Appendix A

Theory of the THz antenna

When a femtosecond (fs) laser excites a biased semiconductor with photon energies greater than its bandgap, electrons and holes are produced at the illumination point in the conduction and valence bands, respectively. With the help of an antenna, Fast changes of the density of photocarriers and the acceleration by dint of the applied dc bias (V_b) produce an electromagnetic field radiation. The carrier lifetime in the semiconductor decides the production of ultrashort currents with a full-width half-maximum (FWHM) of 1ps or less strongly [14]. The carrier density behavior in time is given by

$$\frac{dn}{dt} = -\frac{n}{\tau_t} + G(t) \qquad \text{(a.1)}$$

where n is the carrier density and $G(t) = n_o \exp(\frac{t}{\Delta t})^2$ is the generation rate of carriers due to laser pulse excitation, with Δt the laser pulse width, n_0 the generated carrier density at $t = 0$, the carrier lifetime τ_t can be engineered by modifying the annealing temperature for LT-GaAs. The generated carriers are accelerated by the electric field bias with a velocity rate given by

$$\frac{dv_{e,h}}{dt} = \frac{-v_{e,h}}{\tau_{rel}} + \frac{(q_{e,h}E)}{m_{eff,e,h}} \qquad \text{(a.2)}$$

where $v_{e,h}$ is the average velocity of the carrier, $q_{e,h}$ is the charge of the electron and hole, τ_{rel} is the momentum relaxation time, and E is the local electric field, which is less than the applied bias E_{b} due to the screen effect of space charges. More precisely,

$$E = E_b - \frac{P}{3\varepsilon_r} \qquad \text{(a.3)}$$

where ε_r is the dielectric constant and P is the polarization induced by the separation of electrons and holes. The polarization depends on time according to the expression.

$$\frac{dP}{dt} = -\frac{P}{\tau_{rec}} + J \tag{a.4}$$

where $\tau_{\rm rec}$ is the recombination time between electrons and holes ($\tau_{\rm rec}$ = 10 ps for LT-GaAs) and $J = env_h + (-e)nv_e$ is the current density. The far-field radiation is given by

$$E_{THz} \propto \frac{\partial J}{\partial t} \propto ev\frac{\partial n}{\partial t} + en\frac{\partial v}{\partial t} \tag{a.5}$$

where $v = v_e - v_h$. The transient electromagnetic field $E_{\rm THz}$ consists of two terms: the first term describes the carrier density charge effect while the second term describes the effect of charge acceleration due to the electric field bias.

For the detection of THz field, the electric field of a Gaussian beam on the detector [15] can be expressed as:

$$E(x, y) = E_o \exp[\frac{-(x^2 + y^2)}{w_1^2}] \tag{a.6}$$

where w_1 is spot size. The total resistance over the detector is:

$$R = \frac{\rho_M L_M + \rho_s L_S}{td} \approx \frac{\rho_s L_s}{td} \tag{a.7}$$

where L_M is the total length of the metal electrodes, L_S is the length of the switch area between the two electrode tips, ρ_M and ρ_S are their resistivities, respectively, and d is the width of the electrode and the gap area. The average resistivity ρ_S is much larger than ρ_M owing to the low duty cycle of the driving laser (100 fs/10 ns $=10^{-5}$). The resistivity ρ_S depends on the photogenerated carrier density, which for homogeneous illumination of power $P_{\rm laser}$ scales as

$$\rho_s = \frac{L_S d}{\xi \cdot P_{laser}} \tag{a.8}$$

where ξ is a conversion factor between laser power and number of photogenerated carriers. The average field strength $\overline{E}$ across the detector gives rise to a potential difference $U = \overline{E}(L_M + L_S)$, so the average current is

$$I = \frac{U}{R} = \frac{\overline{E}(L_M + L_S)}{{L_S}^2} td\xi \cdot P_{laser} \tag{a.9}$$

The average electric field across the detector area is

$$\overline{E(L,d)} = \frac{1}{Ld}\int_{-\frac{L}{2}}^{\frac{L}{2}}\int_{-\frac{d}{2}}^{\frac{d}{2}} E(x,y)dxdy = \frac{E\pi {w_1}^2}{Ld} Erf(\frac{L}{2w_1}) Erf(\frac{d}{2w_1}) \tag{a.10}$$

where *Erf* is the error function, and $L = L_M + L_S$. The peak strength of the electric field, E_0, can be expressed in terms of the total power in the THz beam:

$$P_{THz} = \frac{1}{2}c\varepsilon_o \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E^2(x,y)dxdy = \frac{1}{2}\pi {w_1}^2 c\varepsilon_o {E_o}^2 \tag{a.11}$$

$$\Rightarrow Eo = \frac{2}{w_1}\sqrt{\frac{P_{THz}}{\pi c\varepsilon_o}} \tag{a.12}$$

By inserting Eq. (a.12) into the expression for the detector current, Eq. (2.9), we get

$$I(v) = \xi \cdot P_{laser}\sqrt{\frac{cP_{THz}}{\pi\varepsilon_o}} \frac{2R_L t}{{L_S}^2 dw_o(n-1)} \frac{1}{v} Erf[\frac{L}{2}\frac{(n-1)\pi w_o}{cR_L}v] Erf[\frac{d}{2}\frac{(n-1)\pi w_o}{cR_L}v] \tag{a.13}$$

when focusing spot size $\lim\limits_{\lambda \to o} w_1(d_{focus}) = \frac{c}{\pi v w_o}\frac{R_L}{(n-1)}$.