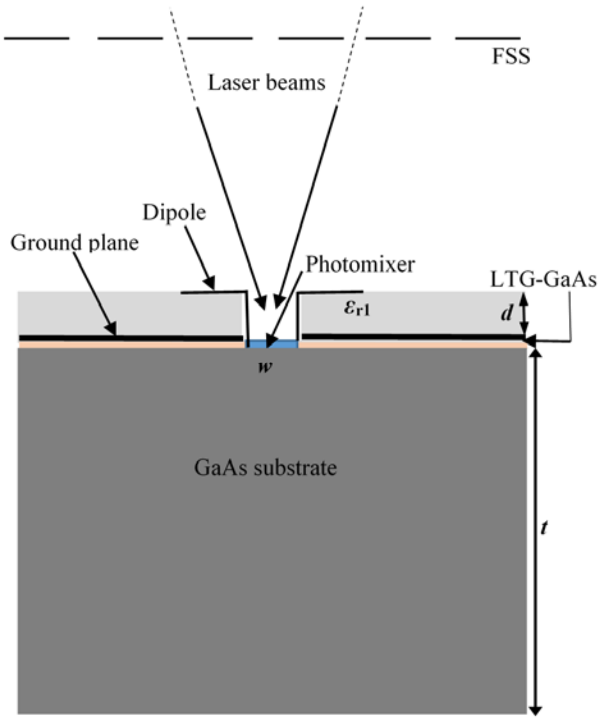

Figure 1. Schematic of a THz dipole above a thick GaAs substrate with an isolating metallic surface.

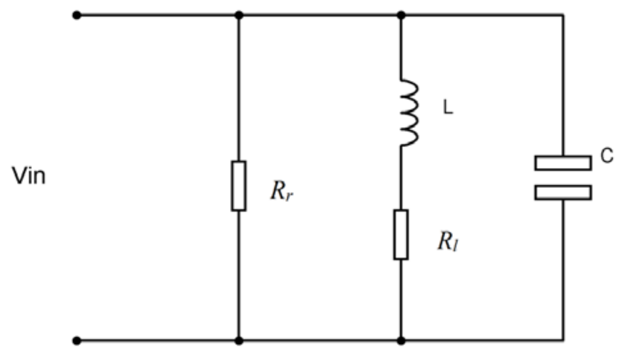

Figure 2. Equivalent circuit of a lossy parallel resonant antenna where antenna's inductance, capacitance, radiation and loss resistances are denoted as L, C, R_r, and R_ℓ, respectively.

losses reduces the input resistance, which subsequently lowers the matching efficiency. An expression for the radiation efficiency can be derived as

$$\eta_r = \frac{\left(V_{in}^2/2R_r\right)}{\left(V_{in}^2/2R_{in}\right)} = \frac{R_{in}}{R_r} \tag{2}$$

It is well known that owing to the current magnification phenomena of a parallel resonance circuit, the current through the inductor is larger than that flowing through the radiation resistance by a factor of $Q_p = (R_r/X_L)$. As a result, the dissipated power increases considerably, which reduces the radiation efficiency. Therefore, an alternative expression for the radiation efficiency of an anti-resonance antenna can be derived by substituting Equation (2) in (1) as

$$\eta_r = \frac{R_r}{R_r + Q_p^2 R_\ell} \tag{3}$$

From Equations (1) and (3), it is evident that a small loss resistance of few ohms may have a considerable impact on radiation as well as matching efficiencies. Although a larger radiation resistance is needed to improve the matching efficiency, the increased Q_p will result in a reduced radiation efficiency.

3. RESULTS

The presented design has been simulated using the Computer simulation Technology (CST) Microwave Studio package [18], where the photomixer has been modelled as a THz discrete port with a typical source impedance of 10 kΩ. In addition, the interdigitated electrode capacitor has been considered by adding a lumped capacitance of 1 fF in parallel with the discrete port as illustrated in Fig. 3. Furthermore, since the photomixer is placed within a square slot in the metal ground plane, an additional capacitor exists between the photomixer and the surrounding ground plane. Therefore, the interdigitated electrode

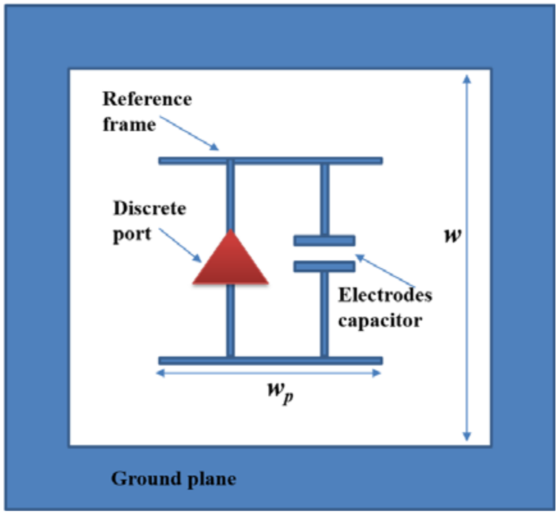

Figure 3. The photomixer source model surrounded by a metal ground plane.

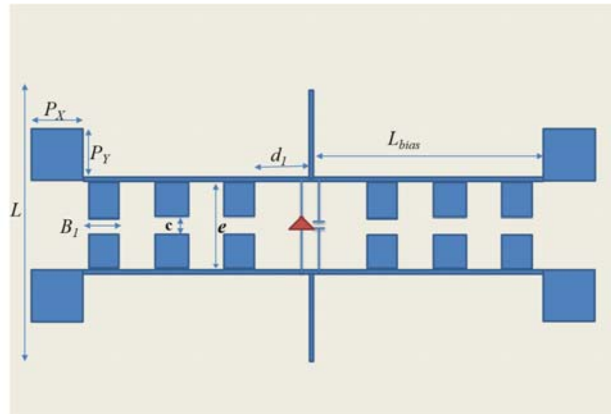

Figure 4. Top view of a THz dipole driven at the center by a photomixer with the CPS DC bias network with dimensions given in Table 1.

Table 1. CPS dimensions in (μm).

P_xP_y	L_{bias}	B_1	d_1	c	e
100	600	50	20	1	5

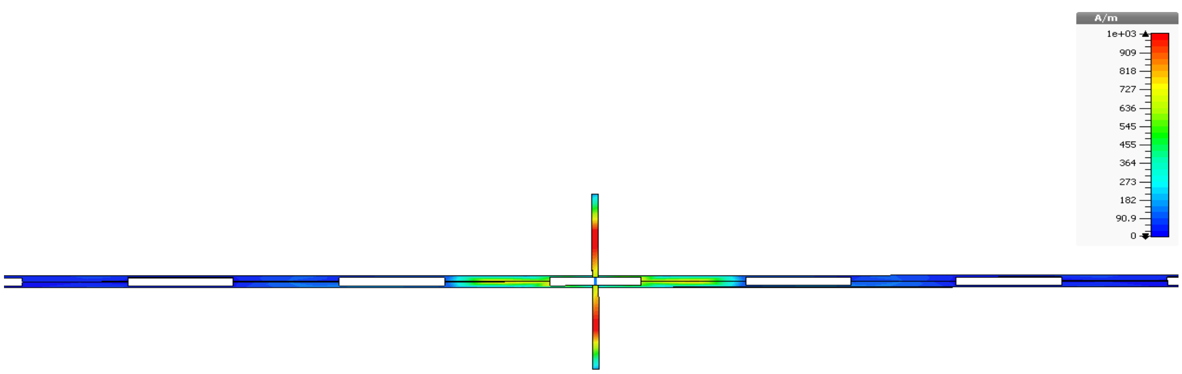

Figure 5. Surface current along the antenna and the CPS terahertz chock.

frames have been incorporated in the source model as shown in Fig. 3 in order to take account of this capacitive coupling. The parasitic capacitor can be tuned out by an inductive component that can be obtained using a transmission line section with a length of d_1 as illustrated in Fig. 4 [19]. From this diagram it can be noticed that this line is connected to a coplanar stripline (CPS) biasing network, which acts as a terahertz choke that eliminates the flow of the THz current to the DC bias [19]. The THz choke consists of alternating high and low impedance quarter wavelength transformer sections. The d_1 length line is connected to a low impedance section of the CPS network, hence an inductive reactance is introduced at the input of the dipole, which tunes out the parasitic capacitors at the design frequency. The required tuning has been accomplished by adjusting the length d_1. The optimized d_1 and CPS dimensions are illustrated in Table 1. Fig. 5 illustrates the surface current along the antenna structure, where it can be noticed that the CPS network has eliminated the flow of any THz current towards the DC bias.

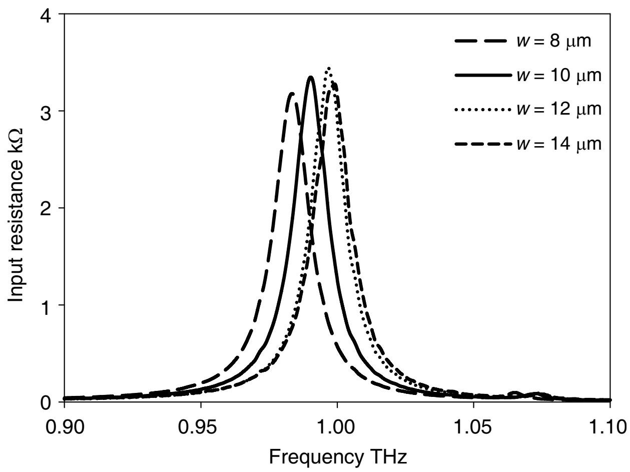

Figure 6. Input resistance of a THz dipole antenna isolated from the GaAs substrate using a metallic ground plane with a central square slot size of w. The dipole has respective length and width of 105 μm and 3 μm.

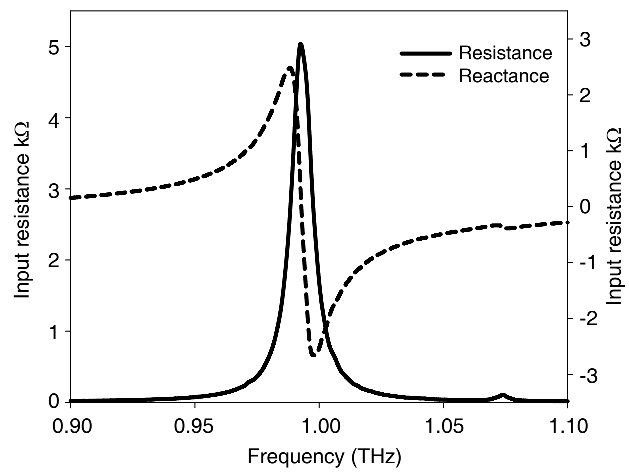

Figure 7. Input resistance of a PEC dipole that is isolated from the GaAs substrate using a metal ground plane. The dipole has respective length and width of 105 μm and 3 μm.

The variation of the input resistance as a function of the square slot and the illumination gap size, w, is presented in Fig. 6 where it can observed that there is a slight variations in the resonance resistance as well as frequency using a cavity size of $10 \leq w \leq 14$ μm. It should be noted that the minimum slot's size is limited by the required size of the photomixer, w_p, which is in the order of 5 μm [5]. However, using a smaller slot may result in creating a short circuit between the ground plane and the photomixer's electrodes as well as with the vertical feeding probes in addition to creating stronger capacitive coupling between the photomixer and the ground plane. Therefore, the size w has been chosen as 10 μm, which results in a resonance resistance of ~ 3.3 kΩ at a center frequency of 0.99 THz. As a reference, the input impedance of the PEC dipole is presented in Fig. 7, where it can be observed that the radiation resistance is approximately 5 kΩ, which provides a matching efficiency of 90% compared to 75% for the Gold dipole. These results demonstrate that a considerable electromagnetic decoupling has been attained between the dipole and the GaAs substrate in the proposed configuration. Therefore, the well-known limitations of utilizing an electrically thick GaAs substrate have been eliminated. In addition, the antenna can be simulated and optimized assuming a thickness of 50 μm, which accelerates the simulation time and provides a considerable saving in the required computational resources. A broadside radiation has been achieved with a directivity of $\sim$ 6 dBi, which is expected from a dipole printed on a thin grounded substrate.

Although the broadside radiation eliminates the GaAs substrate modes as well as the need for a Si lens, the achieved gain is not sufficient at the THz range owing to strong wave reflections and attenuation. However, the gain can be increased considerably by creating a Fabry-Perot resonator antenna, in which a FSS superstrate is placed at a distance of $\sim 0.5\lambda_o$ above the ground plane. The FSS has been created using a metallic strip unit cell as shown in Fig. 8, where (13×38) unit cells have been used [20]. This unit cell has been chosen since it provides an FSS with air gaps that eliminates any obstruction to the incident laser beams. The FSS superstrate has been placed at a height of 162 μm above the isolating ground plane. It should be noted that no interference is expected between the incident laser beams and the radiated THz wave owing to the considerable difference between the frequencies of the incident and radiated signals. The total efficiency of the whole structure has been calculated as $\sim$ 40%, which has been accomplished in the presence of an electrically thick supporting substrate. The radiation pattern is illustrated in Fig. 9, where it can be noticed that the presence of the FSS superstrate results in a significantly higher directivity of $\sim$ 22 dBi, which results in a gain of $\sim$ 19 dBi. The achieved directivity is comparable to that obtained using a conventional Silicon lens placed at the lower side of the GaAs substrate, albeit with smaller vertical dimensions. In addition, employing the FSS eliminates the energy

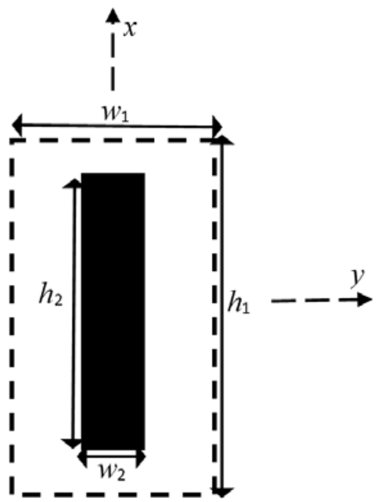

Figure 8. The FSS superstrate unit cell with the following dimensions: $h_1 = 138.5\,\mu\text{m}$, $w_1 = 48\,\mu\text{m}$, $h_2 = 132\,\mu\text{m}$, and $w_2 = 18\,\mu\text{m}$, where the black colored component represents the metallic strip.

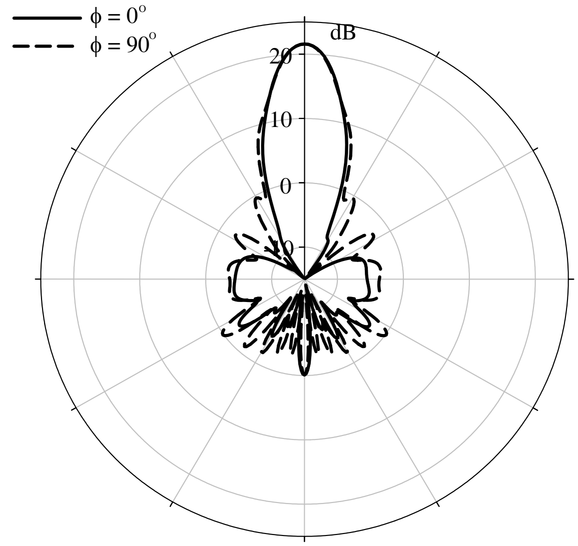

Figure 9. Far field of a THz antenna isolated that is covered by an FSS superstrate.

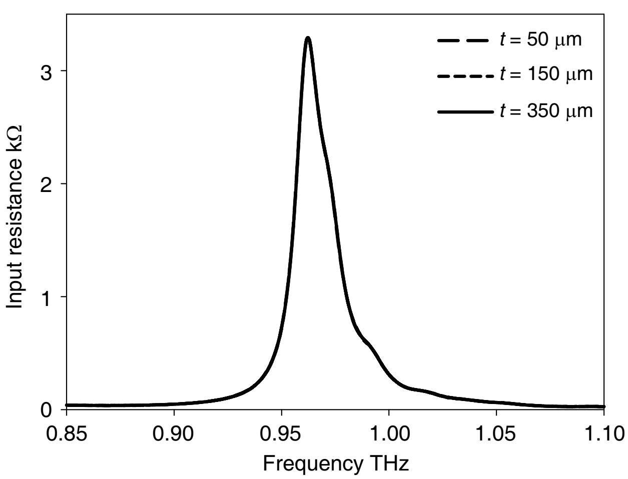

Figure 10. Input resistance of the THz Gold dipole antenna that is covered by an FSS superstrate for various GaAs substrate thicknesses.

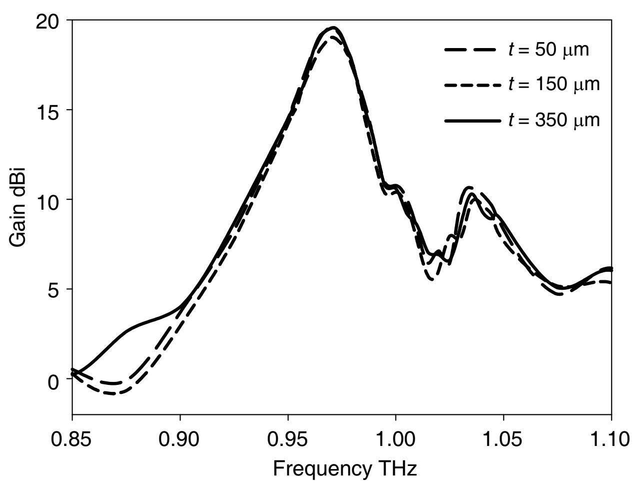

Figure 11. Broadside gain of the THz dipole antenna that is covered by an FSS superstrate for various GaAs substrate thicknesses.

losses due to internal reflections that are associated with hemispherical Si lens [21, 22]. The effectiveness of the achieved decoupling between the radiating element and the supporting GaAs substrate has been investigated by varying the height of the latter. Fig. 10 illustrates the variation in the input resistance at various GaAs substrate heights, where it can be observed that the substrate thickness has a marginal effect on the input resistance. In addition, the variation of the broadside gain as a function of the substrate height is illustrated in Fig. 11 where it can be noticed that the same gain has been achieved when the GaAs substrate height is increased from 50 to 350 μm. These results demonstrate that the required electromagnetic decoupling between the THz antenna and the thick GaAs substrate has been achieved successfully.

4. POTENTIAL FABRICATION METHODS

The structure described here presents possible difficulties in manufacture on two levels. Firstly, the dielectric spacer thickness ($d = 12\,\mu\text{m}$) may result in potentially long plasma enhanced chemical vapour deposition (PECVD) times, which has typical rates of $\sim 40\,\text{nm/minute}$. More importantly, residual stress in the deposited layer makes thick layers difficult to deposit without cracking or adhesion problems. Such issues have been solved for MEMS applications where removal of the dielectric material in non-essential regions reduces residual stress and wafer bowing effects [23]. Another potential route to realizing this structure would be through multiple spin/cure cycles for spin-on dielectric materials [24].

The second possible issue is the fabrication of the FSS for enhanced directivity, which is $\sim 150\,\mu\text{m}$ above the dipole as described in Fig. 1. We consider that an aligner/bonder process would be required. This would involve taking a $\sim 150\,\mu\text{m}$ silicon substrate and thermally oxidising the surface to provide a supporting membrane for the metal antenna layer, and etch-stop for a subsequent wet silicon etch. This silicon dioxide layer is patterned with the FSS described in Fig. 8. The wet silicon etch would open windows below this FSS structure, which would be subsequently aligned to the excitation aperture to the photo-mixer. The silicon frame would then be attached to the dielectric surface through the use of standard anodic bonding techniques at $\sim 300\,\text{C}$. Typical alignment accuracies from commercially available tools are $\sim 1\,\mu\text{m}$.

5. CONCLUSIONS

A photomixer driven THz antenna has been considered in the presence of a thick GaAs substrate. A considerably large input resistance of $\sim 3.3\,\text{k}\Omega$ has been achieved by inserting an isolating layer between the antenna and the supporting GaAs substrate. It should be noted that the THz antenna input resistance in the absence of an isolating layer has been calculated as $\sim 300\,\Omega$. As a result, a pronounced improvement in the impedance matching has been accomplished when the antenna is connected to a photomixer with an impedance of $10\,\text{k}\Omega$. Therefore, the presented antenna offers a substantial electromagnetic decoupling between the THz radiating element and the electrically thick GaAs substrate. In addition, the impact of ohmic losses on matching and radiation efficiencies has been discussed. Furthermore, an FSS superstrate has been employed to achieve a broadside realized gain of $\sim 19\,\text{dBi}$. Special attention has been given to the choice of the FSS and dipole-photomixer connection to eliminate any obstruction to the illuminating laser beams. According to the achieved results, it can be concluded that the proposed configuration offers a design in which the supporting GaAs substrate is effectively invisible to the THz radiating element. Therefore, any degrade in the antenna performance owing to the presence of the thick substrate has been eliminated. This is important for fabricating a practical device as well as for an efficient thermal flow.

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