An Efficient Photomixer Based Slot Fed Terahertz Dielectric Resonator Antenna

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Abstract—A slot fed THz dielectric resonator antenna driven by an optimized photomixer is presented. The localized optical E-field at the centre of the photomixer electrodes has been improved to 9.9V/m by utilizing a frequency selective surface superstrate. This corresponding to an enhancement factor of 4.7 compared to a conventional photomixer, which results in a considerable improvement in the optical-to-THz conversion efficiency. Moreover, the utilization of THz DRA offers a broadside gain of 9dBi and an input resistance of 700Ω.

Keywords—Frequency Selective Surface, Photomixer antenna, Dielectric resonator antenna, Dielectric superstrate.

I. INTRODUCTION

The future development of communication systems with the ever increasing high-speed demands result in higher attention being paid to terahertz (THz) that extends from 300GHz to 10THz. Such a band is located in the transition region between electronic and photonic domains, and provides higher data rate as well as alleviate the crowded spectrum at the microwave band [1].

However, traditional THz sources usually involve cryogenic cooling and other bulky equipment [2]. On the other hand, a photomixer represents a promising source of continuous wave (CW) THz radiation generation at room temperature. Conventional THz photomixer consists of two set of electrodes that are printed on photoconductive Low-Temperature Growth Gallium Arsenide (LT-GaAs) layer, which is usually supported by a bulky GaAs substrate. As the two CW frequency off-set laser beams illuminate the electrodes, THz photocurrent is generated at the beating frequency by applying a DC biased voltage to the electrodes [3]. However, the laser-to-THz conversion efficiency of a photomixer is typically as low as 0.1% which limits the application of THz radiation [4-5]. To date, an enhancement factor of 4 in the optical-to-THz power conversion efficiency has been achieved by utilizing optical frequency selective surface (FSS). The simulation has been conducted using the Computer Simulation Technology (CST) Microwave Studio [17].

Furthermore, due to the presence of the bulky GaAs substrate, the resistance of the THz antenna is reduced by √((εr+1)/2), where εr is the dielectric constant of the substrate. As a result, the matching efficiency of THz antenna is rather poor considering the high output resistance of photomixer, which is in the order of ~10kΩ [10]. However, a 2.6kΩ input resistance has been achieved by using a full-wavelength dipole as the driver element of THz Yagi-Uda array [11]. On the other hand, a dipole printed on thin dielectric slab with an isolation metallic ground plane has achieved a 3.3kΩ input resistance [12]. Moreover, since THz radiation suffers from high atmospheric path losses [13], THz antenna designers need to pay more attention to the radiated power enhancement. Therefore, various Si lenses have been considered, such as cylindrical lens [14] and hemi-elliptical lens [15]. Besides, Si lens can be used to avoid most of the power absorbed by the thick GaAs. Nevertheless, the presence of the Si lens increases the overall size of the antenna configuration. In this study, dielectric resonator antenna (DRA) is considered as it represents a promising solution owing to attractive features such as small size, high radiation efficiency and gain as well as the low cost [16]. As a result, high gain has been achieved by truncating the supporting GaAs substrate in order to create a THz DRA. Furthermore, the optical-to-THz conversion efficiency has been improved by utilizing optical frequency selective surface (FSS). The simulation has been conducted using the Computer Simulation Technology (CST) Microwave Studio [17].

II. PHOTOMIXER DESIGN

A. Theory

Fig. 1 presents the photomixer’s equivalent circuit, from which an expression for the generated THz power can be derived as [18]:

\[ P_{THz} = \frac{W \cdot e \cdot \mu \cdot \tau}{Lh \cdot f} \left( 1 - R \right) \left( 1 - \exp(-\alpha \cdot T_{stub}) \right)^2 \]

\[ \left( \frac{m \cdot R_{antenna} \cdot V_{bias}^2}{(1 + \omega \cdot R_{antenna} \cdot C_{electrode})^2(1 + \omega \cdot \tau)^2} \right) I \delta^2 \]

(1)

where the equation’s variables are listed in the Table below:
| Terms   | Explanation                                    |
|---------|-----------------------------------------------|
| $W$     | Top width of electrodes’ tip                  |
| $e$     | Electron charge                               |
| $\mu_e$ | Electron mobility of LT-GaAs                  |
| $L$     | Length of electrodes’ tip                     |
| $h$     | Plank constant                                |
| $f_l$   | Mean laser frequency                          |
| $I_0$   | LT-GaAs’ surface optical intensity            |
| $R$     | Reflectivity of air-LT-GaAs interface         |
| $\tau_c$| Carrier lifetime                              |
| $\alpha$| Optical absorption coefficient                 |
| $T_{sub}$| Depth of photoconductive region               |
| $m$     | Laser mixing efficiency                       |
| $\omega_{THz}$ | THz angular frequency                        |
| $t$     | Time variant factor                           |
| $R_{antenna}$ | Antenna input resistance                   |
| $V_{bias}$| DC bias voltage                               |
| $C_{electrodes}$ | Capacitance cause by structure of electrode |

Equation (1) demonstrates that the generated THz power depends strongly on the following parameters; $\omega_{THz}R_{antenna}C_{electrodes}$, $\omega_{THz}$, and $I_0^2$ terms. Therefore, rather than optimizing the structure of the photomixer electrodes and studying the properties of the photoconductive material, a design is proposed to improve the optical intensity on the surface of LT-GaAs. According to (1), the generated THz power is proportional to the 4th power of optical E-field magnitude between the electrodes [18].

**B. Photomixer Design**

In order to design a slot fed THz DRA, a metallic ground plane has been added on top of the LT-GaAs layer with a central slot that accommodates the photomixer and acts as a feed to the THz DRA. An optical FSS can be used as a superstrate above the photomixer. Due to the multiple bouncing of the electromagnetic wave between the FSS and ground plane surrounding the photomixer, the optical intensity on the surface of the LT-GaAs can be enhanced significantly.

The electrodes configuration is illustrated in Fig. 2 and have been simulated as Palik gold with $M=0.5 \mu m$, $B=0.2 \mu m$, $W=0.1 \mu m$, $e=0.5 \mu m$, $P=2.3 \mu m$, $L_{tip}=1.13 \mu m$, $D=0.8 \mu m$, $T_{end}=4 \mu m$, $H=1 \mu m$ and $G=13.68 \mu m$. The photomixer has been mounted on a 0.44 $\mu m$ thick LT-GaAs substrate with a relative permittivity of 12.9. The unit cell of the FSS is illustrated in Fig. 3 with periodicity, hole radius and thickness of $a=0.72 \mu m$, $r=0.3a$ and $h=0.2a$, respectively. Furthermore, 19×19 unit cells have been utilized in the FSS layer that has been placed at a distance of 0.3 $\mu m$ above the photomixer. The reflectivity of the FSS is demonstrated in Fig. 3. The incident laser beams have been modelled as a plane wave with magnitude of 1V/m in parallel with the electrodes. The E-field magnitudes in the centre of the

Fig. 1. Equivalent circuit of THz photomixer

Fig. 2 Top view of the photomixer within slot

Fig. 3. Reflectivity of 19×19 unit cells and top view of FSS unit cell

Fig. 4. Optical E-field magnitude on the surface of LT-GaAs at the centre of photoconductive region
photomixer are presented in Fig. 4, and the cross-section of E-field distributions are illustrated in Fig. 5.

The cavity created by the FSS and ground plane improved the optical E-field magnitude from 2.1V/m to 9.9V/m, which corresponds to an enhancement factor of 4.7. As can be noted from (1), the generated THz power is proportional to the 4th of the E-field. Therefore, it can be concluded that the generated THz power has been increased by 487 times, which dramatically enhances the optical-to-THz power conversion efficiency.

Next, this optimized photomixer can be used to feed a THz antenna. As mentioned earlier, the supporting GaAs substrate reduces the input impedance and absorbs most of the THz power, which impacts both of the matching and radiation efficiencies. Consequently, further optimization is required to improve the total efficiency of the THz antenna.

III. THz DIELECTRIC RESONATOR ANTENNA DESIGN

A. Antenna Configuration

In order to optimize the matching and radiation efficiencies, the GaAs substrate has been truncated to create a dielectric resonator antenna that operates in the higher order mode. Moreover, the size of the DRA should be large enough to mechanically support the photomixer. Since the dimensions of the photomixer and coupled optical FSS are sufficiently small at the THz band, their presence will not impact the performance at this frequency range.

The antenna geometry is illustrated in Fig. 6. A square DRA with width of $W_{\text{DRA}}=250\mu$m and height of $H_{\text{DRA}}=60\mu$m is placed on a gold ground plane with size of $W_{\text{ground}}=400\mu$m and fed by a slot with length of $L_{\text{slot}}=65\mu$m and width of $W_{\text{slot}}=5\mu$m. Fig. 7 illustrates a coplanar stripline (CPS) that has been incorporated to minimize the THz power leakage. The dimensions of the feeding network have been chosen as: $L_{\text{Tx}}=120\mu$m, $W_{\text{Tx}}=1\mu$m, $L_{\text{stub}}=91\mu$m, $W_{\text{stub}}=0.5\mu$m, and $g_{\text{stub}}=50\mu$m, and the gap between the CPS stub and ground plane as well as the width of the slot surrounding the feeding line are $W_{\text{gap}}=0.5\mu$m and $g_{\text{Tx}}=3\mu$m, respectively. The ground plane has been divided into two halves that are separated by a narrow slot with $W_{\text{separate}}=0.5\mu$m so that the ground plane could be used as DC biased pad. At THz frequencies, the photomixer has been modelled as a discrete port with a 10kΩ input impedance in parallel with a 3Ff lumped capacitance that is placed in the middle of feeding slot and connected to the biased DC pad.

Furthermore, a THz GaAs dielectric superstrate with thickness and width of $T_{\text{sup}}=60\mu$m and $W_{\text{sup}}=400\mu$m has been placed at a height of $H_{\text{sup}}=30\mu$m above the DRA since $\lambda=0.25\left((\phi_2-\phi_1)/2\pi+0.5\right)$, where $\phi_1, \phi_2$ are superstrate and antenna groundplane’s reflection coefficient phases, $\lambda$ is the wavelength at designed frequency [19]. In addition, the bandwidth can also be improved by utilizing a dielectric superstrate [20].

B. Results and Discussion

Fig. 8 presents the DRA input resistance with/without a CPS network, where it can be noticed that the input resistance of DRA has been increased from 430Ω to 700Ω. Therefore, the corresponding matching efficiency has been improved from 15.8% to 24.4%. The radiation patterns of the DRA are illustrated in Fig. 9 where it can be observed that
A photomixer with high optical-to-THz power conversion efficiency has been designed and used to excite a slot-fed THz antenna. The photomixer has been coupled with a frequency selective surface to confine a cavity between the ground plane and FSS. As a result, an improved optical electric field at the center of photconductive region has been achieved. According to (1), the generated THz power is proportional to the power of 4 of the localized E-field, which means the generated THz power has been improved by 487 times. Moreover, the supporting GaAs substrate of the photomixer has been truncated into a DRA that is driven by the proposed optimized photomixer. By utilizing CPS and THz dielectric superstrate, the gain and matching efficiencies of the DRA have been improved by 2.5dBi and 1.5 times, respectively. Consequently, the overall enhancement factor of antenna’s total efficiency that include optical-to-THz conversion efficiency, marching efficiency and radiation efficiency is 1240.

IV. CONCLUSION

the gain has been increased from 6.5dBi to 9dBi with the presence of superstrate.

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