3D-integration of a log spiral antenna onto a dual grating-gate plasmon-resonant terahertz emitter for high-directivity radiation

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3D-integration of a log spiral antenna onto a dual grating-gate plasmon-resonant terahertz emitter for high-directivity radiation

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Abstract. We report a high-directivity plasmon-resonant terahertz (THz) emitter (PRE) incorporating a 3D-integrated antenna complex. The emitter structure is based on a high electron mobility transistor having unique doubly interdigitated grating gates as a broadband THz antenna that can convert non-radiative plasmons to radiative electromagnetic waves. Due to the sub-wavelength aperture of practical grating-antenna dimension, however, present structure of PRE exhibits undesirable diffraction effect, resulting in poor directivity. We developed a new device structure featuring a 3D-integration of tightly-coupled multiple-antenna complex to improve the directivity. The directivity of a new device was dramatically improved by a factor of 5.7 over the frequencies from 1.8 to 4.0 THz.

1. Introduction

Two-dimensional (2D) plasmons in high-electron mobility transistors (HEMT’s) have attracted attention due to their nature of instability promoting terahertz (THz) electromagnetic (EM) radiation, which is expected to realize integrated THz sources [1-4]. We have recently proposed a plasmon-resonant THz emitter (PRE) [3, 4], which is based on a InGaP/InGaAs/GaAs HEMT incorporating original doubly interdigitated grating gates (DGG’s) acting as a broadband THz antenna (Fig. 1(a)). Due to the sub-wavelength aperture (~100 μm²) of the DGG’s region which is limited by the gate-to-channel breakdown voltage, however, the PRE exhibits undesirable EM diffraction effect, resulting in poor directivity. On the other hand, self-complimentary antennae like log-spiral antennae (LSA’s) [5] are well populated for broadband THz radiation, which has been utilized in a stand-alone manner [6] or in combination with THz discrete optics [7]. In this work, to improve the radiation directivity of the PRE, we propose a device structure featuring 3-D integration of a tightly-coupled DGG’s-LSA complex.
2. 3D-Integration of Complex Antenna Systems

A fine patterned planar LSA is dedicated on a separate Si substrate, which is tightly stacked onto the PRE chip via micro-bump interconnection [8] (Fig. 1(b)). The distance between the DGG’s and LSA plane is only 5 μm, which is far shorter by orders than the wavelength of EM waves emitted from the PRE. The micro-bump interconnection, thus, efficiently feeds the EM radiation induced at the active regions of the PRE into the LSA throughout the DGG’s. Fig. 1(c) shows an infrared microscopic image viewed from the bottom of the LSA-integrated PRE.

A log-spiral antenna is geometrically defined by the equations: \( r_1 = r_{1}e^{a\phi} \) and \( r_2 = r_{1}e^{a(\phi-\pi/2)} \) that make up one spiral arm, where \( r_1 \) outer radius, \( r_2 \) inner radius, \( r_1 \) the initial outer radius, \( a \) the wrap tightness, and \( \phi \) spiral turns. Based on the semi-empirical formulae [5], those geometric parameters are designed to be \( r_1 = 14.14 \) μm, \( a = 0.395 \) rad\(^{-1} \), \( \phi = 2.75\pi \) rad, \( r_1 = 430 \) μm, and \( r_2 = 231 \) μm so as to cover the original radiation bandwidth of PRE ranging from 0.5 to 5 THz. The antenna structure is fabricated lithographically with a Ti (30 nm)/Al (250 nm) metallization directly on a Si substrate.

Theoretical calculation suggests that the radiation intensity of the LSA itself to the normal direction (\( \theta = 0^\circ \)) is enhanced by a factor of 2.5 from an isotropic radiation. Taking account of a numerical aperture of the LSA (ideally 0.5), the radiation intensity of the simplified model of the PRE with a free-standing LSA is expected to be enhanced by a factor of \( \leq 1.25 \) with respect to the PRE without LSA. When the directivity is evaluated as the half-power beam width (HPBW) [9], corresponding directivity of the simplified model is also calculated to be improved by a factor of \( \sim 2.0 \) with respect to the PRE without LSA.

3. Experimental Results and Discussions

We characterized the THz-EM radiation property of the fabricated samples (LSA-integrated PRE’s and PRE’s without LSA) by using a Fourier-transform far-infrared spectrometer (FTIR) [4]. The
effectively measurable lower cutoff frequency of the FTIR is \( \lesssim 1 \) THz. The radiation spectra were measured at polar angles \( \theta \) from 0 (normal to the surface) to 90°. Figure 2 shows a typical result at \( \theta = 0^\circ \) as the relative intensity where the background thermal (black-body) radiation is scaled as “100” so that the baseline at 100 means no excess radiation. The original PRE without LSA shows broadband radiation from 1 to 6 THz, which is up-shifting by \( \sim 1 \) THz from the nominal bandwidth of the LSA. The spectrum of the LSA-integrated PRE almost traces the designed bandwidth of the LSA although the radiation intensity is unexpectedly attenuated. Such a radiation loss is thought to be caused by the impedance mismatch and excess losses along with the DGG’s-LSA propagation originated from undesirable high contact resistance among the micro-bump interconnection. Improvement on the interconnection process to recover the original radiation gain is the future subject.

Figure 3 shows the polar-angle dependence of the radiation intensity at typical four different frequencies: 1.8, 2.4, 3.2 and 4.0 THz. The vertical scale is normalized to the maximum radiation intensity for each type of the sample among those frequencies. As seen in Fig. 3(a), the PRE without LSA exhibits a poor directivity \( \sim 8 \) dBi (Table 1) with a broad distribution from 0 to \( \sim 40^\circ \) at all the frequencies; corresponding HPBW is \( \sim 80^\circ \) (Table 1). In contrast, as seen in Fig. 3(b), the radiation

<table>
<thead>
<tr>
<th>Devices</th>
<th>HPBW (deg.)</th>
<th>Directivity (dBi)</th>
<th>Relative intensity at 0°</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSA-integrated PRE</td>
<td>14</td>
<td>-23</td>
<td>106</td>
</tr>
<tr>
<td>PRE without LSA</td>
<td>-80</td>
<td>-8</td>
<td>112; 121</td>
</tr>
</tbody>
</table>

(*Background thermal radiation is scaled as 100.)
The pattern of the LSA-integrated PRE exhibits an extraordinary sharp main-lobe in the normal direction \((\theta = 0^\circ)\) and relatively broad side-lobe(s) around \(\theta \approx 40^\circ\) at all the frequencies from 1.8 to 4.0 THz. The side-lobe is suppressed below 50% of the main peak. As a result, the directivity is greatly improved to \(\sim 23\) dBi; corresponding HPBW is \(\sim 14^\circ\) (Table 1). The improvement factor in HPBW is 5.7, which is about three times as high as the estimated value for the simplified model mentioned in section 2.

One can consider a left-handed metamaterial effect on parasitics of the tightly-coupled DGG’s-LSA interconnection to explain the causes of such extraordinary directivity. The physical structure of connecting portion can be modelled as a serial capacitor and a shunt inductive/resistive element along with the antenna pattern. Due to the propagation angle the capacitance value may change depending on the distance while the shunt inductance will be monotonically decreased with frequency. This might cause a specific frequency response with electromagnetic bandgap(s) in specific range(s) of the polar angles, which may modulate the original frequency response and radiation pattern. Further investigations and accurate modelling/calculation should be followed, which will be the future subject.

4. Summary

We proposed a high-directivity THz PRE featuring a LSA-integrated 3D antenna complex structure. Although the impedance mismatch caused by undesirable interconnection losses deteriorates the radiation intensity almost by one third of the PRE without LSA, extraordinary sharp radiation directivity was successfully obtained over the broadband frequencies from 1.8 to 4.0 THz. The tightly-coupled DGG’s-LSA complex metamaterial structure is considered to work for manipulating extraordinary propagation of EM waves.

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References