Broadband Slotted Bow-tie Antennas for Terahertz Resonant Tunnelling Diode Based Oscillators

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Abstract— A broadband slotted bow-tie antenna is presented. The antenna is fed by coplanar waveguide (CPW) and fabricated on an InP substrate for same chip integration with the promising resonant tunnelling diode (RTD) terahertz (THz) oscillator which has the capability of room temperature operation and with relative high power. The antenna exhibits a very wide bandwidth (return loss $S_{11} < -10\,\mathrm{dB}$) around the design frequency (300 GHz). However, due to the large dielectric constant of the InP substrate, most of the radiation is directed into the substrate. To re-direct the energy into air, a bow tie antenna employing a reflector ground plane underneath a thin substrate of low dielectric constant is presented. Initial simulation results of this technique are reported and experimental validation at lower frequency (17 GHz) shows the feasibility of the concept.

1. INTRODUCTION

Terahertz (THz) radiation, whose frequency range lies between millimetrewaves and infrared light in the electromagnetic spectrum has many potential applications in different scientific fields such as medical diagnostics, security imaging, and wireless communication [1–3]. Resonant tunnelling diode (RTD) based THz oscillators in integrated circuit (IC) form have recently been shown to be the technology in which many of these applications could be implemented [4, 5]. They operate at room temperature and have the potential to produce output power of around 1 mW at these frequencies [6].

An efficient antenna is a key element to couple the THz radiation into free space. A high gain and directive antenna is preferable in order to radiate most of the RF power into specific direction and, as a consequence, offer larger coverage distance. RTD THz oscillators employing integrated slot antennas [4] and planar horn antennas [7] have been demonstrated. The slot antenna is a resonant antenna with infinity input impedance at the centre of the slot and zero at the edges. For antenna dimensions of a few microns (at THz frequencies), proper impedance matching for this antenna is difficult. The planar horn antenna, on the other hand, radiates the signal energy along the substrate, whilst radiation perpendicular to the substrate would be more desirable [8]. An elevated patch antenna was proposed to suppress the substrate effects, however, the bandwidth still narrow [9].

This paper describes a bow-tie slot antenna designed for operation at 300 GHz. This antenna has a controlled input impedance of 50 Ohms. The bow-tie slot antenna is also compatible with the novel power combining RTD oscillator circuits being developed in the group [10]. Most of the radiation in the present design is directed into the substrate due to the large dielectric constant of the Indium Phosphide (InP) substrate [11]. A practical and common solution to this problem has been to use a hemispherical lens on the backside of the substrate to extract the RF power and increase the antenna gain [12–17]. Instead of using lenses, a promising alternate realisation to have most of the energy radiated away from the substrate is proposed and described in this paper. It employs a reflector ground plane underneath a thin substrate of low dielectric constant which can be spun on the top of the high dielectric constant substrate. The ground plane acts as a reflector and also isolates the high dielectric constant substrate from the high frequency radiation. The frequency of 300 GHz has been suggested for applications such as short-link and medium-link wireless communication systems. This is mainly due to the fact that it is unregulated and in moderate atmospheric attenuation band [18].

2. BOW-TIE ANTENNA ON HIGH DIELECTRIC CONSTANT SUBSTRATE

2.1. Antenna Design

A bow-tie antenna is a simple version of planar slot antennas which can offer large bandwidth. A simple CPW-fed bow-tie antenna adopted in this work was proposed in Reference [19]. Fig. 1 shows the geometry of the adopted design.

For a desired operating frequency, the dimensions (a), (b), (L), and (W) are calculated as follow:

$$a = 1.6\lambda_0/\sqrt{\epsilon_r} \tag{1}$$
$$b = 0.5\lambda_0/\sqrt{\epsilon_r} \tag{2}$$
$$L = a/0.85 \tag{3}$$
$$W = b/0.45 \tag{4}$$

The antenna was designed to operate at 300 GHz on a semi-insulating Indium Phosphide (InP) substrate with dielectric constant of $\epsilon_r = 12.56$. Thus, the dimensions a, b, L, and W are 451.5 µm, 141 µm, 531 µm, and 313.5 µm, respectively. The CPW line dimensions ($g = 20$ µm and $s = 13.8$ µm) were calculated to give a 50 Ω characteristic impedance. The conducting element is made of 0.4 µm thick gold and patterned on the top of the substrate. The antenna was simulated in HFSS simulation package which employs finite element method to solve Maxwell's equations. The antenna was fed by a waveport assigned to a rectangular patch facing the substrate side and the edge of the CPW metals.

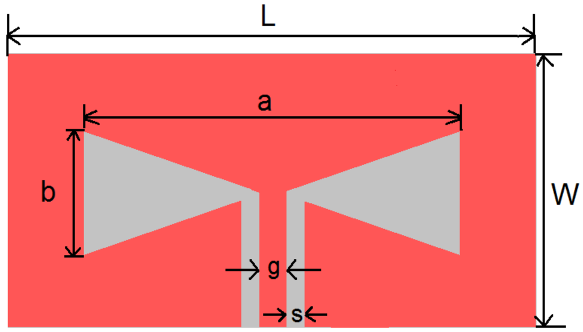

Figure 1: The geometry of the adopted bow-tie antenna [19].

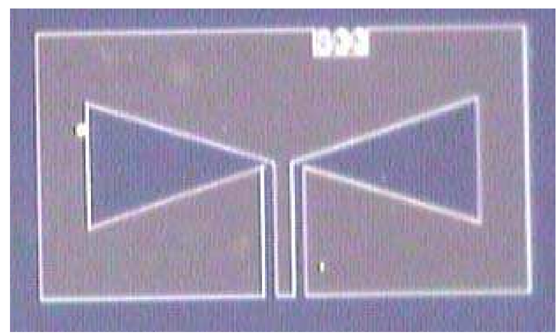

Figure 2: The fabricated bow-tie antenna.

2.2. Antenna Fabrication

The antenna was fabricated using electron beam lithography process. Electron beam resist PMMA was used. The spun PMMA on the InP sample was baked for 3 minutes at 160°C, followed by e-beam pattern writing using Vestec VB6 beam writer. After development in 1:1 IPA:MIKB, Ti/Au (20 nm/400 nm) metal scheme was deposited using an electron beam evaporator followed by lift-off in acetone. Fig. 2 is a micrograph of one of the fabricated antennas.

2.3. Results and Discussion

The antenna was measured using a J-band (220–325 GHz) Cascade Microtech millimeter wave vector network analyzer (VNA) with G-S-G infinity probes. The VNA was calibrated for 2-port S-parameter measurements using the short-open-load-thru (SOLT) two port calibration process on a Cascade impedance substrate standard. Fig. 3 shows the measured and simulated return loss of the designed bow-tie antenna. The bandwidth spans almost the entire frequency band from 220–325 GHz. This bandwidth is by far larger than that obtained from microstrip antennas. The discrepancy between the measured and simulated results can be attributed to unwanted signal reflections from surrounding objects during measurements.

The simulated radiation pattern is shown in Fig. 4. Due to the large dielectric constant of the InP substrate, most of the radiation is directed towards the substrate. This is a common problem with antennas fabricated on high dielectric constant substrates and requires a practical solution in order to enable air-side radiation [11]. A practical solution to this problem has been to use a hemispherical lens on the backside to collect the power from the bottom side of the substrate [12–17]. Our current work (Section 3) aims at designing antennas that can be integrated with RTD THz IC oscillators and which radiate into the air perpendicular to the substrate, to realise compact sources.

3. GROUNDED BOW-TIE ANTENNA ON THIN AND LOW DIELECTRIC CONSTANT SUBSTRATE

One possible way to achieve air side radiation is through employing a (thin) substrate of low dielectric constant and with a ground plane on the bottom side of the substrate to reflect the radiation upwards. The substrate used is benzocyclobutene (BCB) with dielectric constant $\epsilon_r = 2.6$. This substrate is realised by spinning it, for instance, on a carrier substrate such as InP substrate with a coating of metallisation to act as the ground plane and so isolate the high permittivity InP substrate from the high frequency radiation. The antenna dimensions were calculated following the same procedure described above with the difference that the substrate is grounded (ground plane is placed on the bottom side of the BCB substrate to act as a reflector). Therefore, the CPW dimensions (g and s) have to be calculated to get 50 Ω characteristic impedance grounded-CPW line (GCPW). In initial investigations, the aim was to establish the thinnest possible BCB thickness that could provide acceptable performance and allow for simple fabrication processes. Through simulations, it was found that the antenna using a BCB thickness of 50 μm (designed for 300 GHz) gives acceptable performance. The simulated return loss for the antenna is shown in Fig. 5.

It can be seen that the antenna bandwidth extends from around 316 GHz to 338 GHz (for return loss less than −10 dB). The 3D radiation pattern of the antenna (at 321 GHz) is shown in Fig. 6. The proposed antenna exhibits unidirectional radiation with single major lobe and radiates toward the air side (perpendicular to the substrate) which proves the advantages of both the low dielectric constant material and the ground plane placed on the bottom side of the BCB substrate. The 2D radiation patterns in the xz-plane and yz-plane are shown in Figs. 7 and 8, respectively. The front-to-back ratio (FBR) is about 12 dB and the beamwidth of the antenna is about 50° in the xz-plane and 60° in yz-plane. The antenna gain is 8.3 dB and the radiation efficiency is 95.6%.

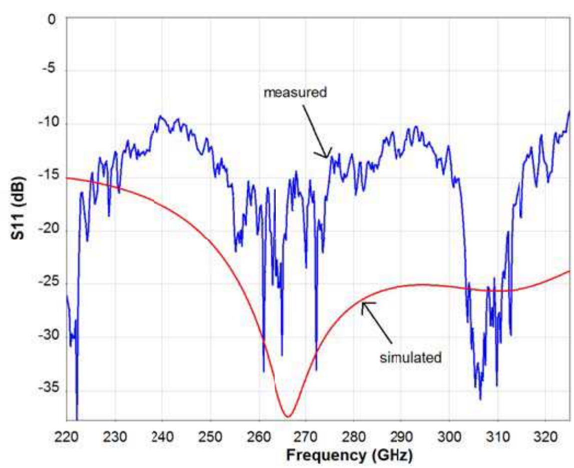

Figure 3: Return loss of the bow-tie antenna on InP substrate.

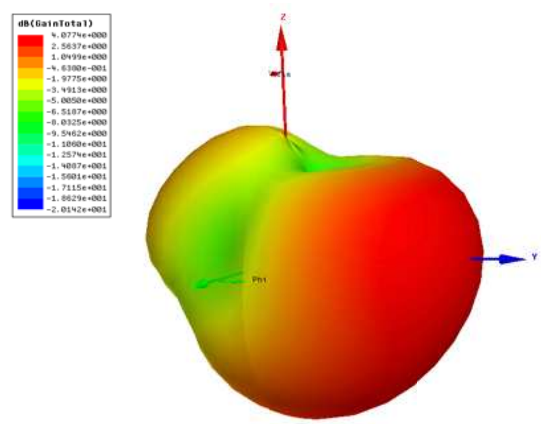

Figure 4: Radiation pattern of the bow-tie antenna on InP substrate at 300 GHz.

4. EXPERIMENTAL VALIDATION OF THE PROPOSED CONCEPT

Experimental validation of the proposed concept includes designing grounded bow-tie antenna using the Rogers substrate of thickness 762 μm at lower frequency so the antenna can be measured in the anechoic chamber in the University of Glasgow which can measure radiation pattern of antennas up to around 20 GHz. The first step is to determine the frequency of operation. In the previous design (bow tie on 50 μm BCB at 321 GHz) the 50 μm is found to be:

$$0.08\lambda_0/\sqrt{\epsilon_r} = 50\,\mu\text{m} \tag{5}$$

where $\epsilon_r = 2.6$ (the dielectric constant of the BCB), and λ_0 is the free space wavelength at 321 GHz.

Now, to determine the frequency for the 762 μm Rogers ($\epsilon_r = 3.48$), we have:

$$0.08\lambda_0/\sqrt{\epsilon_r} = 762\,\mu\text{m} \tag{6}$$

$$\lambda_0 = \frac{762 \times 10^{-6}\sqrt{3.48}}{0.08} \tag{7}$$

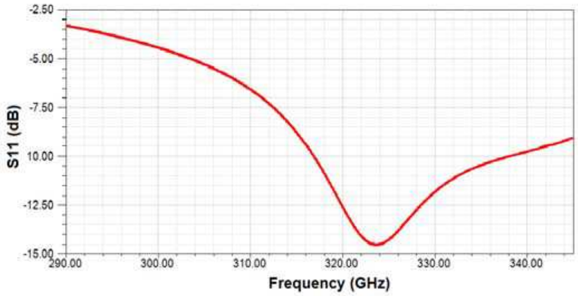

Figure 5: Return loss of the bow-tie antenna on 50 µm thick grounded BCB substrate.

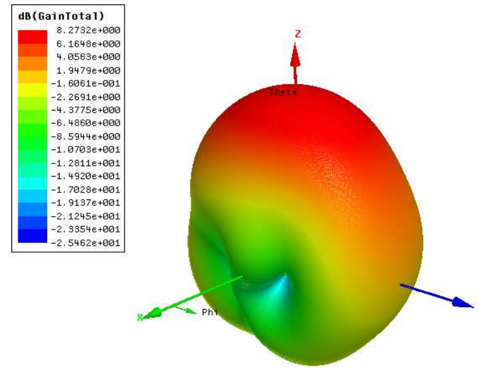

Figure 6: Radiation pattern of the proposed bow-tie antenna on 50 µm thick grounded BCB substrate at 321 GHz.

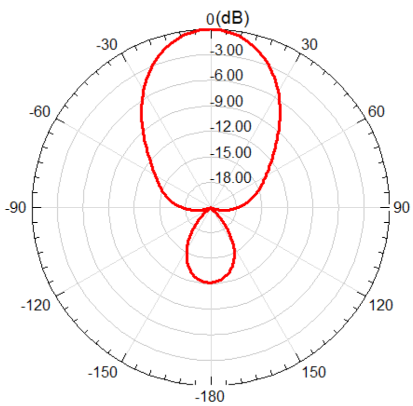

Figure 7: 2D radiation pattern of the proposed bow-tie antenna on 50 µm thick grounded BCB substrate at 321 GHz (xz-plane).

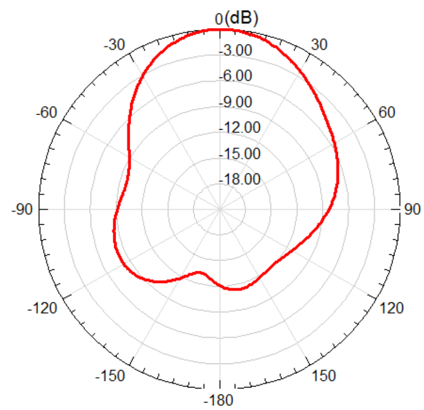

Figure 8: 2D radiation pattern of the proposed bow-tie antenna on 50 µm thick grounded BCB substrate at 321 GHz (yz-plane).

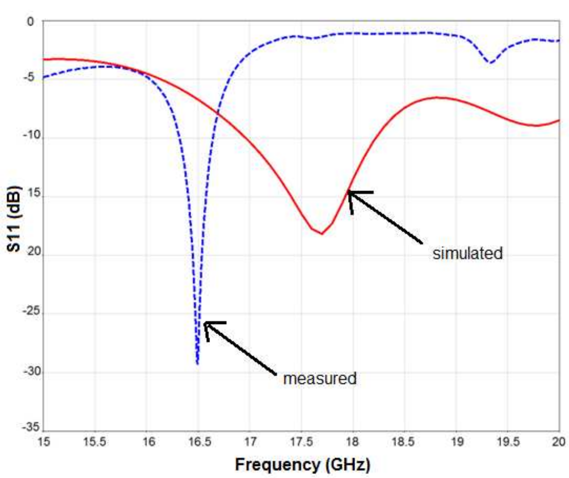

Figure 9: Return loss of the bow-tie antenna on 762 µm thick grounded Rogers substrate.

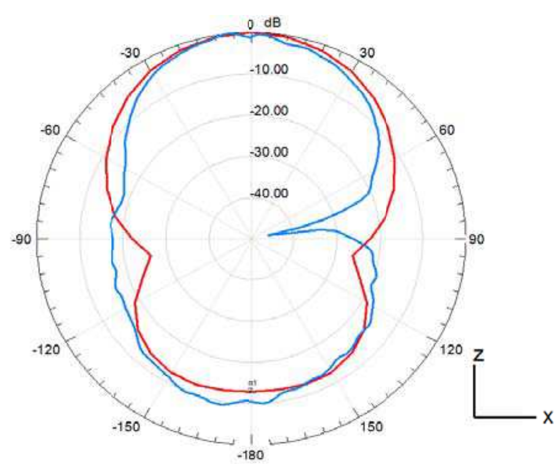

Figure 10: Radiation pattern of antenna at 16.5 GHz in xz-plane (Red: Simulation, Blue: Measurement).

Thus, $f_0 = 17\,\text{GHz}$.

The antenna was then designed for 17 GHz, simulated in HFSS and fabricated for experimental measurements. Fig. 9 shows the return loss of the simulated and measured antennas. It can be seen that the simulation shows resonant at 17.7 GHz ($S_{11} = -18\,\text{dB}$) while the measurement shows resonant at 16.5 GHz ($S_{11} = -28$ dB). Radiation patterns at 16.5 GHz are shown in Fig. 10 and Fig. 11. Fig. 12 illustrates the planes at which the patterns were plotted. Simulated and measured pattern in Fig. 10 are in a good agreement with around 10 dB front-to-back ratio. The measured pattern in Fig. 11 (in general) follows the simulated one (at many directions) although the ripples shown which might be caused by unwanted reflections from the SMA connector which is large in size compared to the whole antenna geometry.

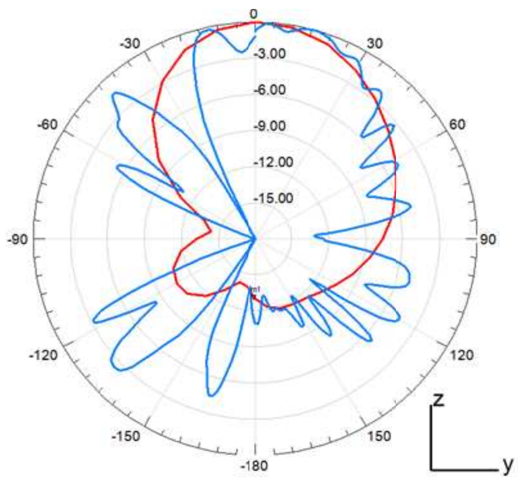

Figure 11: Radiation pattern of antenna at 16.5 GHz in yz-plane (Red: Simulation, Blue: Measurement).

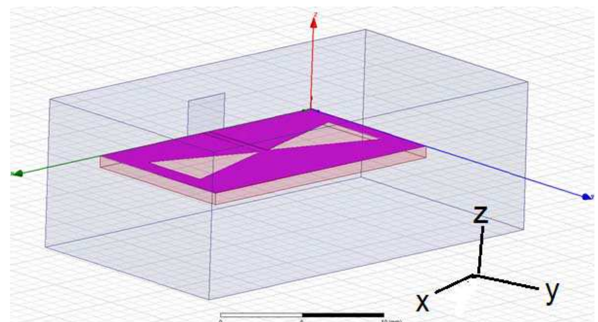

Figure 12: Antenna geometry shows the planes at which the radiation pattern were plotted.

5. CONCLUSION

In this paper, a grounded bow-tie slot antenna for terahertz applications was presented. It offers a known input impedance and radiates into the air perpendicular to the substrate. Future work is focused on integrating this antenna with InP-based RTD THz oscillators.

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