Exchange Visit Grant

Scientific Report

The scientific report (WORD or PDF file – maximum of eight A4 pages) should be submitted online within one month of the event. It will be published on the ESF website.

Proposal Title:

Design and integration of power-efficient components and new focusing elements for the THz-range

Application Reference Nº:

4884

1) Purpose of the visit

The concept of "conventional" arrays has been discussed for a long time as one of the possibilities to increase the intensity and the directivity of emitted THz beams. In addition, arrays provide the possibility of beam steering by controlling the phase of the laser beams. Although very appealing results can be expected from 2-dimensional arrays of lumped element photoconductive or p-i-n-diode THz emitters, this concept still suffers from several drawbacks:

(1) The maximum tolerable optical power and, hence, the THz power emitted by the individual elements of the array is limited due to the small active device area required to keep the RC roll-off at a reasonable level.

(2) (Hyperhemispherical) lenses are required for efficient collection of the radiation emitted into the substrate under different angles.

(3) As the minimum pitch of the arrays is determined by the diameter of the individual antennas, only one central element of the array can be positioned on the optical axis of the lens. Therefore, the off-axis positions of the other array elements result in the emission of the focused beams under quite different angles, unless the diameter of the lens is chosen unreasonably large. Even in this case, additional, high quality THz focusing elements are required to obtain a reasonably collimated beam exhibiting coherent superposition of the THz fields originating from the individual elements.

(4) An alternate approach, avoiding these problems, is based on an array of emitters with individual lenses. The realization of this approach, however, is technologically extremely demanding.

(5) Last, not least, the illumination of the individual elements of the array by laser beams focused onto their small active areas requires a well-adjusted microlens array, a suitably designed diffractive element, or a fiber bundle. An even distribution of the optical power and the alignment are challenging.

To overcome such problems, a new concept/topology for generating THz power called large area emitters (LAEs), has been studied in this research stay. LAEs can be considered as high-density arrays, or, more correctly, as continuous arrays. It will be shown that they represent an elegant approach, which avoids the previously mentioned problems.

2) Description of the work carried out during the visit

It has always been assumed that the THz radiation emitted by photoconductive or p-i-n photodiode THz emitters is due to the temporal changes of a photocurrent, generated in the semiconductor device and fed into an antenna. However, antennas are not a sine qua non, since, according to basic electrodynamics, electromagnetic fields are generated by each photogenerated charge carrier, if accelerated by the DC electric field present in a photoconductor or a p-i-n photo diode. As typical charge carrier acceleration and deceleration times at intermediate and high fields in semiconductors are in the 100 fs range, these carriers will emit THz pulses. If many charge carriers are generated simultaneously by fs laser pulses within a large illuminated area, the superposition of the coherently emitted electromagnetic fields of these carriers will result in the emission of strong THz pulses. Limitations by local heating and saturation, as occurring in lumped element devices, can be circumvented by using larger areas. In fact, there are numerous earlier reports about such “large area emitters” (LAEs) in the literature, in which this approach had been used. Early demonstrations date back to the 1990s where “large aperture photomixers” used a large photoconductive gap (in the range of ~ 1 mm), biased with hundreds of volts in order to achieve accelerating fields in the low kV/cm range. Higher fields were not possible due to break down at the electrodes. In the meantime, LAEs were used within the framework of pump & probe experiments as a tool for the investigation of high-field transport phenomena in (quasi) bulk semiconductors, or surface depletion fields, or for the study of novel transport phenomena such as Bloch oscillations in semiconductor superlattices, or plasmon excitation. In the mid-2000s a new layout of LAEs that allowed emission into the far field with much shorter gap widths (~10 um) where experimentally demonstrated. During the past few years, the generation of THz current pulses by laser pulses in LAE photoconductors has found increasing interest as an alternate method for the generation of THz pulses. In fact, record THz fields generated by photomixers have yet been reported. Recently, this LAE approach, has successfully been used also for the generation of CW-THz radiation by photomixing.
The goal of this research stay was an evaluation of the microscopic mechanism responsible for THz emission and of the characteristic features of LAEs under CW photomixing conditions with emphasis on the radiation pattern and the achievable THz power. Photoconductive based LAEs are investigated. **We find that the fundamental as well as the technological problems associated with discrete arrays can be avoided in LAEs and that higher THz power in combination with a nearly ideal Gaussian beam profile can be obtained.**

The THz field emitted by an emitter with antenna (“antenna emitter”, AE) can be introduced in terms of the time derivative of the photo current $I_{ph}(t)$. The contribution of the electrons to the photocurrent density at the time t, $\vec{j}_{ph}(t)$ can be expressed exactly as the sum of the contributions $e\vec{v}_i(t)$ of all electrons contained in the volume, Vol. In order to take the potential time dependence of the number of carriers moving at velocity $\vec{v}_i(t)$ into account, it can also be expressed in terms of a time-dependent, averaged electron density $n(t)$ and velocity $\vec{v}(t)$,

$$\vec{j}_{ph}(t) = (e/Vol)\sum_i \vec{\mathrm{v}}_i(t) = en(t)\vec{\mathrm{v}}(t) = en\vec{\mathrm{v}}f(t)$$

The function $f(t)$ concatenates all time dependencies, v and n are the respective maximum values. Similar expressions apply for the photogenerated holes. The time derivative of the current density becomes

$$\frac{d\vec{j}_{ph}(t)}{dt} = en\vec{v}\frac{df(t)}{dt} = en\vec{a}(t).$$

In order to derive the characteristic features of the THz radiation emitted by the large number of charge carriers in a large area emitter we will first use the last expression, which expresses the derivative of the photocurrent in terms of a constant carrier density n and the “quasi-acceleration” $\vec{a}(t) = \vec{v}df(t)/dt$.

According to fundamental electrodynamics, the electric field at the time t at the point $\vec{r}$, emitted by an elementary charge e at $\vec{\sigma} = 0$ in a semiconductor and subjected to a time dependent (quasi) acceleration $\vec{a}(t)$, is

$$\vec{E}_e(t,\vec{r},\vec{\sigma} = 0) = \frac{e}{4®£_0 c_0^2}\frac{\vec{r}\times[\vec{r}\times\vec{a}(t_r)]}{r^3}$$

with a field amplitude of

$$E_e(t,\vec{r},\vec{\sigma} = 0) = \frac{e}{4®£_0 c_0^2}\frac{a(t_r)\sin ¯_a}{r^3}.$$

Here, $¯_a$ is the angle between $\vec{a}(t_r)$ and $\vec{r}$ and

$$t_r = t - r/c_{sc} = t - r\, n_{sc}/c_0$$

takes into account the retardation of the field at $\vec{r}$. The radiation intensity $U_e(t,¯)$, emitted under the angle $¯_a$ is defined as the power emitted per solid angle $d\Omega = \sin ¯\, d¯ d¨$ I-i.e.,

$$U_e(t,¯_a) = r^2 S_e(t,\vec{r},¯_a)$$

where $S_e(t,\vec{r},¯_a)$ is the Poynting vector

$$\vec{S}_e(t,\vec{r},¯_a) = c_{sc}£_0£_{sc}[E_e(t,\vec{r},¯_a)]^2\vec{r}/r$$

This yields, with $c_{sc} = c_0/n_{sc} = c_0/£_{sc}^{1/2}$ for the radiation intensity

$$U_e(t,¯_a) = \frac{\sqrt{£_{sc}}}{16®^2£_0c_0^3}\left[ea(t_r)\right]^2\sin^2 ¯_a,$$

and for the total emitted power,

$$P_e(t) = \int U_e(t,¯_a)d\Omega = \frac{\sqrt{£_{sc}}}{6®^2£_0c_0^3}\left[ea(t_r)\right]^2 = \frac{8®}{3}U_e(t,¯_a = ®/2).$$

If, instead of one, N photogenerated carriers are being accelerated, the emitted field increases by a factor N, whereas the radiation intensity and the total power increase by N^2, provided that the carriers are generated within an area or volume of dimensions sufficiently small compared with the THz wavelength to justify neglecting phase differences, i.e.,

$$U_{LAE}(t,¯_a) = \frac{\sqrt{£_{sc}}}{16®^2£_0c_0^3}\left[Nea(t_r)\right]^2\sin^2 ¯_a = N^2U_e(t,¯_a),$$

and

$$P_{LAE}(t) = \frac{\sqrt{£_{sc}}}{6®^2£_0c_0^3}\left[Nea(t_r)\right]^2 = N^2P_e(t).$$

For a calculation of the THz radiation intensity and power generated by real LAEs two important factors, which modify the radiation intensity and power of LAEs, have to be taken into account:

(1) Spatial interference yielding a "continuous array factor". As the dimensions of typical LAEs are comparable or even larger than the THz wavelength, normally, the interference between the fields emitted by charge carriers generated at different points σ $\neq 0$ has to be taken into account. If all the carriers are coherently generated and accelerated, constructive interference is expected for electromagnetic fields propagating in the direction of the exciting laser beam (or, the corresponding directions of refraction or reflection). In Fig. 1(a,b) the situation is illustrated for two important special cases. Case (a) depicts the typical case of a photoconductive LAE with a DC electric field $\vec{E} = (E_x, 0, 0)$ parallel to the surface, illuminated by a Gaussian laser beam of radius °$_{0}$ at normal incidence. In case (b) a DC electric field normal to the surface is assumed, $\vec{E} = (0, 0, E_z)$, corresponding to the typical scenario in LAEs based on a p-i-n photo diode scheme. The THz field emitted in the direction of the accelerating DC-field is zero if a finite angle of incidence ¯$_{vac,0}$ for the laser beam is assumed. In case (a) the direction of fully constructive interference is normal to the surface and coincides with the incoming beam. In case (b) fully constructive interference happens for the radiation into the substrate under the refraction angle ¯$_{sc,0}$ and into the vacuum under the reflection angle ¯$_{vac,r}$ = -¯$_{vac,0}$. It should be noted that the far-field THz *intensities* obtained in all these cases increase with the square of the absorbed laser power and with N^2, independent of the dimensions of the LAE and independent of the THz wavelength. This implies that the thermal which apply to any emitter with antenna (and arrays of those), are drastically relaxed for such large LAEs, as the incoming laser power can be distributed over a large area using the maximum thermally tolerable laser intensity. Destructive interference, however, will become increasingly significant at small angular deviations from the intensity maxima, if the dimensions of the LAE increase. Therefore, the THz *power* will no longer increase quadratically with the area (or laser power, respectively) and N^2. Hence, the increase of the THz *power* will be less than expected for LAEs with large dimensions.

(2) Modifications of the angular radiation intensity $U_e(t,$¯$_a)$ due to the proximity of the accelerated carriers to the semiconductor/air interface. The THz fields are generated within the semiconductor and will be modified at the interface to the air. Only an angle-dependent fraction will cross the interface, whereas another part will be reflected, with an angle-dependent phase shift. In particular, total reflection affects all field components emitted under an angle exceeding the critical angle for total reflection ¯'$_c$. This implies that the intensity and power emitted into air correspond only to that within the small cone at angles smaller than ¯'$_c$. Therefore,

intensity and power emitted into air are significantly smaller than expected.

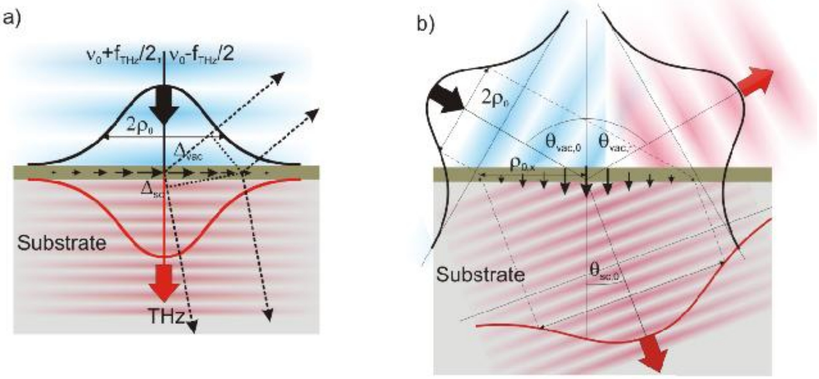

Fig. 1: a) Excitation conditions for a LAE with horizontally oriented dipoles. An excitation with a perpendicularly incident Gaussian beam results in maximum emission of a Gaussian THz wave in the same direction. Off-axis components emitted by different dipole elements experience a phase shift, Δ_{vac}, and Δ_{sc}, respectively, suppressing these components at large angles. b) Excitation scenario for an LAE with vertical dipoles. The photoconductor has to be excited under an angle since the emission of the vertical dipole along its axis is zero.

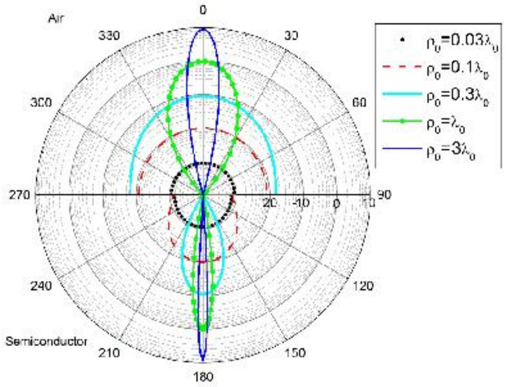

Fig. 2: Array factor for horizontal LAEs for emission into air (top) and semiconductor (bottom) for various excitation spot radii, $°_0$. For small excitation spot radii, $°_0<°_c$, the LAE emits uniformly. At large radii $°_0>°_c$, the emission becomes strongly directional. Due to the large refractive index of the semiconductor, n, the emission towards the substrate is more directional since $°_{c,sc}=:°_{c,vac}/n$.

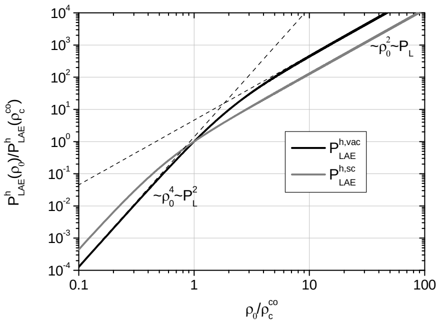

Fig. 3: Emitted power of the horizontal LAE, normalized to the power emitted at the cross-over, $°_0 = °_{c,co}$ .The power emitted into air shows a transition from quadratic laser power dependence to linear laser power dependence at higher spot radii. Therefore, the power emitted into air is higher at a larger radius.

3) Description of the main results obtained

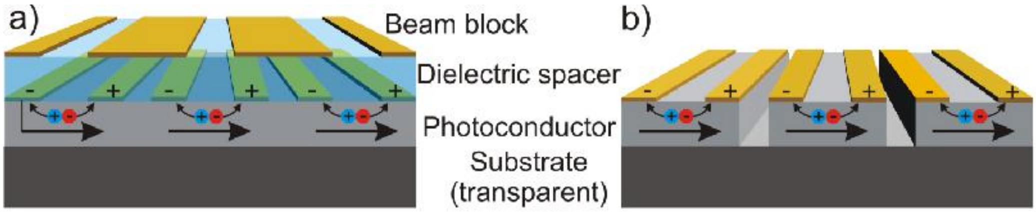

Fig. 4: Device layouts for photoconducting LAEs. a) Every second gap is shadowed by a metal mask (beam block) that is electrically isolated from the photoconductor and the electrodes by an insulating dielectric spacer. Therefore, only photocurrent dipoles of the same sign (indicated by the arrows) are generated, resulting in constructive interference in the far field. In the covered gaps, no electron-hole pairs are generated such that no current flows. b) Alternatively, the photoconductive material of every second gap can be removed. However, this is only possible if the substrate material does not absorb the laser signal. For GaAs and LTG-GaAs that is usually grown on GaAs, a complicated flip-chip method has to be used, transferring the photoconductive material on a new substrate and the original GaAs substrate has to be etched away. In contrast, InGaAs is typically grown on InP with a band gap energy of 1.344 eV whereas the exciting lasers have a photon energy in the range of 0.8 eV. The substrate is therefore transparent.

So far, only one group has reported on CW photomixing experiments with LAEs. Eshaghi et al. present results obtained from a device as shown schematically in Fig. 4(a) with a finger width and spacing of 10 µm fabricated on LTG-GaAs. With a laser power of 900 mW (ª$_L$ ≈ 800 nm) they achieved a maximum THz power of about 2 µW at f_{THz} = 1.2 THz. This value agrees very well with our estimate of 2.5 µW at 1 W laser power for (µ$_{THz}$²$_{rec}$) >1 and °$_0$ ù °$_{c,sc}$. The authors also report measurements of the far-field beam profile, confirming the expected relation between THz beam width and laser beam radius.

Photoconductive LAEs under pulsed excitation

Drastically increased average THz power and optical-to-THz conversion efficiencies are expected for LAEs operated under pulsed excitation with low duty cycle (typically < 10^{-4}).

The best conversion efficiency of $2\cdot10^{-3}$ was achieved with ²$_{pls}$ < 50 fs laser pulses with ª$_L$ = 800 nm at an excitation density of 20 µJ/cm^2 and DC fields of 70 kV/cm. The optimum fluence was determined as the upper limit for linear increase of the THz field amplitude at fixed laser spot radius. With the available pulse energy of 3 µJ a maximum total energy of the THz pulses of 6 nJ was achieved at a radius of the illumination spot of about °$_0$ = 2.5 mm.

Our estimates for the maximum THz pulse energy of ≈ 43 pJ and the maximum tolerable laser pulse energy of ≈ 25 nJ were made for °$_0$ = 100 µm, i.e., for an area about a factor of 25^2 = 625 smaller. Scaling up our values by the factor of 625 indicates that our estimate underestimates the experimental value for the maximum tolerable fluence by $\sqrt{2}$ (as the pulse energy scales quadratically with the fluence!). It should be noted that the good agreement between theory and experiment was obtained for a model which assumes monotonous acceleration up to the saturation velocity without velocity overshoot. This indicates that velocity overshoot probably does not play a significant role in SI-GaAs LAEs. Otherwise, much higher THz pulse energies and optical-to-THz conversion efficiencies should have been observed.

Device structures with interdigitated contact stripes on the unstructured sample as depicted in Fig. 4(a) have the disadvantage that typically only about 25 % of the device surface can be used. With a design according to Fig. 4(b) one can improve the active area, in particular, if the active semiconductor layer is thin and the substrate does not exhibit a photoconductive response at the laser wavelength due to a higher band gap.

Comparison with experiments

So far, there are no reports on CW photomixing in p-i-n-based LAEs. There are, however numerous reports on THz emission originating from laser pulse excitation of semiconductors with vertical fields. In many of them, the goal was the investigation of transport phenomena, such as Bloch oscillations in semiconductor superlattices, high-field transport like velocity overshoot, generation of THz plasma oscillations or optical phonon excitation due to the surface space charge field. In some investigations the goal was THz generation. The reported experiments were primarily physics oriented and there are, to our knowledge, no reports about high THz pulse energies obtained by semiconductor structures with vertical fields. In particular, we are not aware of p-i-n diode based LAEs, although, according to our estimates, very attractive results are to be expected.

4) Future collaboration with host institution (if applicable)

The following research lines are still opened:

- Manufacturing a prototype:

A prototype of CW-LAE will be manufactured take into account the hard constraints about the extremely low efficiency of the Hertzian dipoles. This is because, we will try to design other topologies non based in the Hertzian dipoles that make the device more efficient.

- Measuring the device:

After manufacturing the prototype, it will be measured both in Max Planck Institute für Radioastronomie at Bonn and in Carlos III of Madrid. In order to evaluate emitted power properties, comparison with classical antenna emitters will be carried out.

5) Projected publications / articles resulting or to result from the grant (*ESF must be acknowledged in publications resulting from the grantee's work in relation with the grant*)

[1] Alejandro Rivera-Lavado, Sascha Preu, Luis Enrique García-Muñoz, Andrey Generalov, Javier Montero-de-Paz, Gottfried Döhler, Dmitri Lioubtchenko, Mario Méndez-Aller, Florian Sedlmeir, Martin Schneidereit, Harald G. L. Schwefel, Stefan Malzer, Daniel Segovia-Vargas, and Antti V. Räisänen, "Dielectric rod waveguide antenna as THz emitter for photomixing devices", paper accepted for the IEEE transactions on antennas and propagation, 04/2015.

[2] Another journal publication is now under discussion for presenting a array topology for generating THz power and getting beam steering. Design guidelines and measurement results will be published. (2015).

[3] Alejandro Rivera-Lavado, Sascha Preu, Luis Enrique García-Muñoz, Andrey Generalov, Javier Montero-de-Paz, Gottfried Döhler, Dmitri Lioubtchenko, Mario Méndez-Aller, Stefan Malzer, Daniel Segovia-

Vargas, and Antti V. Räisänen, "Ultra-Wideband Dielectric Rod Waveguide Antenna as Photomixer-Based THz Emitter", EuCAP2014.

[4] Antti V. Räisänen, Andrey A. Generalov, Dmitri V. Lioubtchenko, Alejandro Rivera-Lavado, Mario Méndez-Aller, Luis Enrique García-Muñoz, Daniel Segovia-Vargas, and Sascha Preu, Dielectric rod waveguide antennas and their applications at mm-wave and THz frequencies, Global Symposium on Millimeter-Waves 2014 Proceedings, awarded with the first prize.

[5] Book "THz semiconductor technology". To be published by Wiley in 2015, now under proof reading. Main Editors: Enrique Garcia, Antti Raisanen, Guillermo Carpintero, Hans Hartnagel, Sascha Preu.

6) Other comments (if any)

Author would like to thank Dr. Rolf Güsten for his kind support inviting me for a doing a fantastic research at Max Planck Institute für Radioastronomie.