New Device for Continuous-Wave THz Emission: Large Area Emitter

Luis Enrique García-Muñoz, Gottfried Döhler, Javier Montero-de-Paz, Eduardo Ugarte-Muñoz, Alejandro Rivera-Lavado, Sascha Preu, Stefan Malzer, Sebastian Bauerschmidt, Vicente Gonzalez-Posadas, Daniel Segovia-Vargas

Abstract—We discuss two different approaches to overcome the power limitations of CW THz generation imposed to conventional photomixers. The increase in power achievable by using arrays of AEs is studied. Then “large area emitters” are proposed as an alternate approach to overcome the power limitations. In this antenna-free new scheme of photomixing, the THz radiation originates directly from the acceleration of photoinduced charge carriers generated within a large semiconductor area. The quasi-continuous distribution of emitting elements corresponds to a high-density array and results in particularly favorable radiation profiles.

I. INTRODUCTION

The well-established method of generation of continuous-wave Terahertz (CW-THz) radiation by photomixing [1] consists of two basic steps. Two laser beams, slightly differing in their frequencies (the desired THz frequency), are generating a THz photocurrent in a semiconductor device. This current is fed into an antenna, deposited onto the (semi-insulating, THz-transparent) semiconductor substrate, which then emits THz radiation with high efficiency, provided the antenna design is suitable for the chosen THz frequency. The major fraction of the THz power is radiated into the substrate, due to the much smaller wave impedance of semiconductors, attributed to their high dielectric constant. For convenient collection and collimation of the radiation, a hyper-hemispherical lens, fabricated from a material with similar dielectric constant, is placed below the substrate at the symmetry centre of the antenna (Figure 1).

II. ANTENNA EMITTER (AE) APPROACH

In Figure 2 the numerically calculated angular radiation intensity emitted by an AE with horizontal \( \frac{\lambda}{2} \) dipole antenna of length 42\( \mu \text{m} \) at 1 THz placed along the x-axis into the substrate, obtained from the analytical formulation based on Helmholtz's potentials, is shown for the E-plane and the H-plane. Results are consistent with the ones presented [2]-[4]. It has to be pointed out that the backward radiation (radiation into the air) is not plotted in order to have a friendlier picture.

The radiation intensity can be strongly enhanced by the use of a suitably designed hyperhemispherical lens fabricated from a material with a refractive index similar to that of the semiconductor, \( n_{\text{sc}} \approx 3.5 \). At the same time the lens allows collecting nearly all the radiation emitted into the semiconductor. Without the lens, the radiation emitted under an angle exceeding the critical angle for total reflection \( \theta_{c} = \arcsin(1/n_{sc}) \approx 16^\circ \) could not be extracted. The blue full line in Figure 2 depicts the simulated angular radiation intensity for the AE with lens, again for the E-plane and for the H-plane for the same AE as before, but with a lens of radius \( R = 2 \text{ mm} \). The lens has been analyzed with Physical Optics (PO) following the same methodology proposed by Filipovic in [5], taking into account the total internal reflection at the second semiconductor-air interface, where the THz beam leaves the substrate. The radiation intensity at \( \theta = 0^\circ \) is increased by 24.38dB while the 3 dB angle is reduced from 47.72\(^\circ\) to 2.4\(^\circ\). We note that the intensity pattern does not significantly differ from the diffraction-limited pattern of an Airy disk of the same diameter [6].
These restrictions limit the THz power achievable with a single AE (nowadays) to about $P_{THz} < 10 \mu W$ for AEs with resonant and to a few $\mu W$ in the case of broad-band antennas at 1 THz. The most straightforward solution to achieve an increase in THz power from photomixers is using an array.

III. LARGE AREA EMITTER

In this antenna-free new scheme of photomixing the THz radiation originates directly from the acceleration of photo-induced charge carriers generated within a large semiconductor area. The quasi-continuous distribution of emitting elements corresponds to a high-density array and results in favorable radiation profiles without side lobes. Moreover, the achievable THz power is expected to outnumber even large AEs. Last not least, the technological challenge of fabricating LAEs appears to be significantly less demanding.

In Figure 3 the radiation intensities for (a) the vertical and (b) the horizontal LAE at the interface are shown (full and dash-lines) and compared with those of the corresponding LAE embedded in the semiconductor (dashed-dotted and dotted lines), renormalized to the maximum power emitted by the dipole embedded into the semiconductor perpendicular to its axis. The effect of the interface is most pronounced for the vertical dipole (Figure 3(a)). As expected, most of the power is emitted into the semiconductor. Its total emitted power is strongly reduced compared with the embedded dipole. The radiation intensity radiated into the semiconductor exhibits a pronounced maximum at the critical angle for total reflection $\theta = \theta_c$. Even at this maximum the radiation intensity is only the fraction $4/\pi n_c^2 \approx 31\%$ of the maximum value, which would be expected for $\theta = 90^\circ$ for the dipole embedded in the semiconductor. In the range $\theta_c < \theta < \pi/2$ the radiation intensity of the dipole at the interface decreases monotonically and becomes zero at $\theta = \pi/2$, where it would reach its maximum for the embedded dipole. The changes of the power distribution are less pronounced for the horizontal LAE (Figure 3(b)). Here, the maximum is found in the H-plane ($\varphi = \pi/2$) at $\theta = \theta_c$. Its value corresponds to 4 times the power expected at $\theta = 0$ for the horizontal embedded LAE. In the E-plane ($\varphi = \pi/2$), in contrast, zero power is expected at $\theta = \theta_c$.

Higher total laser power can be applied without the risk of thermal failure and without causing screening if an alternative THz emitter concept is found that allows for the laser power to be spread over a large area comparable with the size of the antenna, or even larger. Such a "large area emitter" (LAE) concept (Fig.1(a) and Fig.1(b)) can be implemented by taking advantage of the fact that the charge carriers generated in the semiconductor become elementary Hertzian dipole sources of THz radiation, if subjected to an accelerating DC electric field $E_0$. The THz fields of the dipole interfere constructively and the radiated power increases with laser power quadratically, as in the case of antenna emitters, if the area, in which the carriers are generated, is small compared with the THz wavelength [2]. The angular distribution of the THz power will be the same as that for an elementary dipole in this case ("large area quasi dipole" (LAQD)). If, however, the size of the illuminated area becomes comparable with the THz wavelength or even larger, interference effects will become essential and the radiation pattern will become more narrow. Like in an array of THz antennas, we will find that the maximum radiation intensity still increases quadratically with laser power for the direction of coherent superposition, whereas the total THz power only increases proportional to the
laser power, due to correspondingly decreasing beam width in
the extreme large area limit, if the array dimensions
significantly exceed the THz wavelength.

A single electron in a semiconductor of dielectric constant
e_{ac} characterized by an effective mass m_{\text{eff}} (typically m_{\text{eff}} = (0.04 ...
0.07)m_{0}, where m_{0} = 9.1x10^{-31} kg is the mass of a free
electron), emits a THz pulse if accelerated by an electric field
E_{0}. The total THz power P_{\text{THz}}(t) is given by [1-4]

$$P_{\text{THz}}(t) = \left( \frac{Z_{0}}{6 \cdot \pi} \right) \cdot \epsilon(t) \cdot n_{e} \cdot \epsilon^{3}$$  \(1\)

Here, \(e = 1.602 \times 10^{-19} \text{C}\) as is the elementary charge, \(c = 3 \times 10^{10} \text{cm/s}\) the vacuum velocity of light, \(Z_{0} = (\epsilon_{0}c)^{2} = 376.73 \Omega\) the impedance of free space and \(n_{e} = (\epsilon_{0})^{1/2}\) the refractive index of the semiconductor. In typical III-V semiconductors
and at sufficiently high electric fields (> 3 kV/cm) the time
dependent acceleration \(a(t)\) can be approximated by an initial
“ballistic” acceleration \(a_{\text{ball}} = eE_{0}/m_{\text{eff}}\) up to a maximum ballistic
velocity of about \(v_{\text{ball}}\max = 10^{8}\text{cm/s}\) (in GaAs) and \(2 \times 10^{3}\text{cm/s}\)
in (InGaAs, e.g.), followed by a deceleration due to scattering,
which can be approximated by \(a_{\text{st}} = -a_{\text{norm}}[2,9]\). The superposition of the transient THz fields of the carriers
generated by the modulated laser power \(P_{\lambda}(t)\) yields in the
LAQD-limit

$$P_{\text{LAQD}3}(t) = \frac{1}{2} \cdot R_{\text{LAQD}} \cdot |I_{\text{THz}}(\omega_{\text{THz}})|^{2}$$  \(2\)

with

$$R_{\text{LAQD}} = \left( \frac{2 \cdot Z_{0} \cdot n_{e}}{3 \cdot \pi} \right) \cdot \left( \frac{v_{\text{ball}}}{c} \right)^{2} = (3.2...12.8) \cdot 10^{-3} \Omega$$

for \(v_{\text{ball}} = (1...2) \cdot 10^{8} \text{cm/s}\) \(3\)

and

$$I_{\text{THz}}(\omega_{\text{THz}}) = I_{0,\text{th}} \cdot f(\omega_{\text{THz}})$$  \(4\)

The frequency dependent factor

$$f(\omega_{\text{THz}}) = \left( 1 - \cos(\omega_{\text{THz}} \cdot \tau_{\text{ball}}) \right) \omega_{\text{THz}} \cdot \tau_{\text{ball}}$$  \(5\)

linearly increases with \(\omega_{\text{THz}} \cdot \tau_{\text{ball}}\) at low frequencies, reaches
the maxima at about \(\omega_{\text{THz}} \cdot \tau_{\text{ball}} = (3/8)\pi\) and \((2n+1)\pi\) and the
minima at \(\omega_{\text{THz}} \cdot \tau_{\text{ball}} = 2n\pi\) (\(n = 1, 2, 3, ...\)). This behavior
reflects the fact that, at low THz frequencies \((\omega_{\text{THz}} < \tau_{\text{ball}})^{-1}\),
the fields of accelerated carriers are strongly reduced due to
destructive interference with the opposite fields of decelerated,
previously generated carriers, as the acceleration and
deceleration times, \(\tau_{\text{ball}} = v_{\text{ball}}/a_{\text{th}} = v_{\text{ball}}m_{\text{eff}}/eE_{0}\), are short
compared to the THz period, \(T_{\text{THz}} = 1/\nu_{\text{THz}}\). The main
maximum of \(f(\omega_{\text{THz}})\) occurs close to the frequency at which the acceleration and deceleration times,
\(\tau_{\text{ball}}\) closely correspond to half a THz period \(T_{\text{THz}}\).
The ballistic acceleration time \(\tau_{\text{ball}} = v_{\text{ball}}/a_{\text{th}} = v_{\text{ball}}m_{\text{eff}}/eE_{0}\) can be adapted to
fulfill the condition for maximum THz power, \(\tau_{\text{ball}} = (3/8)\)
\(T_{\text{THz}} = (3/8\nu_{\text{THz}})\). This condition yields \(6 \text{kV/cm} < E_{0} < 60 \text{kV/cm}\) for \(0.5 \text{THz} < \nu_{\text{THz}} < 5 \text{THz}\) for InGaAs, e.g. For the
optimum adapted fields the THz power becomes

$$P_{\text{LAQD}3} = \frac{1}{2} \cdot (1.76...6.7) \cdot 10^{-3} \Omega \cdot f^{2}$$

for \(v_{\text{ball}} = (1...2) \cdot 10^{8} \text{ cm/s}\) \(6\)

The angular dependence of the radiation intensity, i.e. the
power emitted per space angle element \(d\Omega = \sin\theta \cdot d\theta \cdot d\phi\), is the same for a LAQD as for a Hertzian dipole in the far-field. It
increases quadratically with the sine of the angle between the
accelerating DC-field \(E_{0}\) and the vector \(r\) from the center of
the LAE device to the observation point. For a field in \(x\)-
direction, \(E_{0} = E_{0}(0, 0, 1)\), this angle is identical with the
polar angle \(\theta\) and one obtains for the radiation intensity

$$U_{\text{LAQD}}(\theta) = \left( \frac{3}{8 \cdot \pi} \right) \cdot P_{\text{LAQD}3} \cdot \sin^{2}(\theta)$$  \(7\)

whereas, for a field in \(x\)-direction, \(E_{0} = E_{0}(1, 0, 0)\) the
radiation intensity depends on both the polar angle \(\theta\) and the
azimuth angle \(\varphi\)

$$U_{\text{LAQD}}(\theta, \varphi) = \left( \frac{3}{8 \cdot \pi} \right) \cdot P_{\text{LAQD}3} \cdot (1 - \sin^{2}(\theta) \cdot \sin^{2}(\varphi))$$  \(8\)

with \(P_{\text{THz}}\) from Eq.s (2) – (6).

The previous considerations apply to a (hypothetical) large
area quasi dipole (LAQD) embedded into an infinite bulk
semiconductor. In a typical scenario, however, the absorption
of the laser radiation will take place in the semiconductor
close to its interface to air at \(z = 0\). The radiation pattern
pattern of Hertzian dipoles placed in a semiconductor close to
the surface (distance \(z_{0} << \lambda\)) is expected to differ significantly
from the one embedded within the infinite bulk. Therefore, in
the following Section III, the angular power distribution for
the case of a vertical and horizontal Hertzian dipole at the
interface to air, \(U_{v, h, \text{LAQD}}(\theta, \varphi)\), and for the case of a horizontal
dipole, \(U_{h, \text{LAQD}}(\theta, \varphi)\), will be developed.

In order to fully take advantage of the large area emitter
(LAE) concept, the dimensions of the illuminated area will
typically be chosen comparable with the THz wavelength (in
the semiconductor), \(\lambda_{0}/\text{area}\), or even larger. In this case,
interference effects will influence the angular dependence of
the radiation pattern. This situation is being treated in Sections
IV and V for the two field orientations. In order to establish the close connection of such LAEs to the antenna emitter arrays (AEA)s we will first subdivide the actual “continuous array” of elementary Hertzian dipoles into a discrete, but sufficiently dense array of Hertzian dipoles of correspondingly enhanced dipole charge, yielding an array factor for large area emitters, $A F_{LAE}(\rho_0,\theta,\phi)$, depending on their characteristic dimension, $\rho_0$, similar to the one developed in Section IV of Part I of this paper. The actual angular dependence of the radiation intensity at vertical DC E-fields, $U^{LAE}_{v}(\theta,\phi)$, and in-plane DC E-fields, $U^{LAE}_{h}(\theta,\phi)$, will then, again, be given by the product of the angular dependence of the (modified) Hertzian dipole patterns and the array factors

$$U^{LAE}_{v}(\theta,\phi) = U^{LAE}_{v}(\theta,\phi) \cdot A F^{LAE}(\theta,\phi) \quad (9)$$

and

$$U^{LAE}_{h}(\theta,\phi) = U^{LAE}_{h}(\theta,\phi) \cdot A F^{LAE}(\theta,\phi) \quad (10)$$

respectively.

ACKNOWLEDGEMENTS

This work was partially granted by CICYT NeoImag TEC2009-14525-C01 and CONSOLIDER-INGENIO 2010 CSD2008-00068. The work of Javier Montero-de-Paz was supported by the Spanish Education Minister under the program FPU (AP2009-4679). The work of Eduardo Ugarte-Muñoz was supported by the Spanish Economy Minister under the program FPI (BES2010-037676). Prof. G. Dohler work was granted by “Cátedras de Excelencia” from Banco Santander. Authors also would like to thanks Prof. David M. Pozar and Prof. David B. Rutledge for their constructive comments.

REFERENCES


