Generation of THz radiation in semiconductors by photomixing – antenna emitter (AE) vs. large area emitter (LAE)

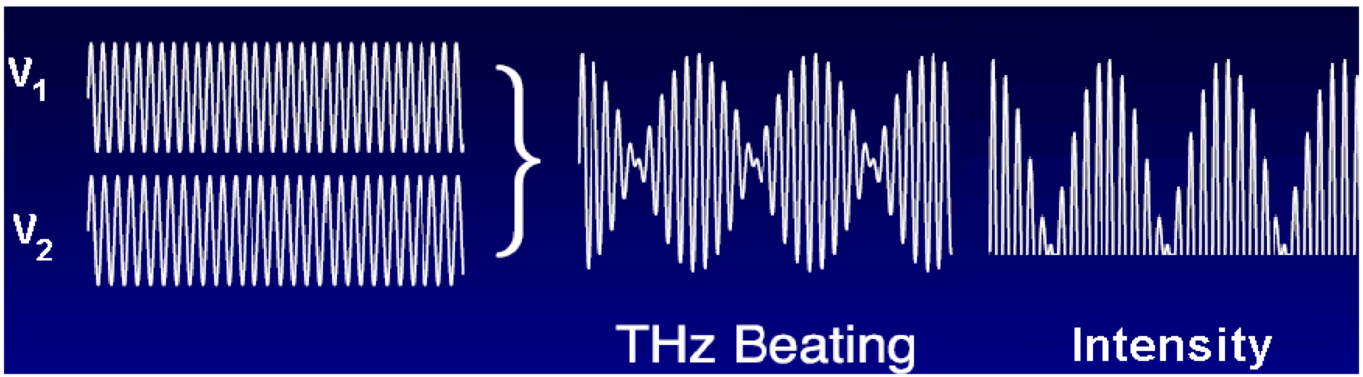
G.H. Döhler, Friedrich-Alexander-University (FAU) and Max Planck Institute for the Science of light (MPL), Erlangen, Germany,
+ many coworkers from FAU, MPL, uc3m, UCSB (USA), TIFR (India)

principle of CW-THz generation by photomixing (1)

2 collimated laser beams:

- same amplitude: $E_1 = E_2 = E_0$
- same polarization: $\mathbf{E_1}$ □ $\mathbf{E_2}$
- small difference in photon frequency: $\nu_2 - \nu_1 = \nu_{THz}$

joint laser field   joint laser intensity



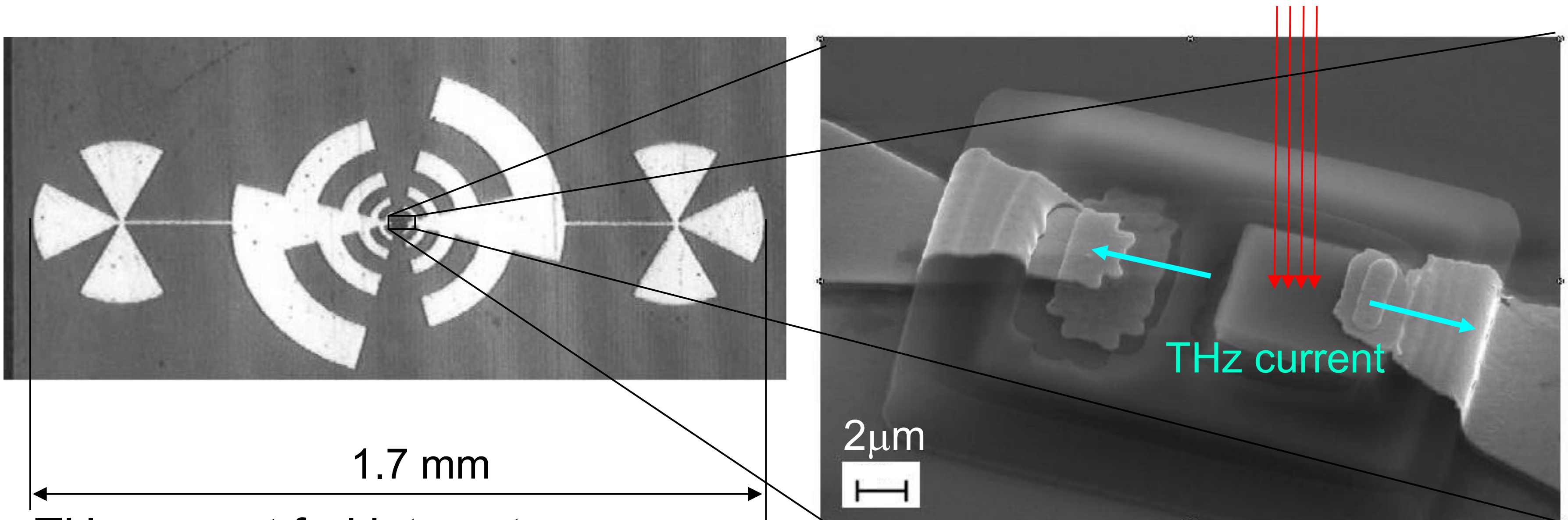
THz-periodic joint laser intensity

If $h\nu_1 \approx h\nu_2 \approx$ band gap energy of semiconductor

THz-periodic electron/hole generation:

dN/dt = dP/dt □ joint laser intensity

conventional principle of CW-THz generation by photomixing



THz current fed into antenna
yields CW – THz radiation
⇒ „antenna emitter“ (AE)

mixer device

Features of THz state of the art photomixers

Advantages of photomixers

- wide tuning range easily achieved with photomixer
- coherence excellent, depends only on the laser quality
- photomixer working at room temperature
- low costs (telecom lasers, e.g.)
- ideally suited for homodyne or heterodyne detection

Problems and limitations of photomixers

low laser-to-THz conversion efficiency

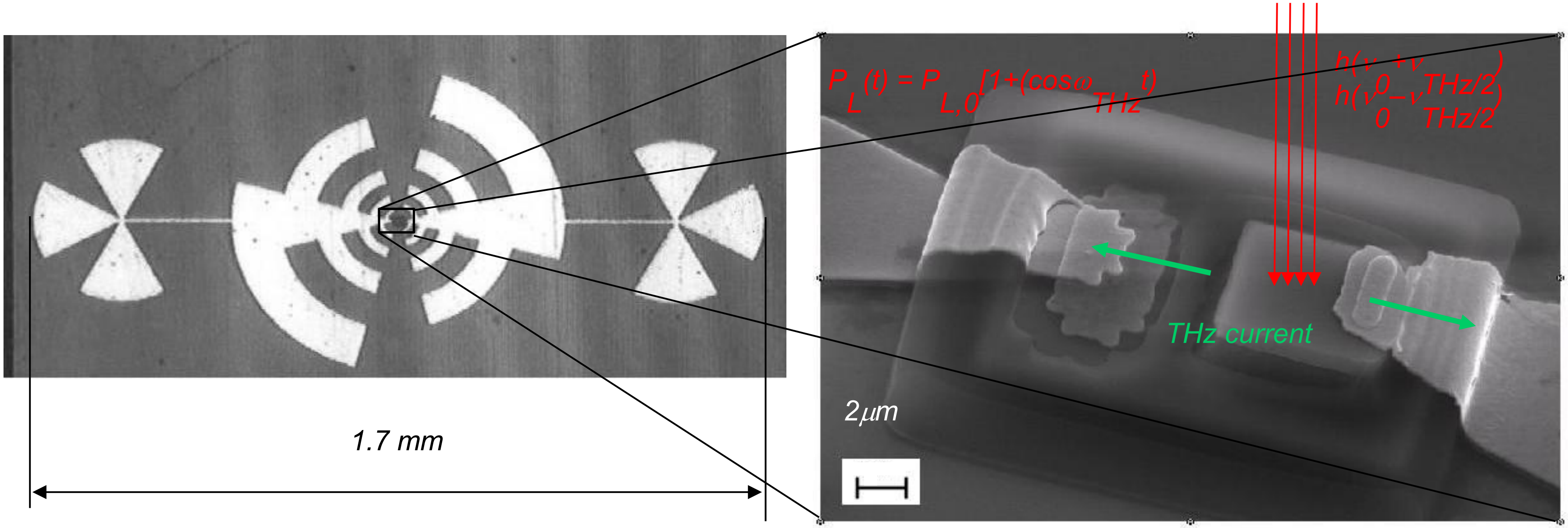
in particular: high-frequency roll-off

photo-current has to be generated in small area/volume

$\Rightarrow$ Upper limit for laser power to avoid thermal failure

$\Rightarrow$ achievable THz power insufficient for many potential applications

ideal photomixer



mixer device with antenna (AE)

mixer device

Assumptions for ideal photo mixer:

each incident photon $h\nu_0$ creates an electron-hole (e/h) pair

each e/h pair contributes (fully) 1e to the THz photocurrent, i.e. $I_{THz} = e(P_L/h\nu_0)$

THz power $P_{THz}^{id} = \frac{1}{2} I_{THz}^2 R_a \quad = \frac{1}{2} [e(P_L/h\nu_0)]^2 R_a \propto P_L^2$!

(R_a = antenna radiative resistance ≈ 70 Ω, e.g.)

comparison ideal vs. real photomixer

ideal photo mixer: THz power $P_{THz}^{id} = \frac{1}{2}\,[e(P_L/h\nu_0)]^2\, R_a \propto I_{THz}^2, P_L^2$!

(R_a = antenna radiative resistance)

example: InGaAs: $h\nu_0 \approx 0.8$ eV (λ_0= 1550 nm),
$R_a \approx 70\ \Omega$, P_L = 20 mW = 100 mW
THz power $P_{THz}^{id} \approx 5$ mW ≈ 125 mW (> P_L !)

real photo mixer

I_{THz} limited by:

- finite „gain" g (<1, if lifetime $\tau_{rec} <$ transit time τ_{tr})
- finite transport time τ_t (transit or life time)
  $\Rightarrow$ transport time roll-off factor: $\eta_t = 1/[1 + (\nu_{THz}/\nu_t)^2]$
- finite capacitance C of the mixer
  $\Rightarrow$ RC roll-off factor: $\eta_{RC} = 1/[1 + (\nu_{THz}/\nu_{RC})^2]$

$\Rightarrow P_{THz}^{real} = P_{THz}^{id}\, g^2\, \eta_t\, \eta_{RC}$

(quasi)-ideal performance only for $g \approx 1$ and $\nu_{THz} < (\nu_t, \nu_{RC})$

for $\nu_{THz} > (\nu_t = \nu_{RC} = \nu_{cr})$, e.g., $P_{THzreal} = P_{THzid}\, g^2\, (\nu_{cr}/\nu_{THz})^4$

examples for real photomixers: (next transparency)

„classical“ photomixer and their limitations

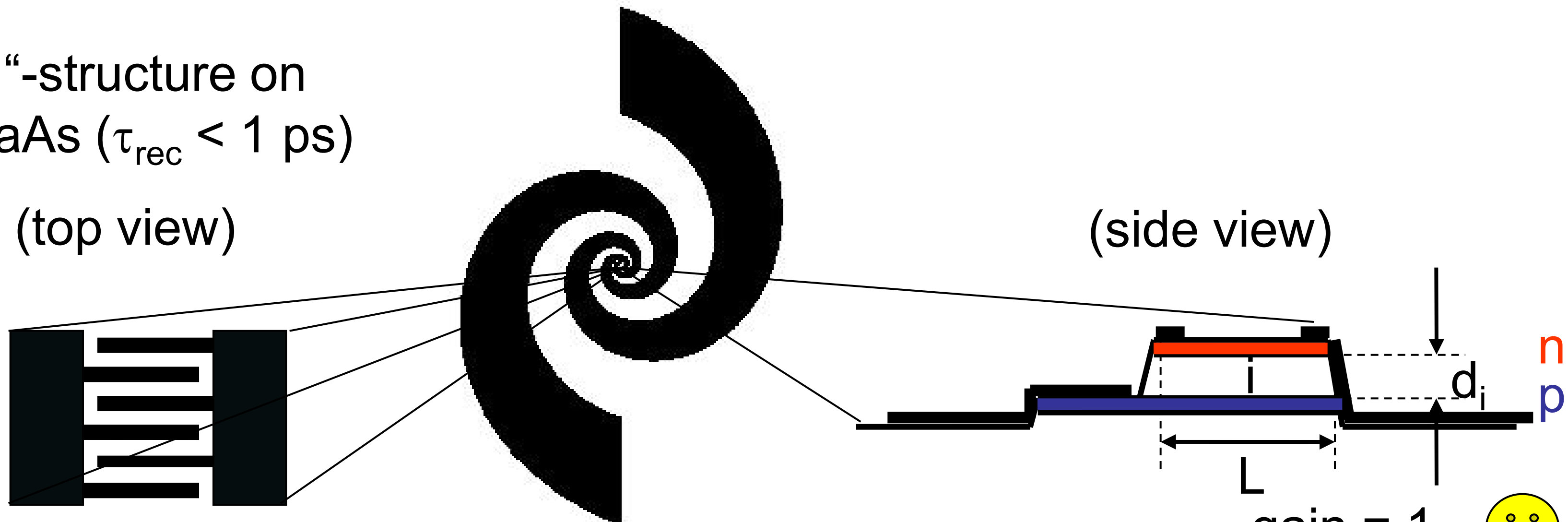
photoconductive mixer

„MSM“-structure on
„LT-GaAs (τ_{rec} < 1 ps)

(top view)

pin-diode mixer

(side view)



gain = 1 ☺

$\tau_{rec} \approx 1$ ps ☺

$\tau_{RC} \approx 1$ ps) ☺

$\tau_{tr} >> \tau_{rec}$; „gain“ = $\tau_{rec}/\tau_{tr} << 1$ ☹

$P_{THz}^{ph.cond} \approx gain^2 \, P_{THz}^{id}$ ☹

⇑

intrinsic problem of pc mixers

can be overcome ⇐

pin mixer ⇒ n-i-pn-i-p mixer

transit time: $\tau_{tr} \approx d_i/v_{av} \propto d_i$

$\nu_{tr} \approx v_{av}/(2\tau_{tr}) \propto d_i^{-1}$

RC time: $\tau_{RC} = R_a C \propto d_i^{-1}$

$\nu_{RC} = 1/(2\pi R_a C) \propto d_i$

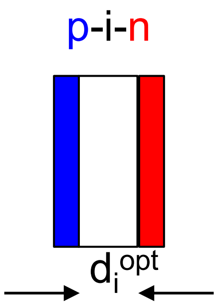
⇒ trade-off: transit- vs. RC- roll-off ☹

example: $L^2 = 50\ \mu m^2$; $\nu_{opt} \approx 140$ GHz ☹

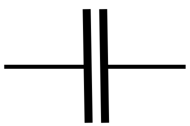
our concept of ballistic n-i-pn-i-p photomixer *

replace simple p-i-n diode by a stack of N (identical) p-i-n diodes

simple pin – diode



$C_{pin} \propto 1/d_i$



transit time roll-off frequency

$\nu_{tr} \approx 1/(2\tau_{tr}) = v_{av}/(2d_i) \propto 1/d_i$

☺ high, if d_i small enough

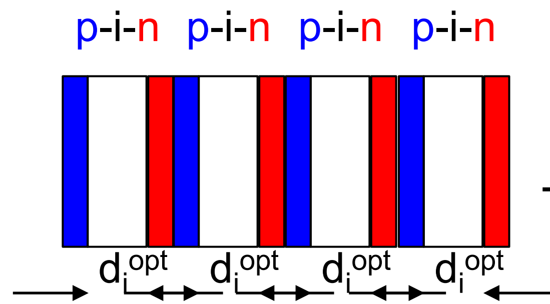
RC time roll-off frequency:

$\nu_{RC} = 1/(2\pi R_a C_{pin}) \propto d_i$

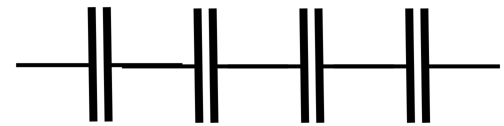
☹ $\nu_{RC} << \nu_{tr}$ if d_i optimized for transittime roll-off

⇒ trade-off: transittime - vs. RC- roll-off

stack of identical pin – diodes



$C_{stack} = C_{pin}/N$



transit time roll-off frequency

$\nu_{tr} \approx 1/(2\tau_{tr}) = v_{av}/(2d_i) \propto 1/d_i$

☺ if d_i small enough

RC time roll-off frequency:

$\nu_{RC} = N/(2\pi R_a C_{pin})$

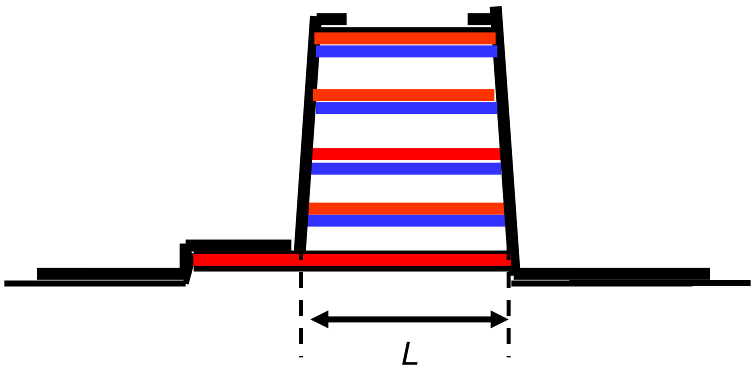
☺ $\nu_{RC} \approx \nu_{tr}$ if, in addition, N optimized for RC roll-off

⇒ transittime and RC- roll-off optimized

* Döhler et al., SST **20**, p.178-190 (2005); S. Preu et al., APL **90**, p. 212115 (2007)

limits for improving CW-AEs

optimized n-i-pn-i-p – antenna emitter (AE)



$P_{THz} = ½ \, R_a \, (I_{ph,0})^2 \, \eta_{roll\text{-}off}(\nu_{THz}) \propto P_L^{\,2}$

cross section ($\propto L^2$) needs to be small
to minimize roll-off factor $\eta_{roll\text{-}off}(\nu_{THz})$

device temperature increase $\propto P_L/L^2$ $\Rightarrow$ thermal failure of mixer device

electric field screening increase $\propto P_L/L^2$ $\Rightarrow$ degradation of device performance

$\Rightarrow$ upper limit for tolerable P_L and, hence, obtainable P_{THz}

similar limitations apply to photoconductive antenna emitters

alternatives?:

- use a coherently pumped array of N identical optimized AEs

$P_{THz}^{Arr} = N \, P_{THz}^{AE}$
$E_{THz}^{max,Arr} = N \times E_{THz}^{max,AE}$
$U_{THz}^{max,Arr} = N^2 \times U_{THz}^{max,AE}$

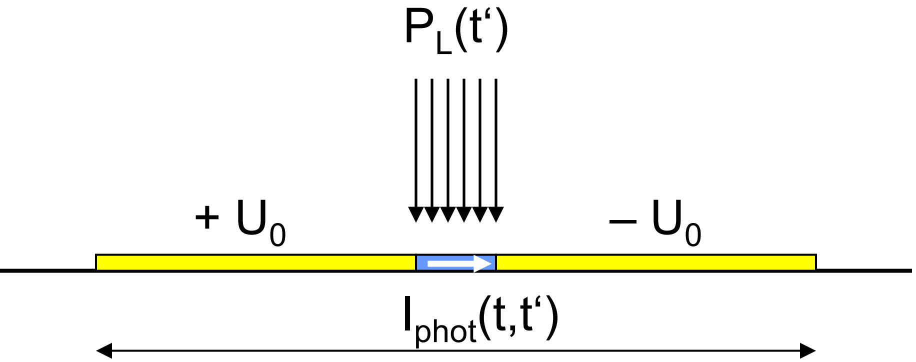
complicated
complex
costly

- THz emission from a large active area without antenna: „large area emitter“ (LAE)

antenna emitter (AE) $\Rightarrow$ large area THz emitter (LAE)

antenna emitter (AE)

laser-induced photocurrent, $I_{phot}(t,t')$, generated in small semiconductor device is fed into antenna



$l \approx \lambda_{THz}/2$, e.g.

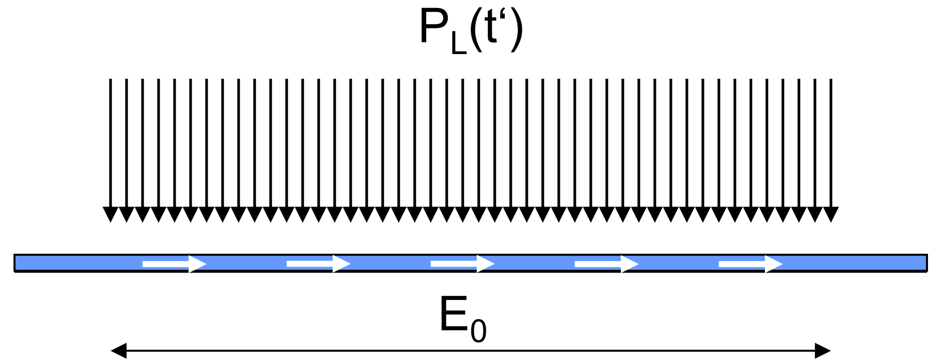
THz radiation emitted by AE:

$P_{THz}^{AE} = \frac{1}{2} R_a I_{THz}^2$

$\propto I_{THz}^2$! $\propto P_L^2$!

large area emitter (LAE)

THz radiation is emitted *directly* by the *laser induced-carriers, accelerated* by an electric field E_0 in the sc



$2\rho_0 \approx \lambda_{THz}/2$, e.g.

radiation emitted into semiconductor:

by a single accelerated electron:

$P_{THz}^{e} = e^2 a^2 n_{sc}/(6\pi\varepsilon_0 c^3)$, with $a = eE_0/m_c$

by N coherently accelerated electrons

$P_{THz}^{Ne} = N^2 P_{THz}^{e}$ $\propto P_L^2$!

upper limits:

tolerable laser intensity < 1 mW/μm^2

maximum absorbing area: 100 μm^2

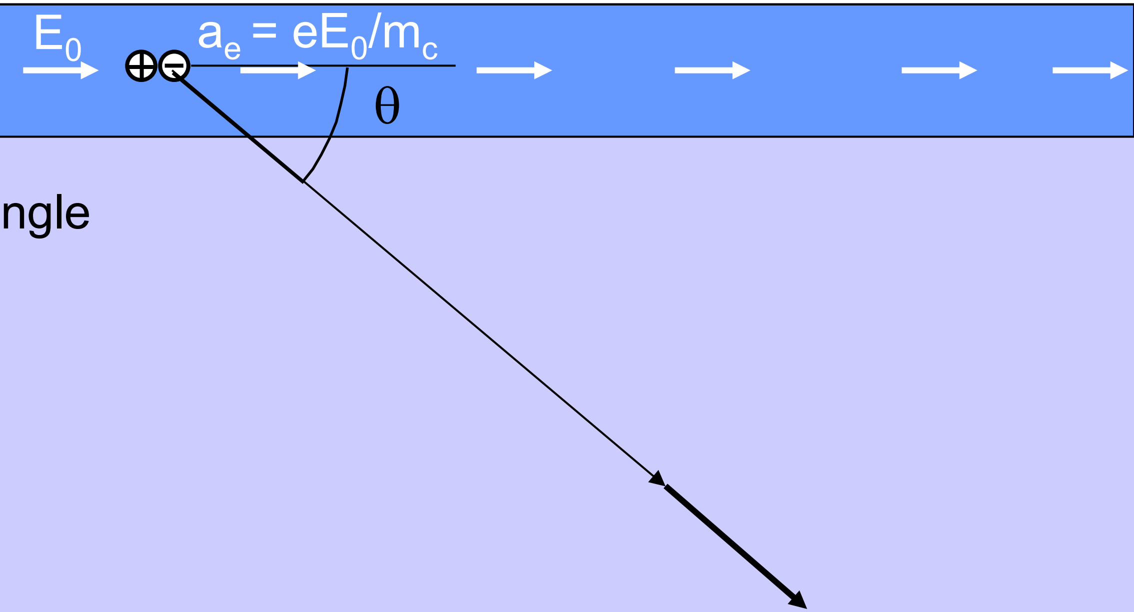
$P_{THz}^{AE,max} \approx 10\ \mu$W @ 1THz

tolerable laser intensity < 1 mW/μm^2

no upper limit for absorbing area

$P_{THz}^{LAE,max}$ no upper limit

simplified picture of large area emitter (LAE) – in-plane field E_0



Intensity of radiation emitted by a single accelerated electron under angle θ:

Poynting vector $\mathbf{S}_{THz}$

$$\mathbf{S}_{\mathbf{e},THz} = \mathbf{r}(ea)^2\varepsilon_{sc}^{1/2}/(16\pi^2\varepsilon_0 c^3 r^3)\,\sin^2\theta$$

THz *power* emitted by this electron

$$P_{THz} = \iint_{sphere} \mathbf{S}_{e,THz}\,\mathbf{df}$$

$$P_{e,THz} = [\varepsilon_{sc}^{1/2}/(6\pi\varepsilon_0 c^3)]\,(ea_e)^2$$

$|S_{e,THz}| \propto \sin^2\theta/r^2$

i.e. :
maximum THz power emitted perpendicular to surface ☺

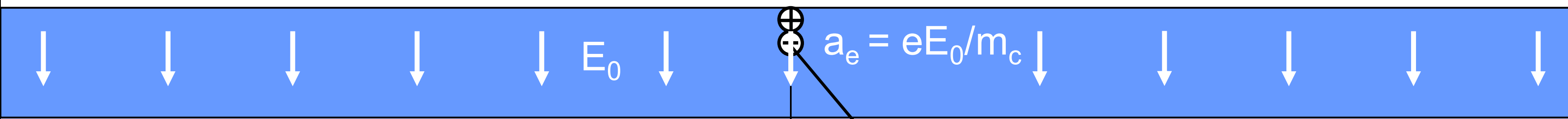
THz *power* emitted by N coherently accelerated electrons

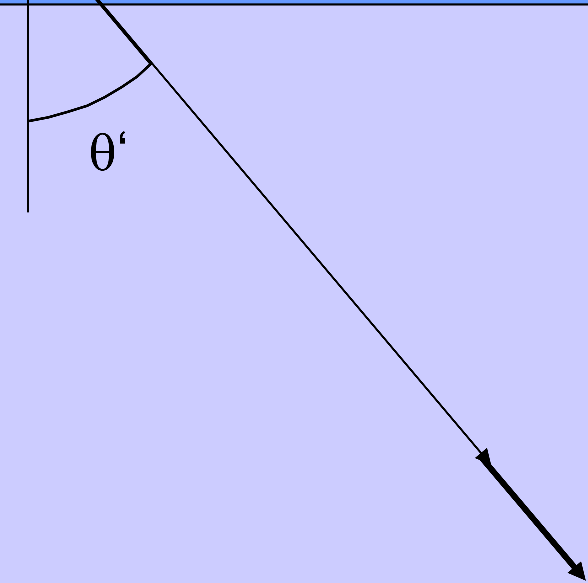
$$P_{Ne,THz} = N^2 P_{e,THz}$$

if interference effects can be neglected, i.e., if dimensions of emitting area $\rho_0 << \lambda_{THz}$

⇔ definition of „large-area quasi-dipole“ (LAQD)

simplified picture of large area emitter (LAE) – vertical field E_0





Intensity of radiation emitted by a single accelerated electron under angle θ':

Poynting vector $\mathbf{S}_{THz}$

$$\mathbf{S}_{\mathbf{e},THz} = \mathbf{r}(ea)^2\varepsilon_{sc}^{1/2}/(16\pi^2\varepsilon_0 c^3 r^3)\ \sin^2\theta'$$

THz *power* emitted by this electron

$$P_{THz} = \iint_{sphere} \mathbf{S}_{e,THz}\mathbf{df}$$

$$P_{e,THz} = [\varepsilon_{sc}^{1/2}/(6\pi\varepsilon_0 c^3)]\ (ea_e)^2$$

THz *power* emitted by N coherently accelerated electrons

$$P_{Ne,THz} = N^2 P_{e,THz}$$

$|S_{e,THz}| \propto \sin^2\theta'/r^2$

i.e. :

no THz power emitted perpendicular to surface

to be discussed later!

LAQD, for photomixing, simplified(!)

THz power emitted by N coherently accelerated electrons generated at time t in a „large-area quasi-dipole“ (LAQD)

$P_{THz}^{LAQD}(t) = (1/6\pi)\,[(eNa)_t]^2 \varepsilon_{sc}^{1/2}/(\pi\varepsilon_0 c^3)$

$(eNa)_t$ = charge being ballistically* accelerated at the time t $a = eE_0/m_c$

laser power $P_L(t) = P_{L,0}\,[1 + \cos\omega_{THz} t]$; $dN/dt = P_L(t)/h\nu_0$; $I_{ph,0}^{id} = (e/h\nu_0)\,P_{L,0}$

(… some calculation)…

$P_{THz}^{LAQD} = ½\, R_{LAQD}\,(I_{ph,0}^{id})^2$, with $I_{ph,0}^{id} = (e/h\nu_0)\,P_{L,0}$

with $R_{LAQD} = (2/3\pi)\,\varepsilon_{sc}^{1/2} Z_0 (v_{bal}/c)^2 \approx 6\times10^{-3}\,\Omega$; $v_{bal} = 2\times10^8$ cm/s in InGaAs, e.g.)

$Z_0 = (\varepsilon_0 c)^{-1} = 377\,\Omega$ = „radiation impedance of vacuum“

$$P_{THz}^{LAQD} = 6\times10^{-3}\Omega\,(I_{ph,0}^{id})^2$$

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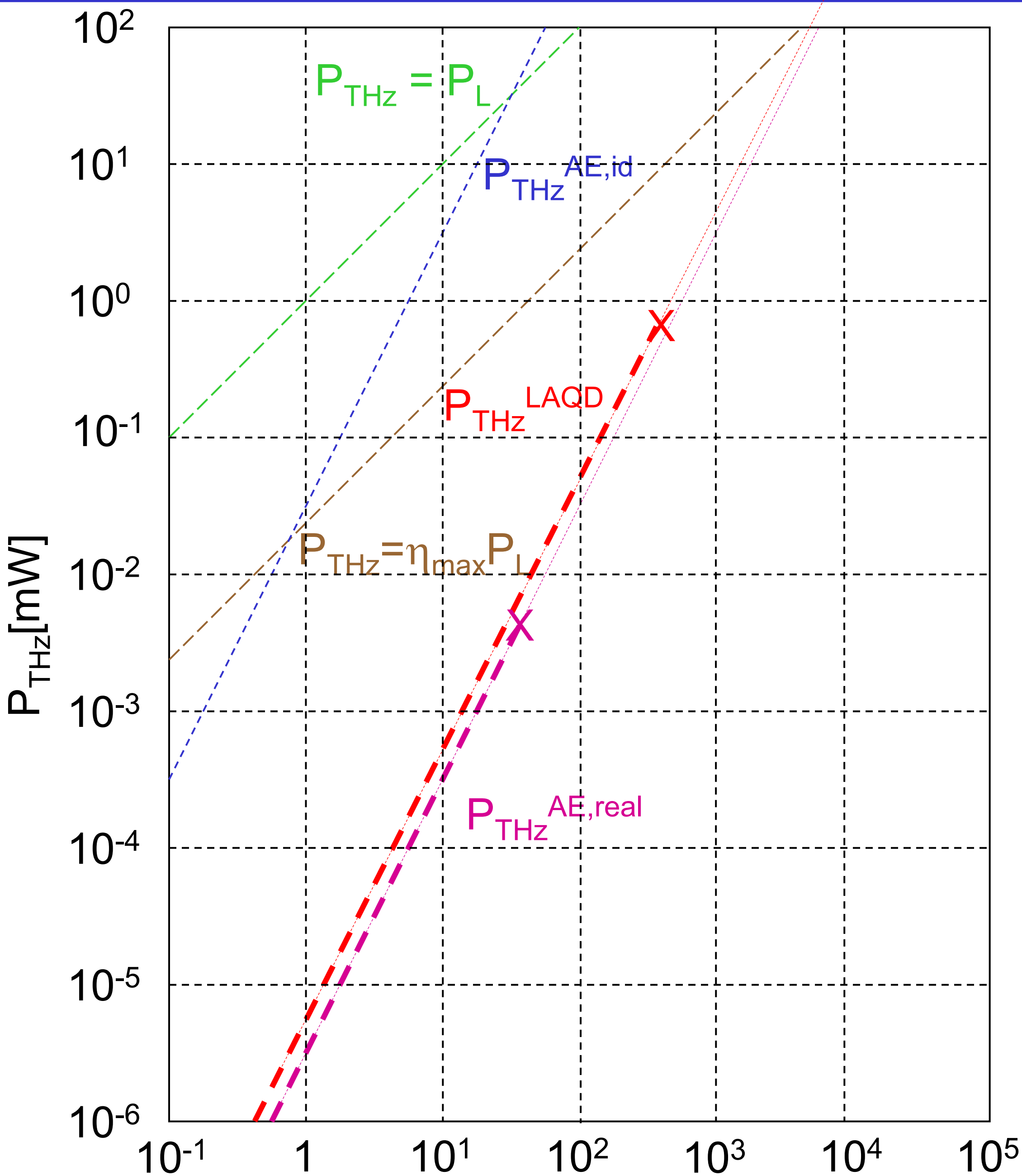
*) ballistic acceleration appears not to be compatible with CW mixing conditions for horizontal electric fields. It works, however, for vertical electric fields

THz power vs. laser power for AE and LAEs



ideal photomixer antenna emitter

$P_{THz}^{ideal} = ½\, R_a\, (I_{THz}^{id})^2$
$= 35\ \Omega\, (I_{THz}^{id})^2$

$I_{THz}^{id} = (eP_L/h\nu_0)$; $R_a = 70\Omega$

conversion efficiency $\eta = 1$

$P_{THz} = P_L$

Manley-Rove (non-linear mixing)

$\eta_{max} = \nu_{THz}/\nu_0$

$P_{THz} = \eta_{max}\, P_L$

photocond. antenna emitter (AE)

$P_{THz}^{AE} = ½\, R_a\, g^2\, (I_{THz}^{id})^2$
$= 3.5\text{x}10^{-3}\Omega\, (I_{THz}^{id})^2$;

($R_a = 70\Omega$, $g = \tau_{rec}/\tau_{tr} = 10^{-2}$)

(illuminated area $100\mu m^2$, e.g.)

Large area quasi-dipole (LAQD)

$P_{THz}^{LAQD} = ½\, R_{LAQD}\, (I_{THz}^{id})^2$;

$R_{LAQD} = 6\text{x}10^{-3}\Omega$,

(illuminated spot $\pi\rho_0^2 \approx 1000\mu m^2$,

corresponding to $\rho_0 = \rho_{LAQD}$)

role of interference, if dimensions of LAE area become comparable with λ_{THz} or larger

We will see:

For sufficiently „small“ LAEs the achievable THz power increases $\propto P_L^2$ and the angular distribution of the radiation intensity does not change

For increasingly „large“ LAEs we will find:

i) interference drastically affects the angular distribution of the THz radiation pattern

ii) the THz intensity becomes highly directional around the angle of vanishing interference

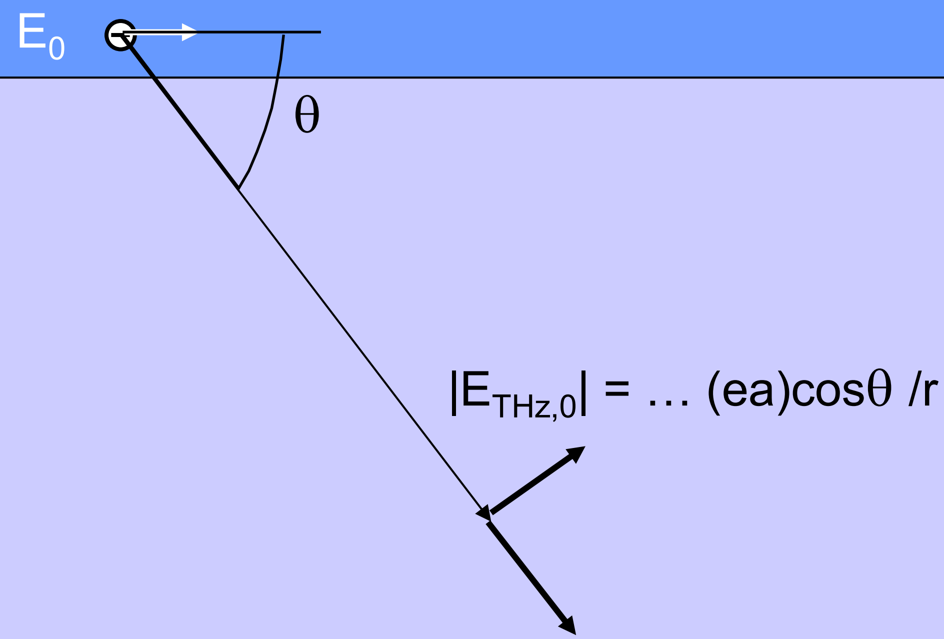
iii) around this angle, the THz intensity continues increasing $\propto P_L^2$

iv) the total THz power increases $\propto P_L$

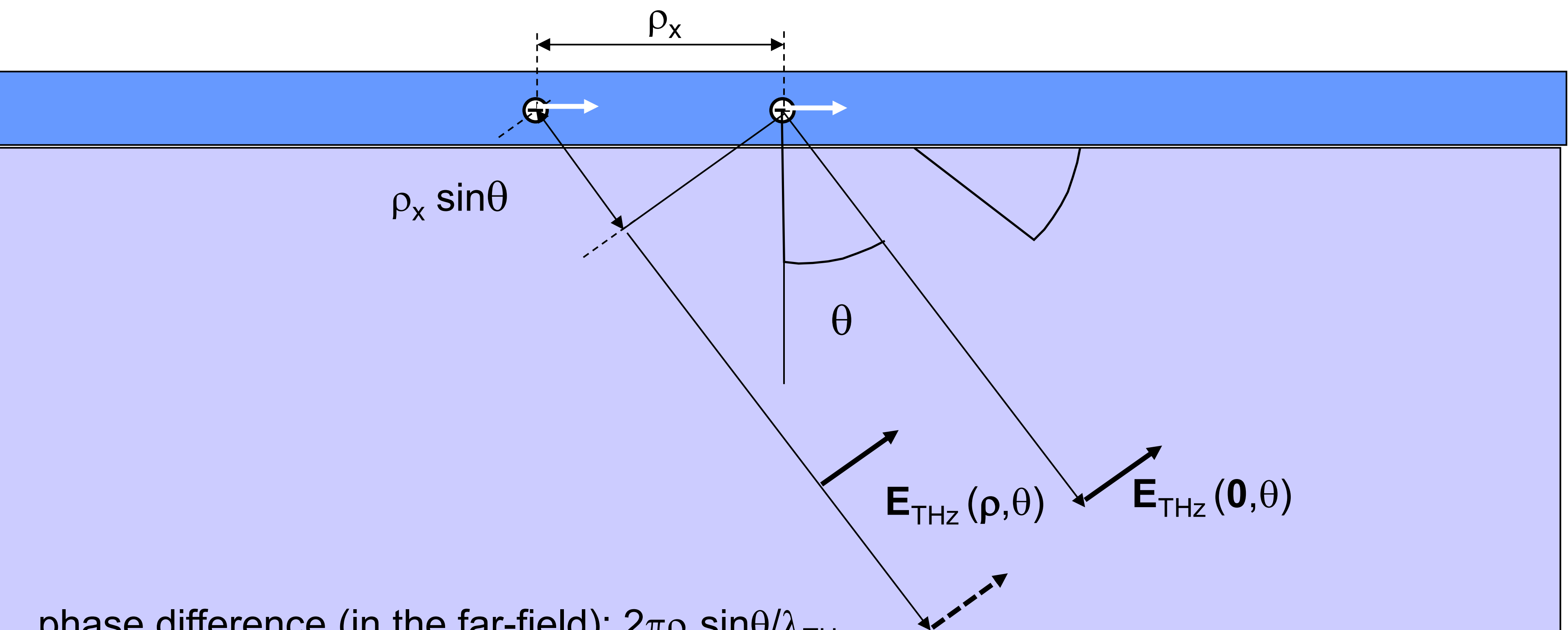
Results can be described in terms of a product:

(radial distribution of the individual elementary emitter) x („continuous array factor“)

E_{THz} emitted by 1 periodically accelerated electron



E_{THz} emitted by 2 coherently accelerated electrons



phase difference (in the far-field): $2\pi\rho_x \sin\theta/\lambda_{THz}$

interference negligible for $\rho_x \sin\theta/\lambda_{THz} << 2\pi$

destructive interference for $\rho_x \sin\theta = \lambda_{THz}/2$ ☹ ☺

for $\theta = 0^0$, constructive interference for arbitrary large ρ_x ☺

for $\theta = 0^0$ *intensity* increases quadratically ☺

E_{THz} emitted by an ensemble of coherently accelerated electrons

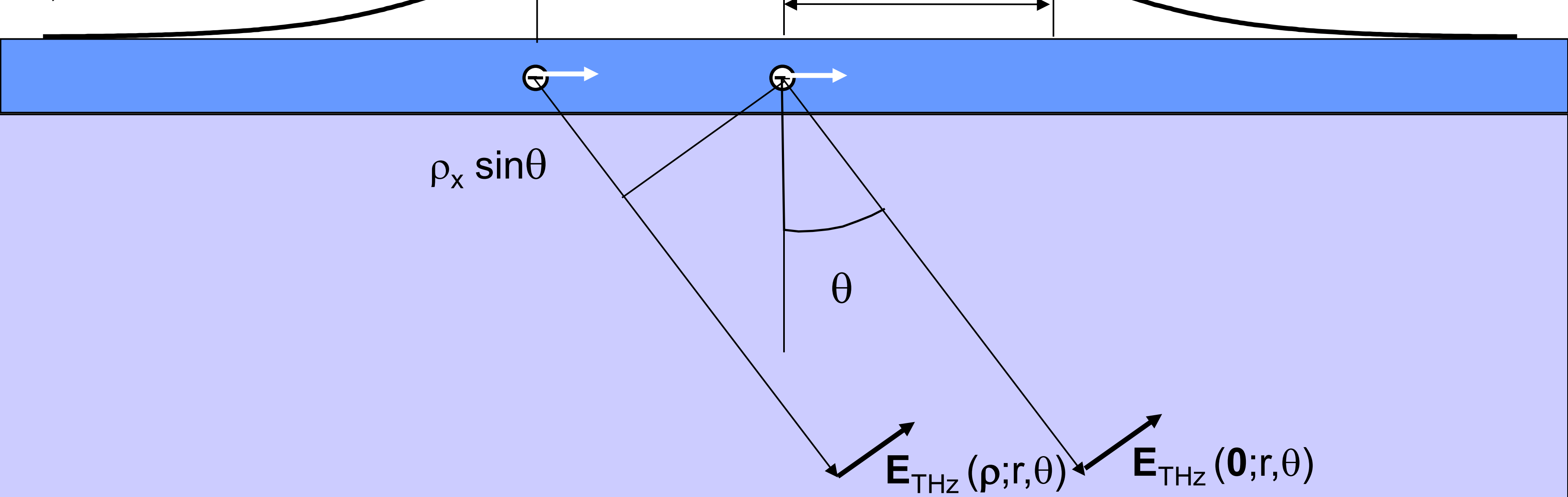
Gaussian laser beam

$\phi_L(\rho) = \phi_{L,0} \exp\{-(|\rho|/\rho_0)^2\}$

$\phi_{L,0} = P_L/(\pi\rho_0^2)$

carrier generation rate:

$dn(\rho)/dt = dp/dt \propto \phi_L(\rho)$



with ρ_0 increasing, constructive interference only for decreasingly small angles θ

with ρ_0 decreasing, destructive interference becomes negligible even for large angles θ

$\mathbf{E}_{THz}(\rho_0,r,\theta) = \int \mathbf{E}_{THz}(\boldsymbol{\rho};\rho_0,r,\theta)d\rho_x d\rho_y$, $\mathbf{S}_{THz}(\rho_0,r,\theta)$ and $P_{THz}(\rho_0)$ can be calculated

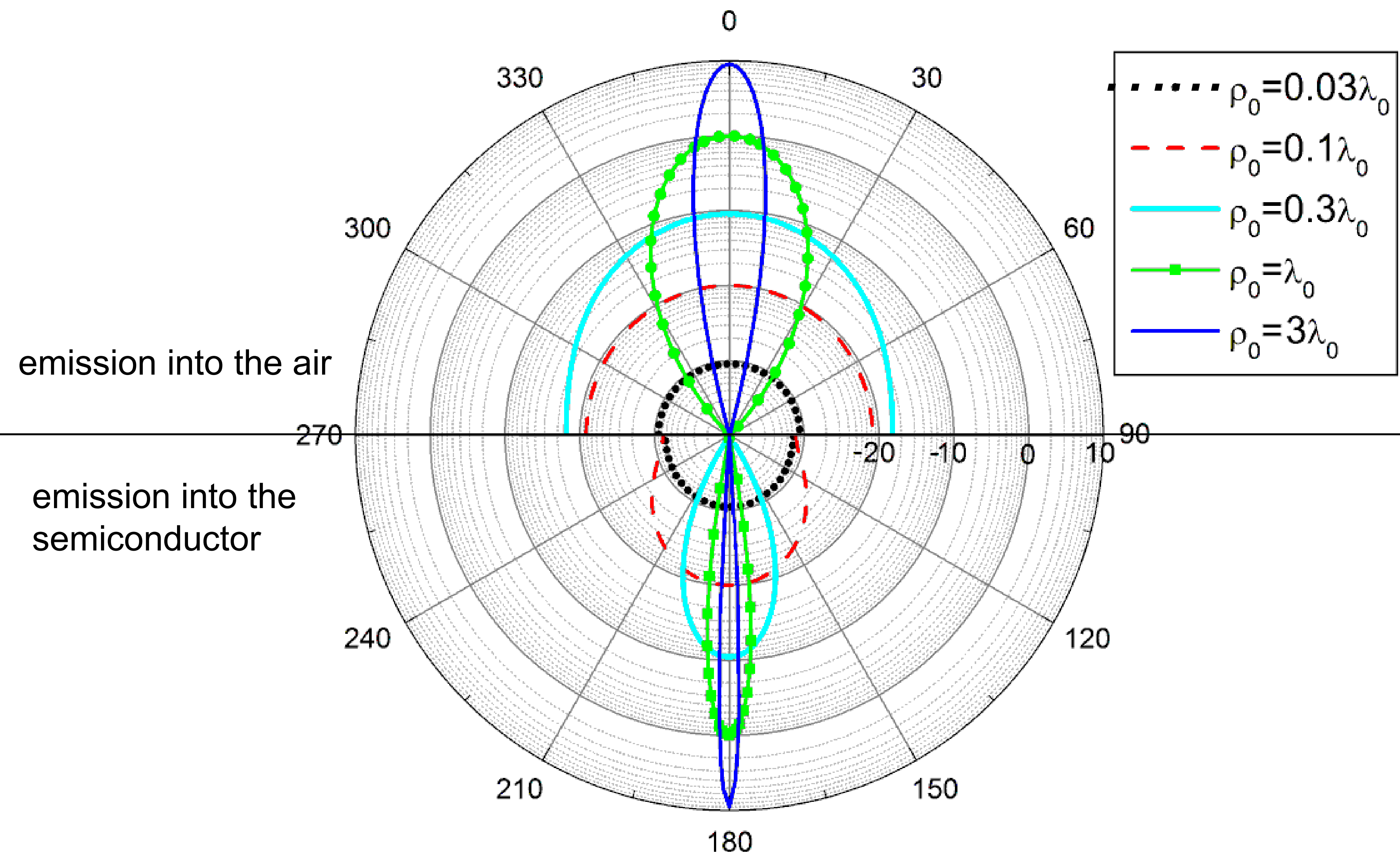
Wide laser beam results in narrow THz beam and vice versa!

In particular, we find the value $\rho_0 = \rho_{LAQD} \approx 0.25\,\lambda$, around which $P_{THz}(\rho_0)$ changes its behaviour from $P_{THz}(\rho_0) \propto \rho_0^4$ to $P_{THz}(\rho_0) \propto \rho_0^2$ (or: from $P_{THz}(\rho_0) \propto P_L^2$ to $P_{THz}(\rho_0) \propto P_L$)

“continuous-array-factor” AF(θ) for horizontal LAEs

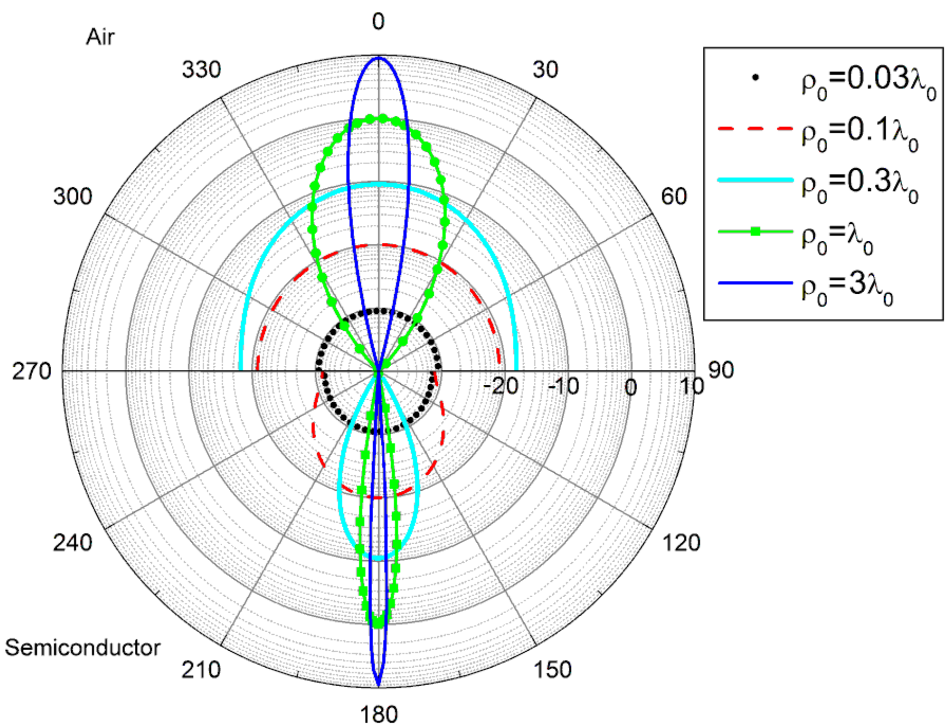
LAEs can be considered as „continuous arrays“ with a homogeneous array density. As a consequence, the emission pattern becomes smooth.

“continuous-array-factor” AF(θ) for horizontal LAEs excited by a Gaussian beam for different values of ρ_0

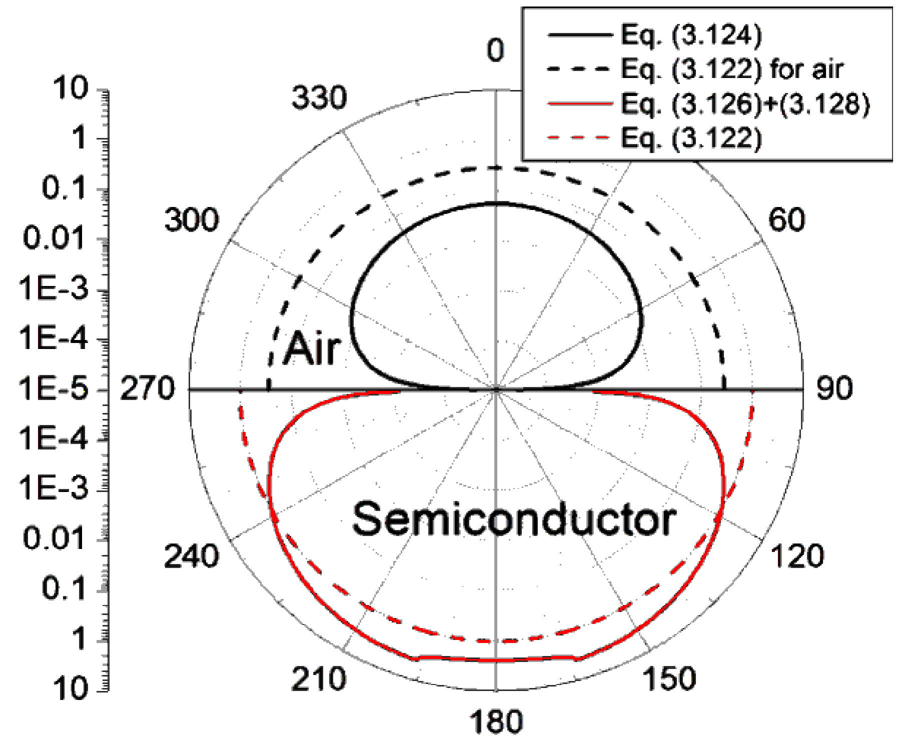


radiation intensity : product of array factor and radiation characteristics of horizontal dipole

„continuous array “ factor



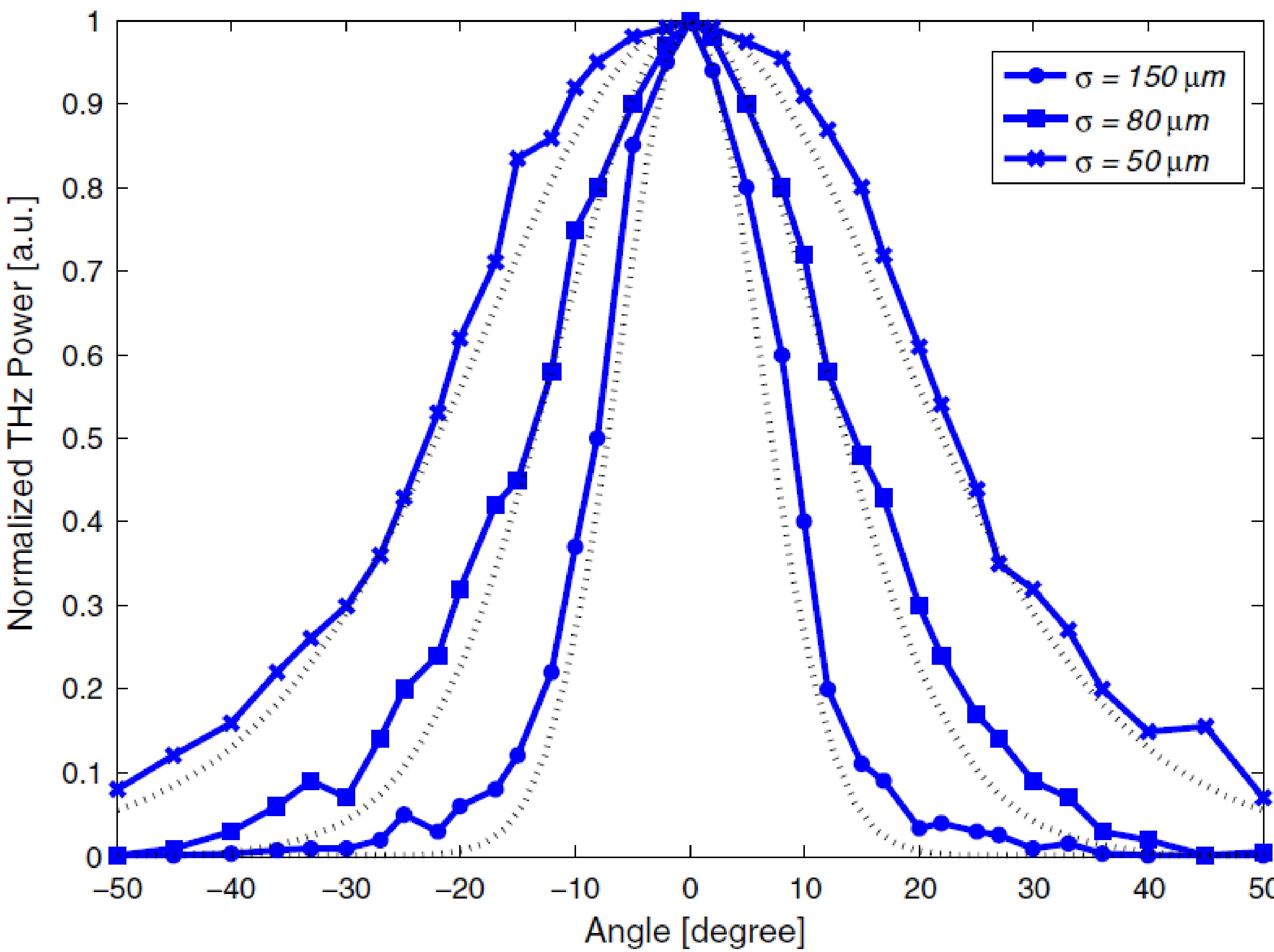
radiation characteristics of horizontal dipole



dashed lines: embedded into semiconductor or air

full lines: embedded into semiconductor

First experimental results for CW photoconductive LAE

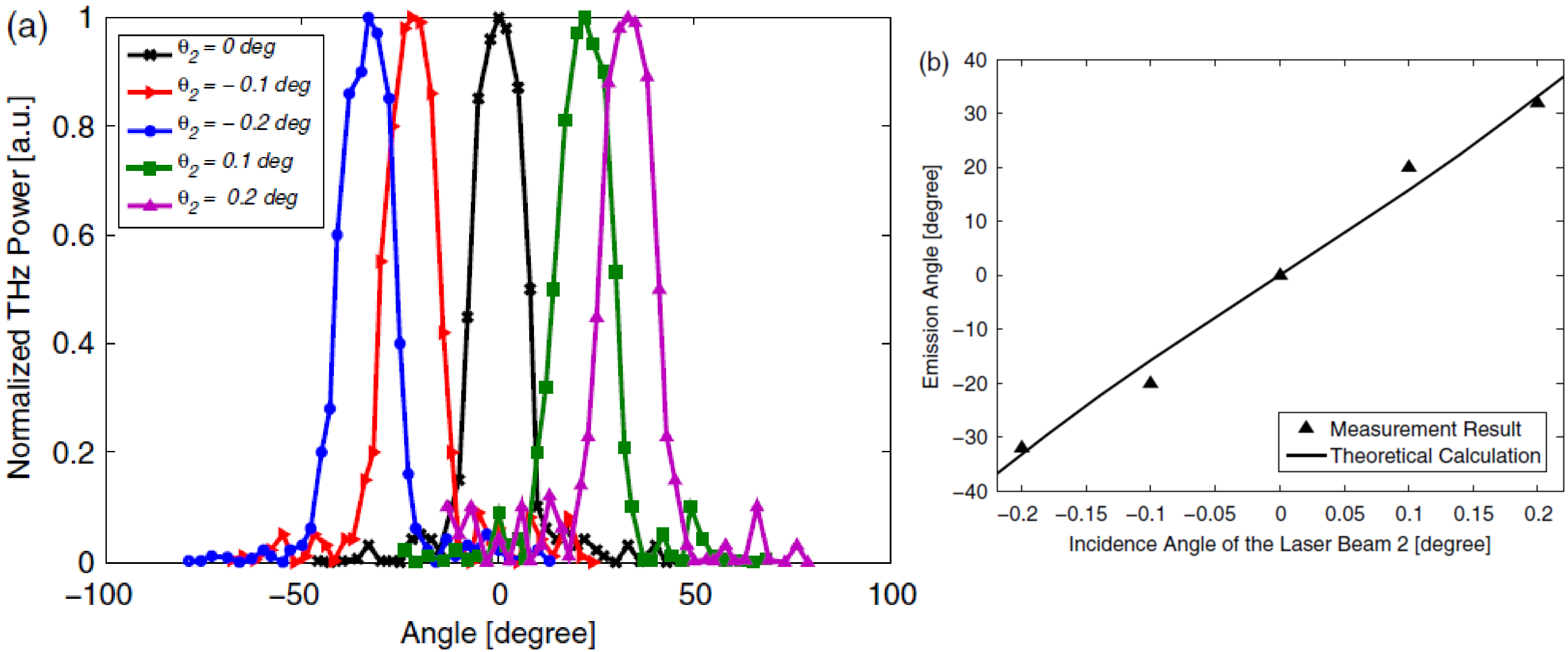


Beam profile narrows with increasing width of Gaussian laser beams

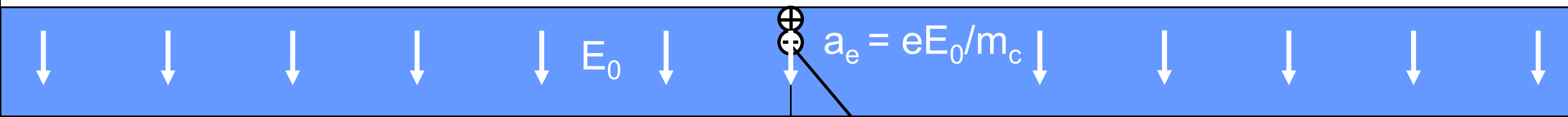
A. Eshaghi, M. Shahabadi and L. Chrostowski, "Radiation characteristics of large-area photomixer used for generation of continuous-wave terahertz radiation", J. Opt. Soc. Am. B 29, 813 (2012)

First results for CW photoconductive LAE

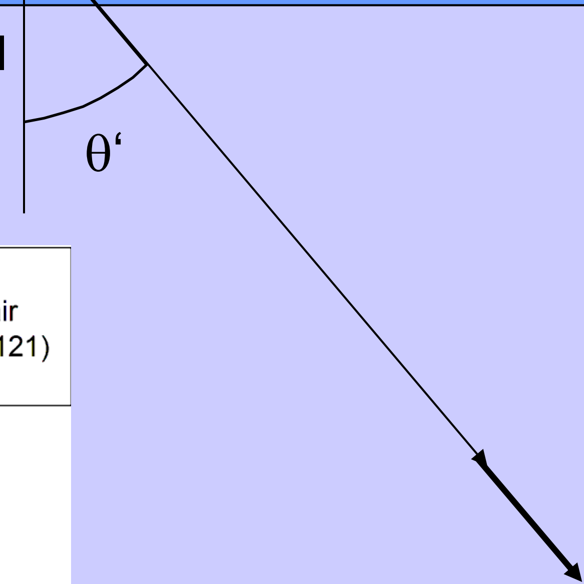
Beam steering

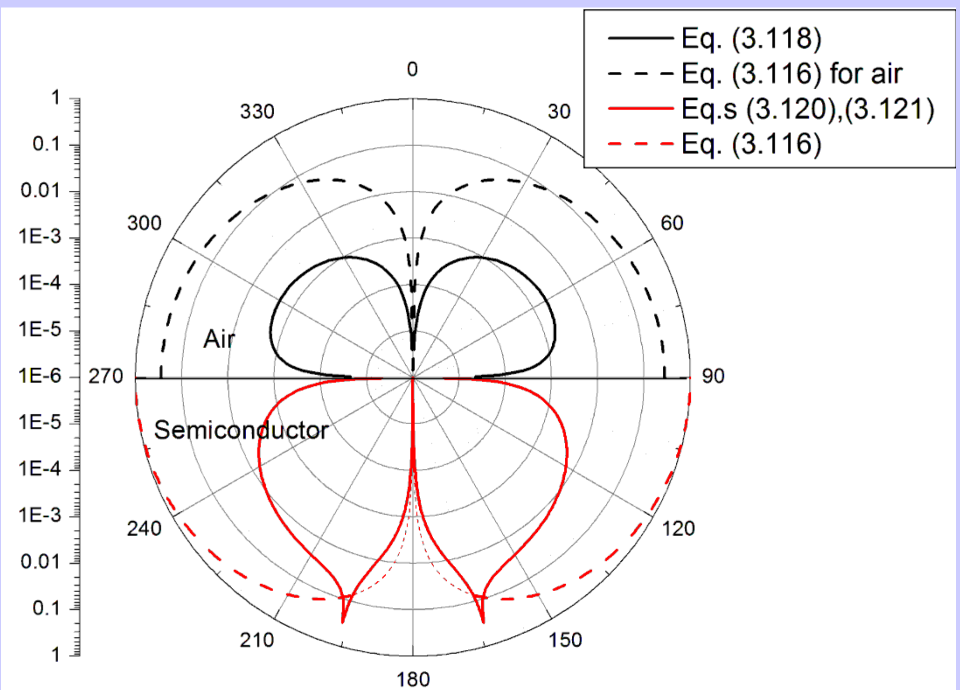


Back to large area emitter (LAE) with vertical field E_0



Modification of radiation pattern of a vertical Hertzian dipole in semiconductor, if in proximity to semiconductor/air interface



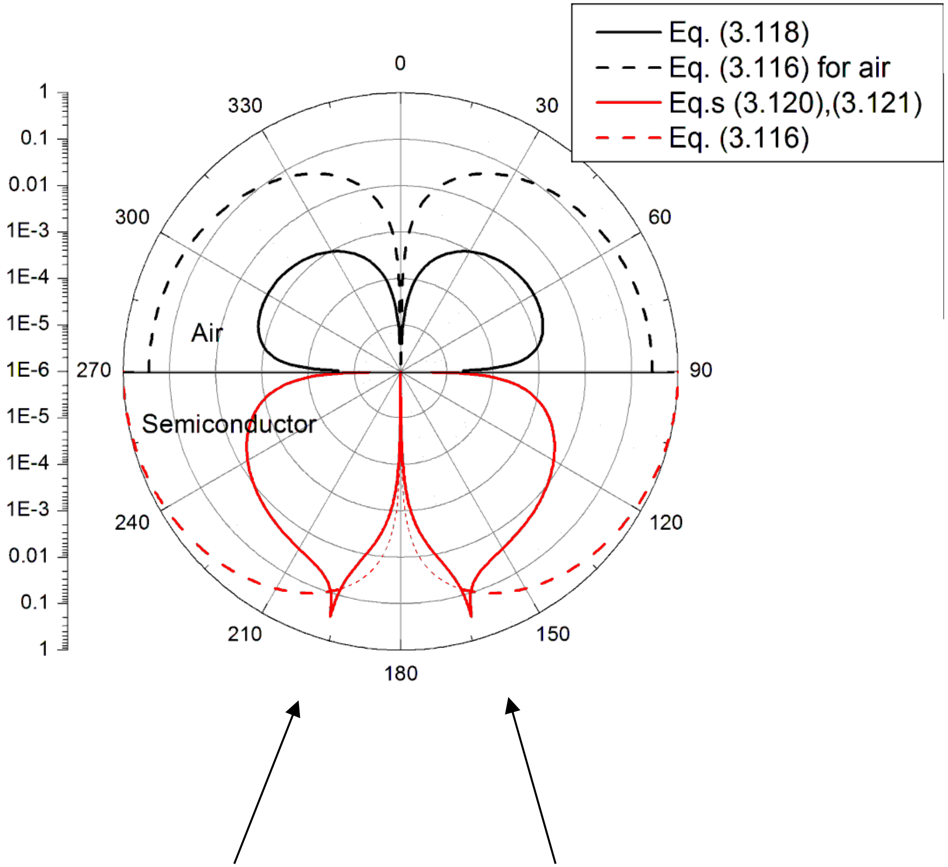


$|S_{e,THz}| \propto \sin^2\theta'/r^2$
i.e. :
no THz power emitted perpendicular to surface

to be discussed later!

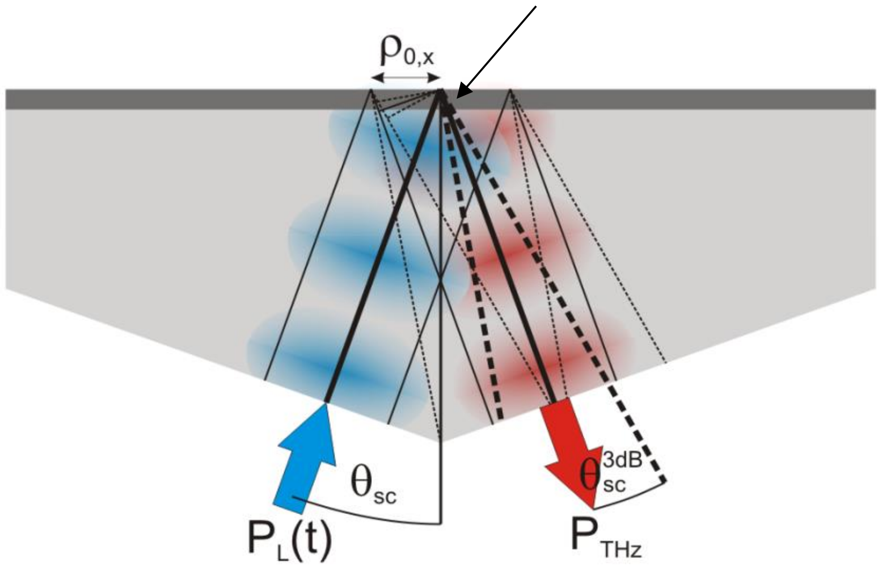
large area emitter (LAE) with vertical field E_0

Modification of radiation pattern of a vertical Hertzian dipole in semiconductor, if in proximity to semiconductor/air interface



Brewster angle

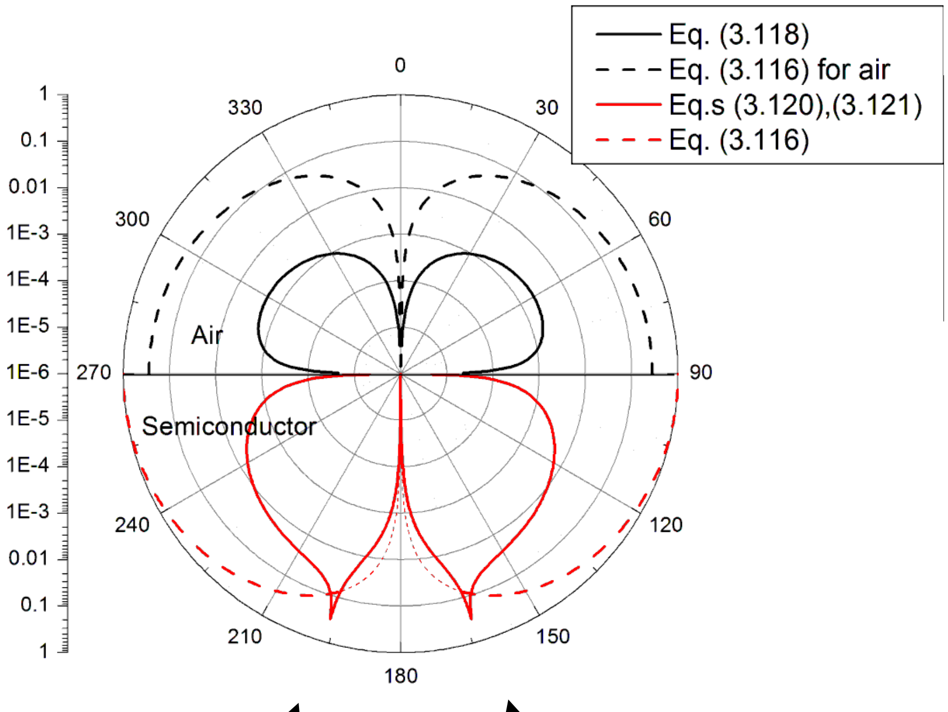
Maximum of radiation pattern at the Brewster angle!



Brewster angle Brewster angle

large area emitter (LAE) with vertical field E_0

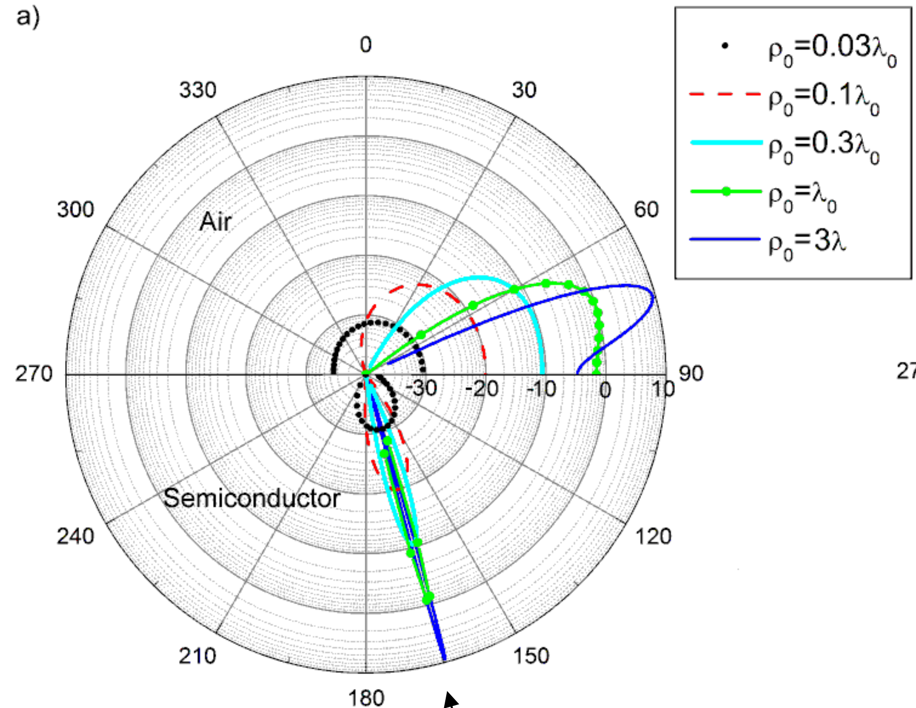
Modification of radiation pattern of a vertical Hertzian dipole in semiconductor, if in proximity to semiconductor/air interface



Brewster angle

Maximum of radiation pattern at the Brewster angle!

continuous-array factor for Brewster plane



Brewster angle

no experimental proof yet!

Conclusion and outlook

large area emitter (LAE) very promising:

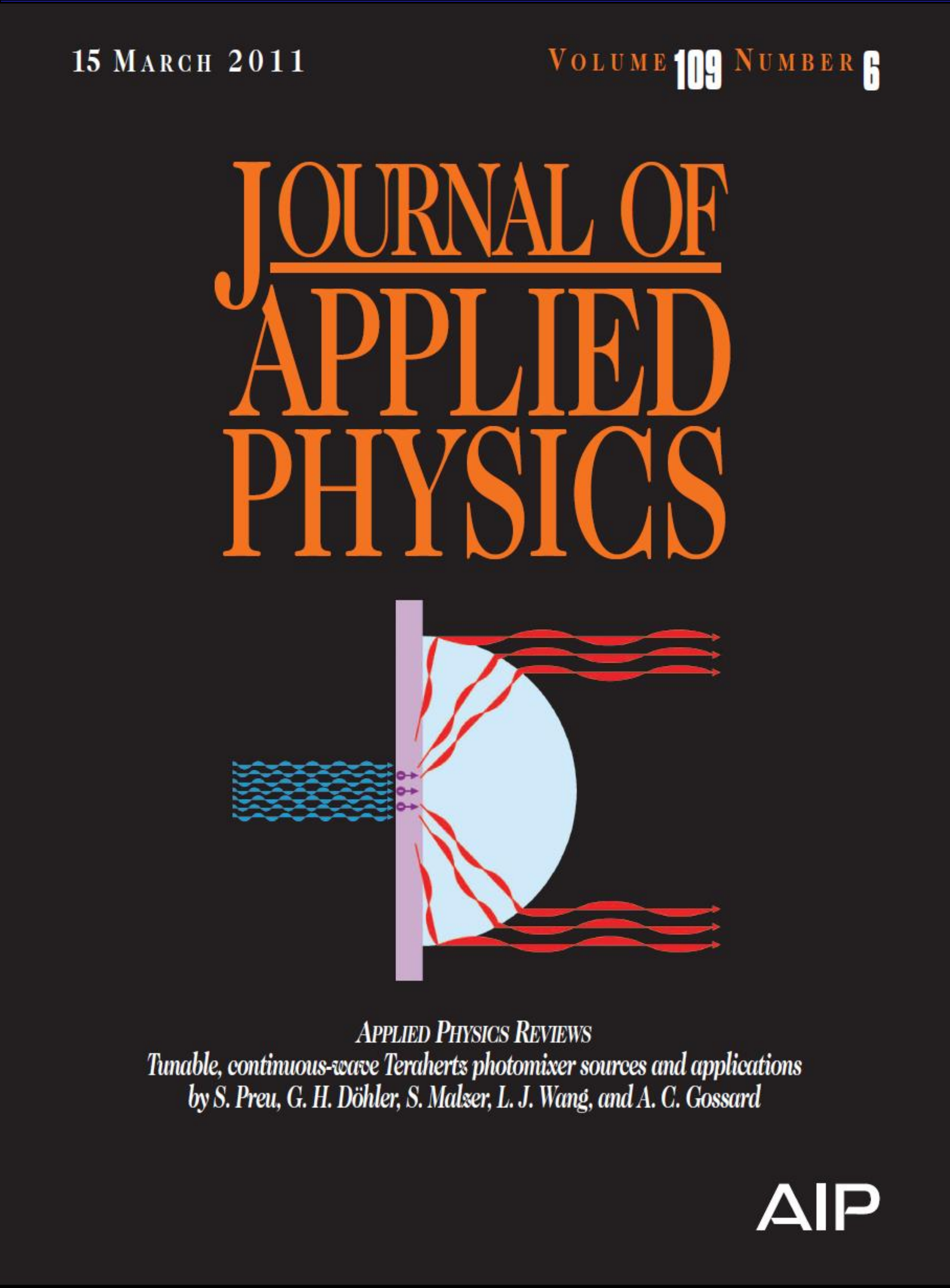
much higher power compared to antenna emitter (AE) achievable

excellent radiation profile

no optical elements (lenses, parabolic morrors) needed

easier to fabricate

… if I am not too optimistic!



Thank you for your attention!

You want to understand more about antenna emitter and Large Area Emitters and about CW THz Photomixers?

Please, ask your questions now (best option!) …

…or read our review (tedious option):

APPLIED PHYSICS REVIEWS

„Tunable, continuous-wave Terahertz photomixer sources and applications"
S. Preu, G. H. Döhler, S. Malzer, L. J. Wang and A. C. Gossard

J. Appl. Phys. **109**, 061301 (2011)

Thank you for your attention!

You want to understand more about antenna emitter and Large Area Emitters and about CW THz Photomixers?

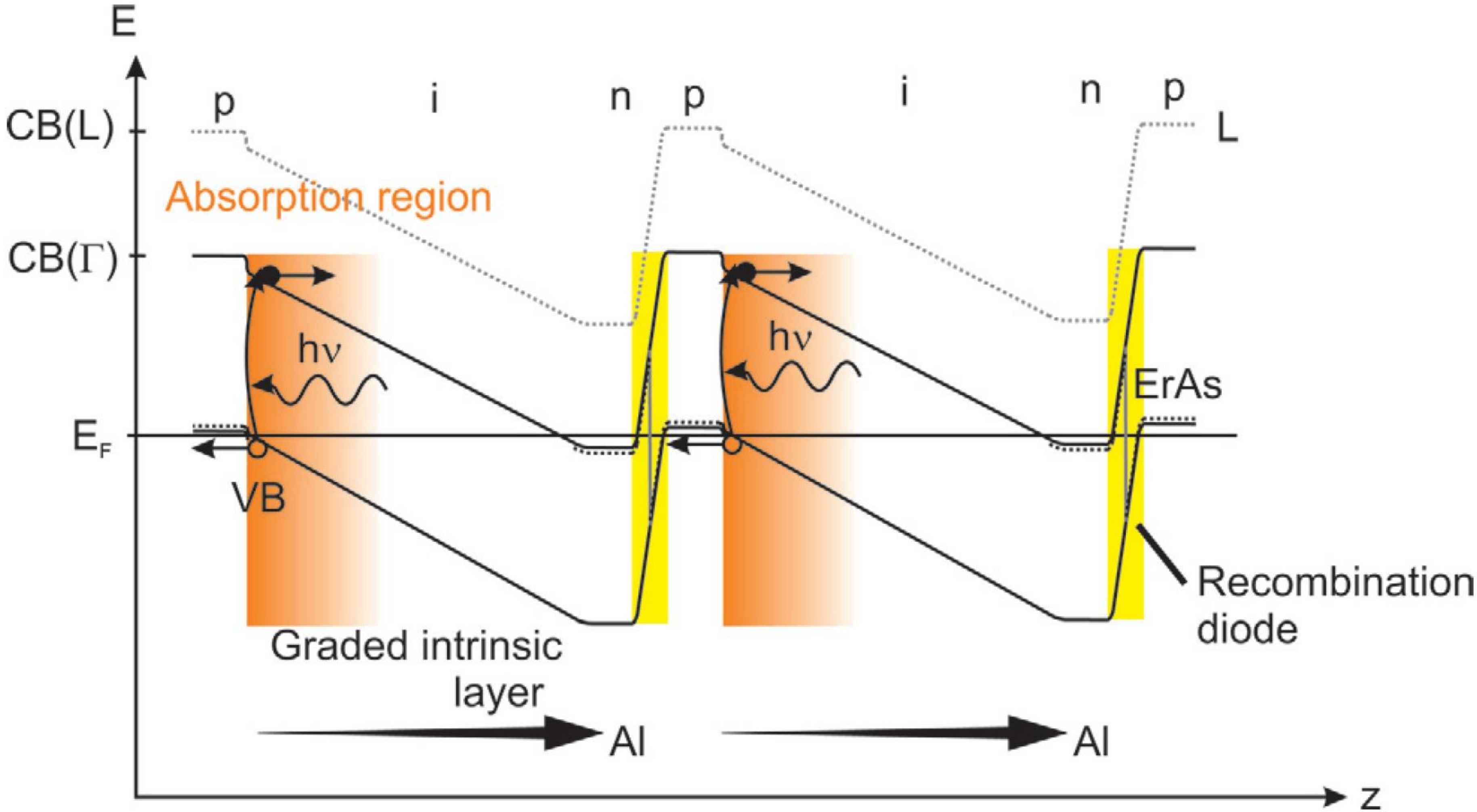
Please, ask your questions now (best option!) …

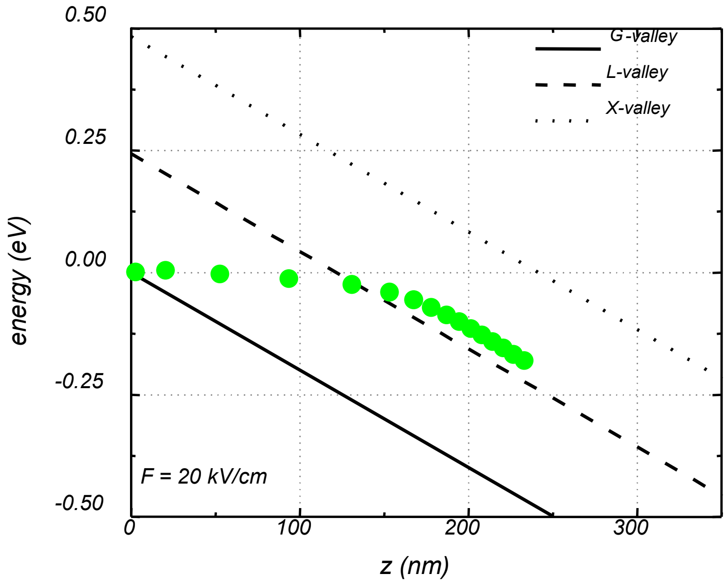
…or read chapters 2 and 3 of the book (even more tedious option):

SEMICONDUCTOR

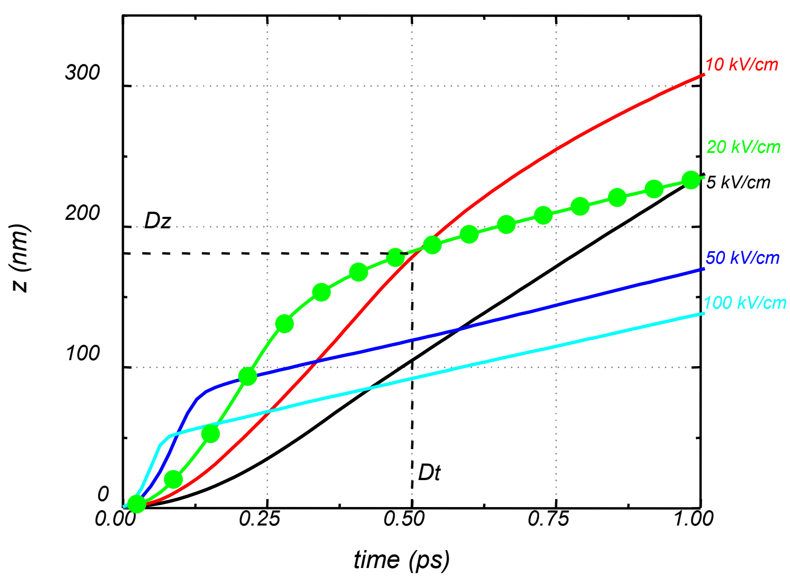
TERAHERTZ TECHNOLOGY

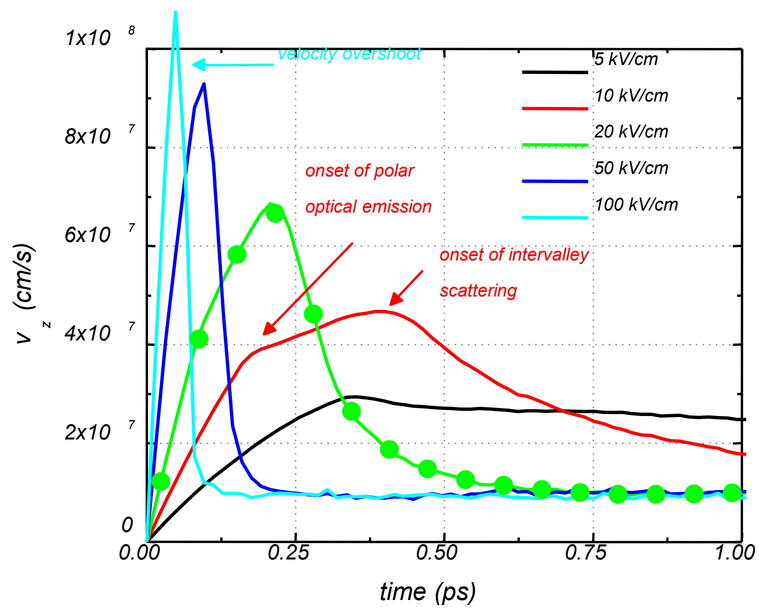
Guillermo Carpintero, Luis Enrique Garcia Munoz, Hans Hartnagel, Sascha Preu, Antti Räisänen

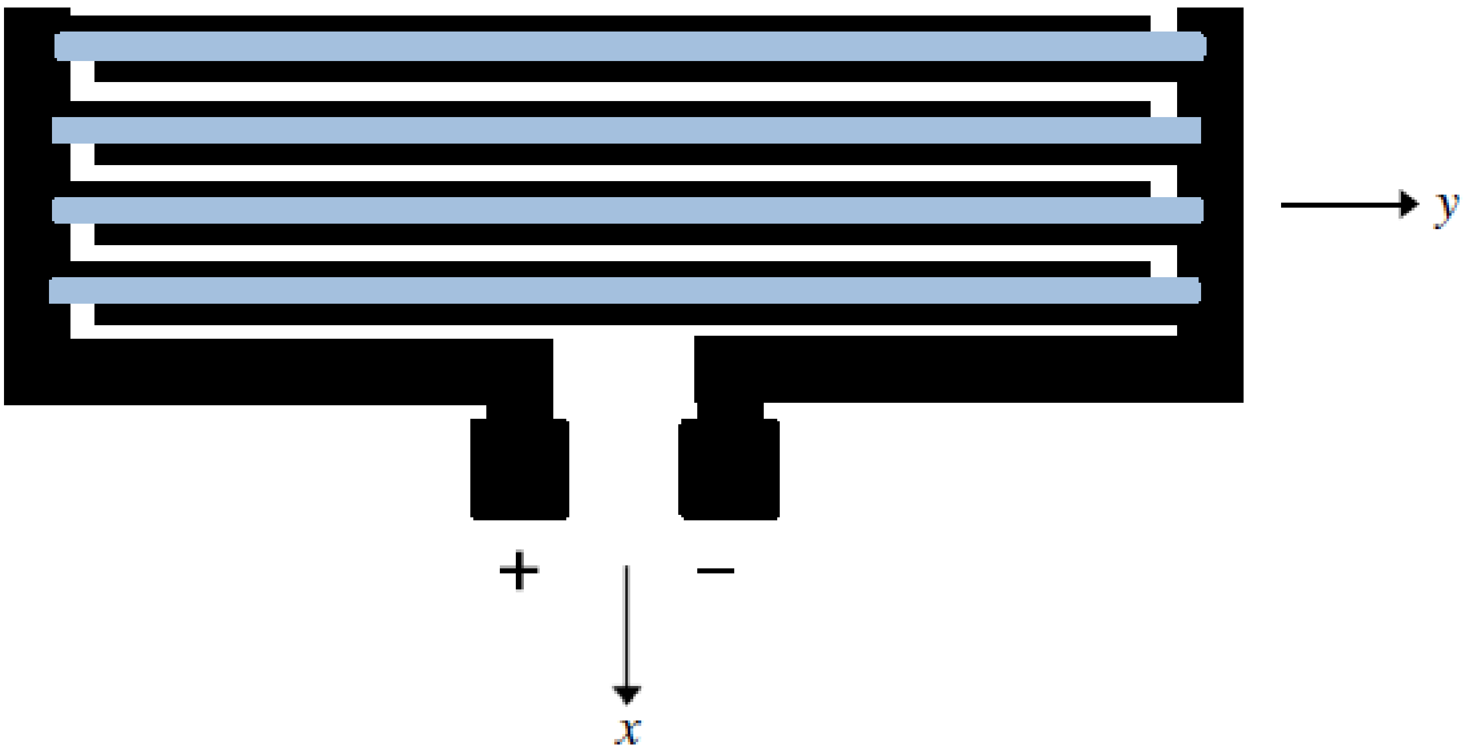

E
CB(L)
CB(Γ)
E_F
p
i
n
p
i
n
p
L
Absorption region
hν
hν
ErAs
VB
Recombination
diode
Graded intrinsic
layer
Al
Al
z

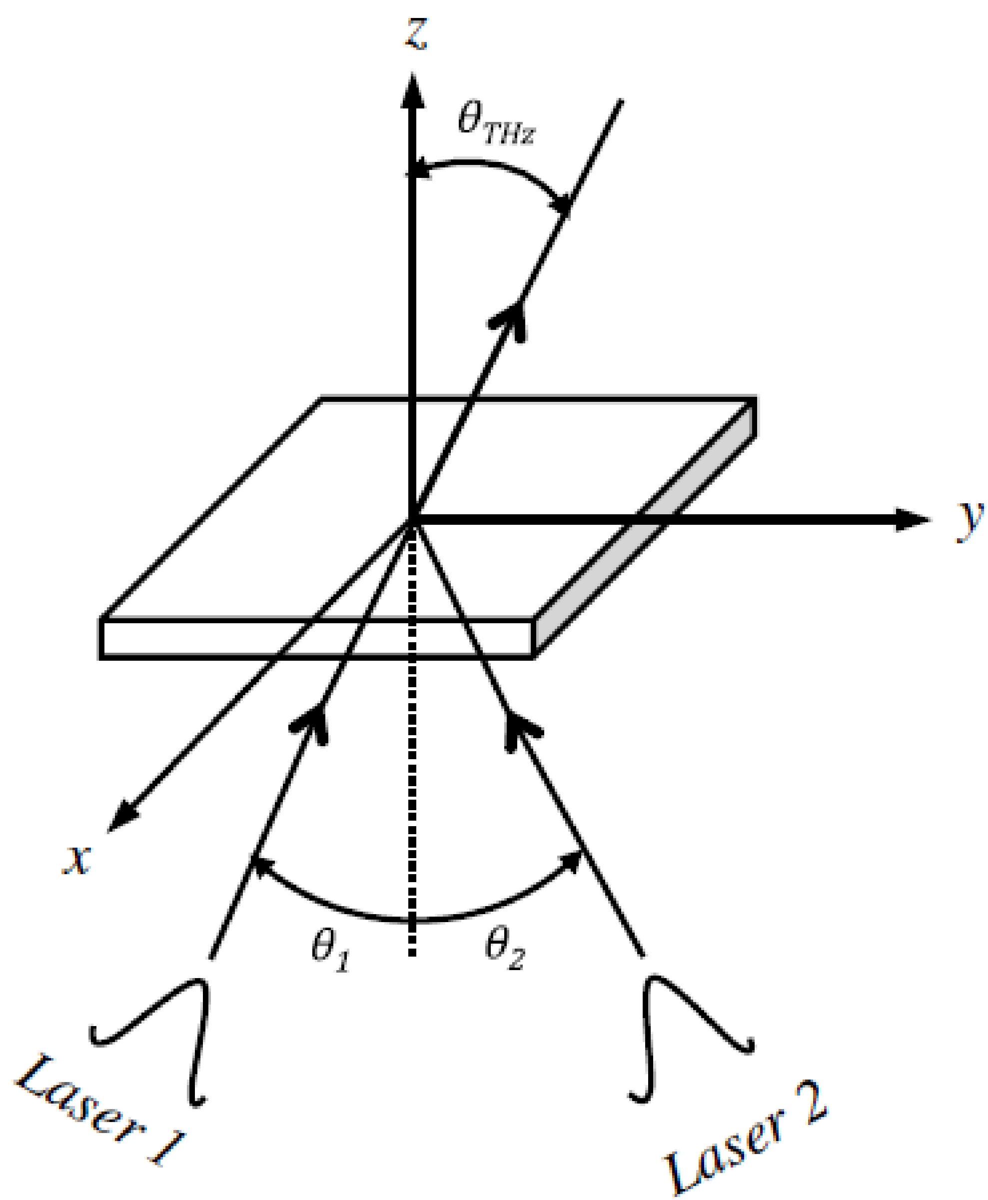


a quasi-ballistic electron can propagate by ca. 200 nm (!) within 0.5 ps at a field of 10 … 20 kV/cm






y
+
−
x


z
θ_{THz}
y
x
θ_1
θ_2
Laser 1
Laser 2

$$\mathbf{E}_1|_{z=0} = \hat{x}A_1 \exp\left(-\frac{x^2 + y^2\cos^2\theta_1}{\sigma_1^2}\right)\cos(\omega_1 t - k_1 y \sin\theta_1), \quad (1)$$

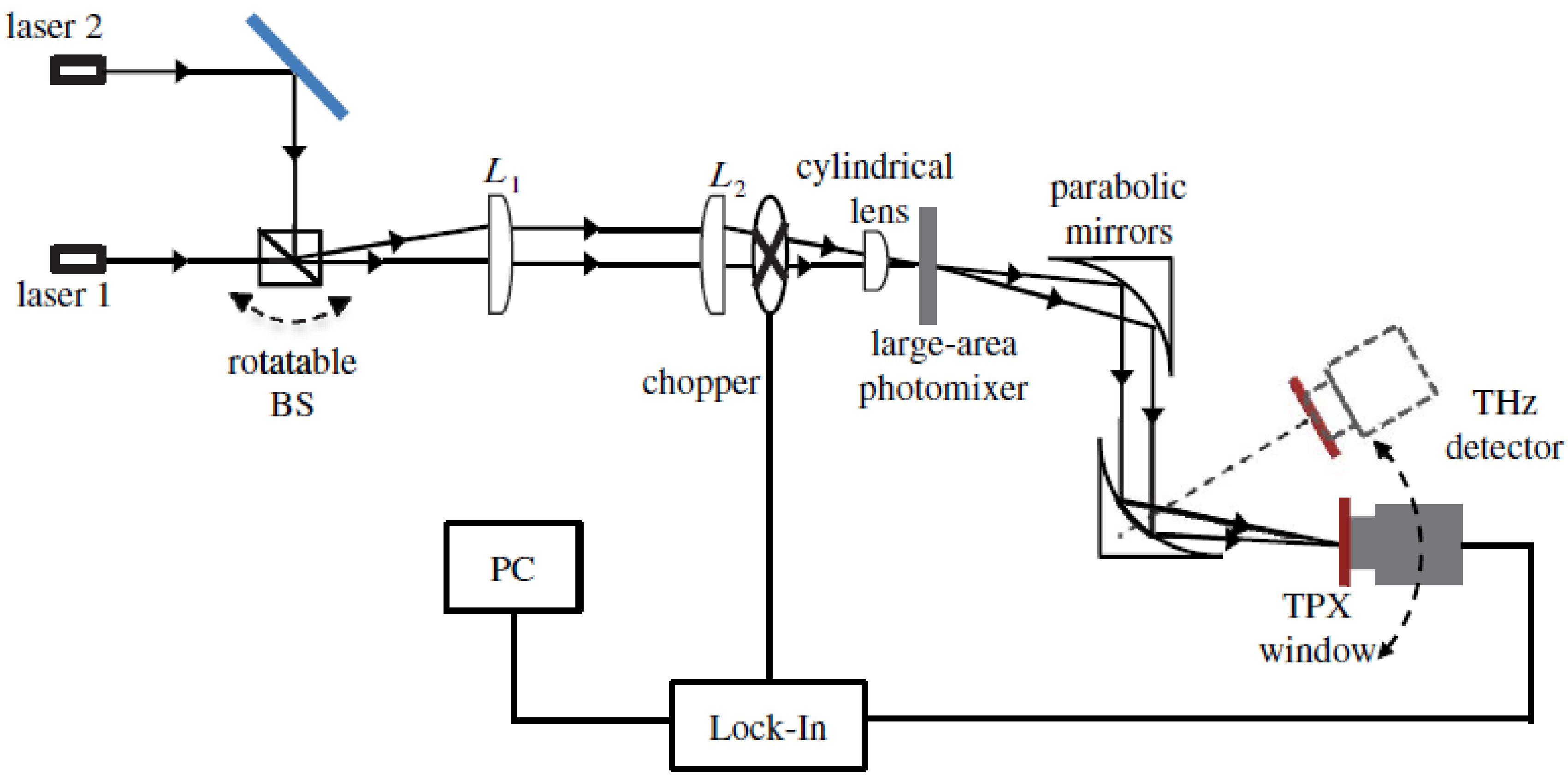
$$\mathbf{E}_2|_{z=0} = \hat{x}A_2 \exp\left(-\frac{x^2 + y^2\cos^2\theta_2}{\sigma_2^2}\right)\cos(\omega_2 t + k_2 y \sin\theta_2), \quad (2)$$

$$I(x, y; t) \propto A_1 A_2 \exp\left(-\frac{x^2 + y^2\cos^2\theta_1}{\sigma_1^2} - \frac{x^2 + y^2\cos^2\theta_2}{\sigma_2^2}\right) \times \cos(\Delta\omega t - (k_1 \sin\theta_1 + k_2 \sin\theta_2)y), \quad (3)$$

$$k_2 \sin\theta_2 = k_{\mathrm{THz}} \sin\theta_{\mathrm{THz}}, \quad (4)$$

$$\theta_{\mathrm{THz}} = \sin^{-1}\left(\frac{\lambda_{\mathrm{THz}}}{\lambda_2} \sin\theta_2\right), \quad (5)$$

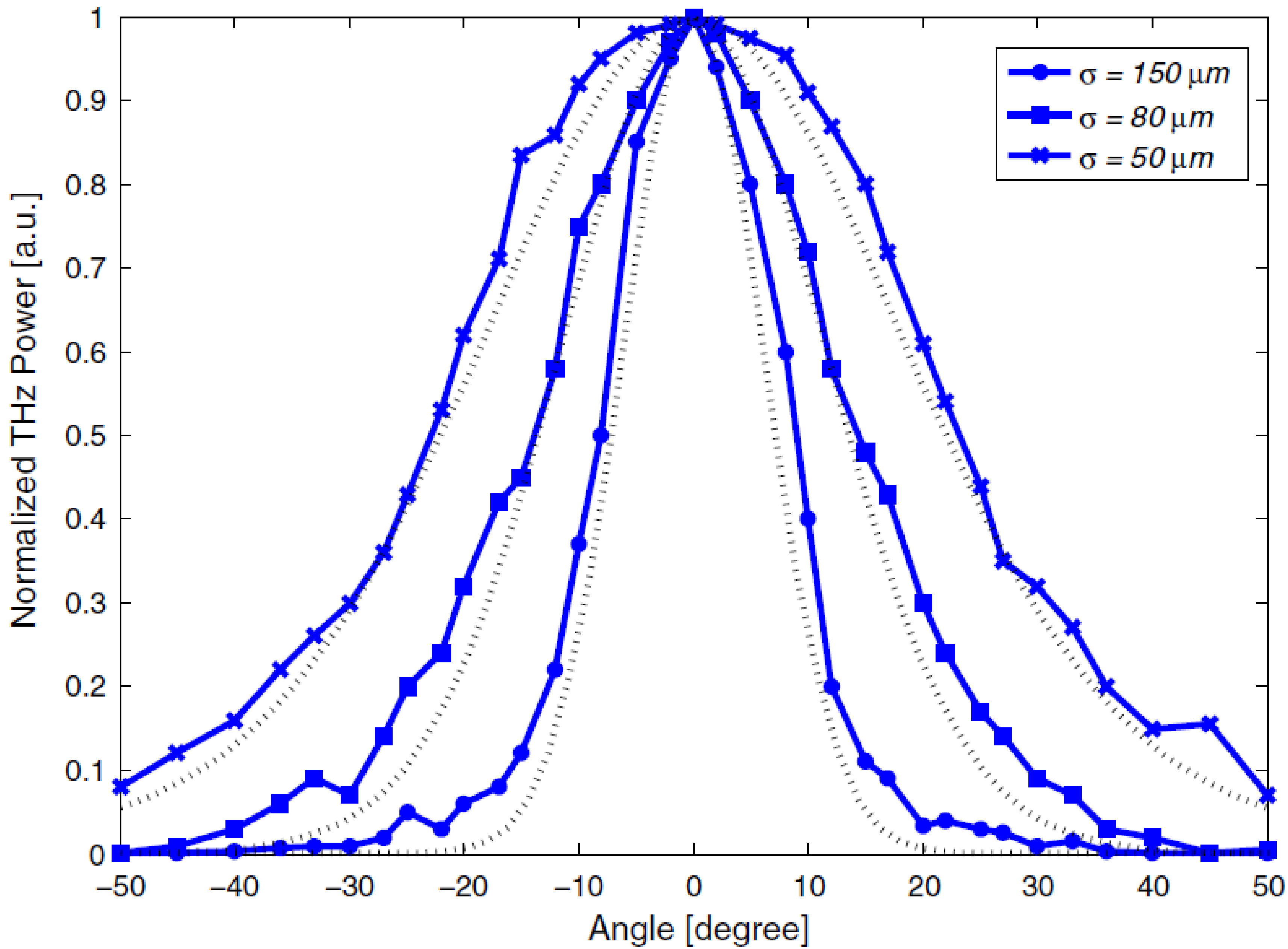
$\sin\theta_{THz} = \lambda_{THz}/\lambda_{FIR} \sin\theta_L \approx 200 \sin\theta_L$, for ν_{THz} = 1 THz



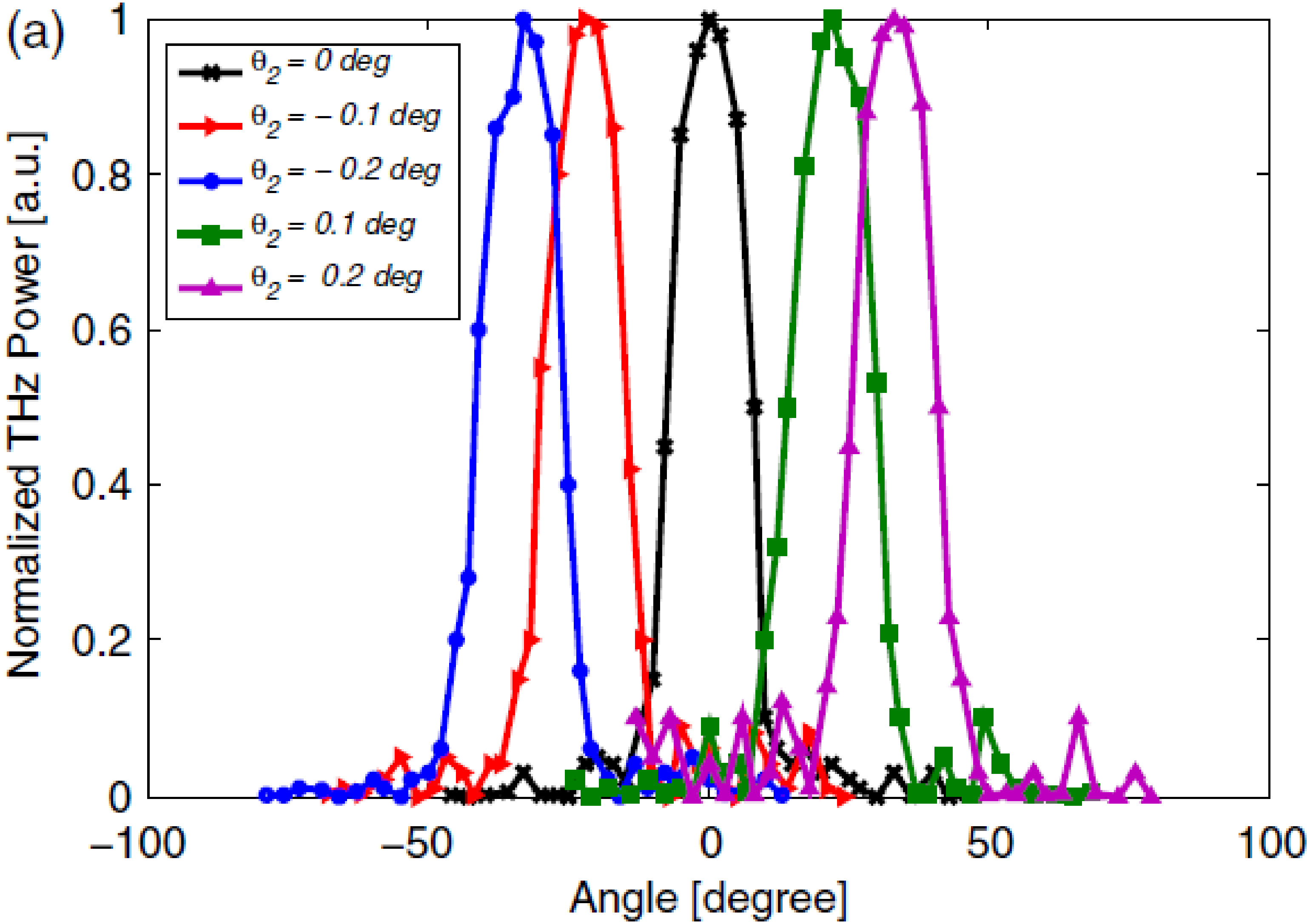
laser 2
laser 1
rotatable
BS
L_1
L_2
chopper
cylindrical
lens
large-area
photomixer
parabolic
mirrors
THz
detector
TPX
window
PC
Lock-In

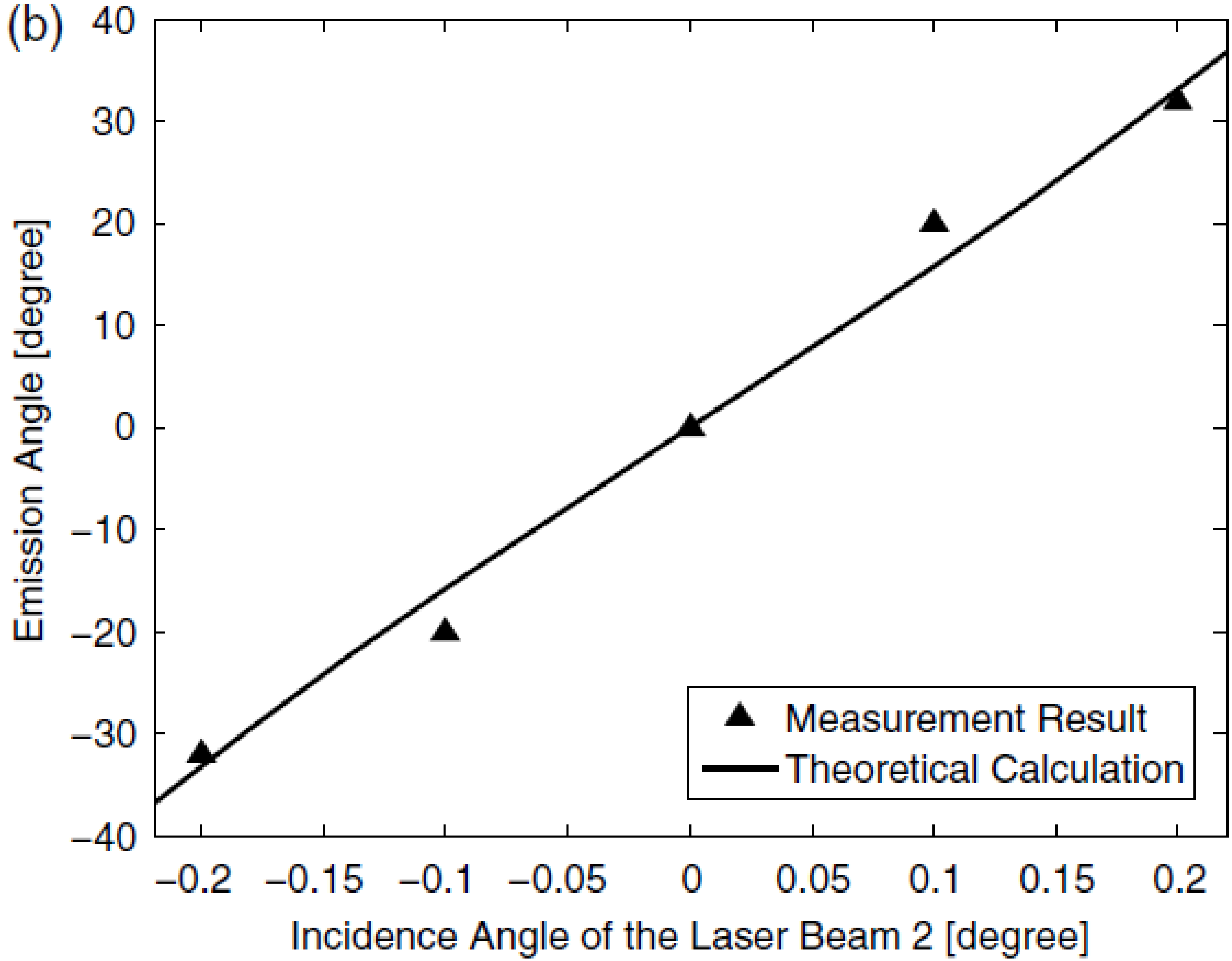
A. Eshaghi, M. Shahabadi and L. Chrostowski,
Radiation characteristics of large-area photomixer used for generation of continuous-wave terahertz radiation,
J. Opt. Soc. Am. B 29, 813 (2012)

Armaghan Eshaghi,1,2,* Mahmoud Shahabadi,1 and Lukas Chrostowski, 2Vol. 29, No. 4 / April 2012 / J. Opt. Soc. Am. B 813



σ = 150 μm
σ = 80 μm
σ = 50 μm
Normalized THz Power [a.u.]
Angle [degree]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
−50
−40
−30
−20
−10
0
10
20
30
40
50

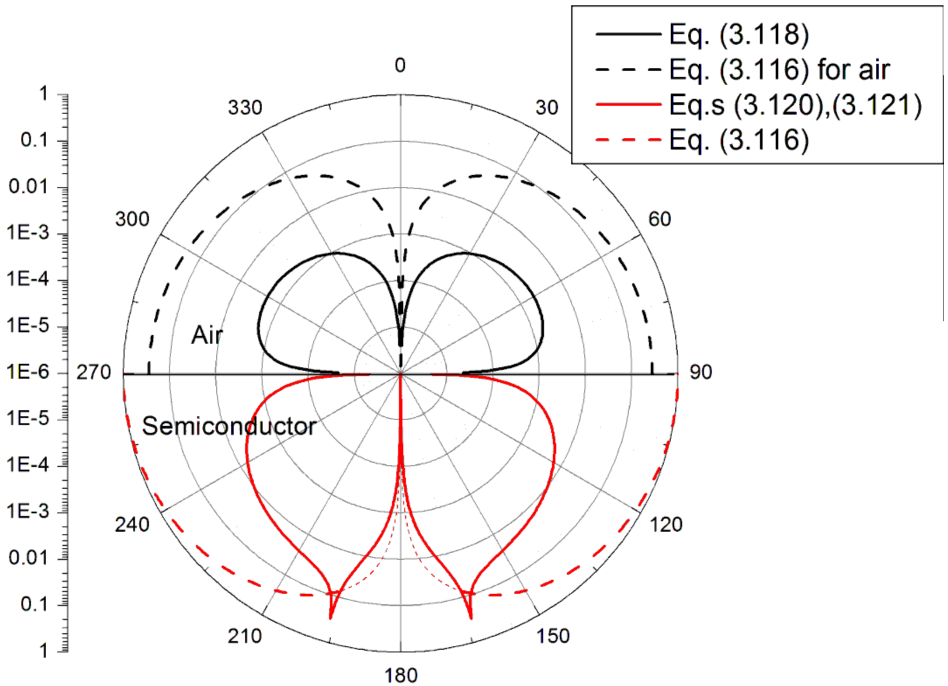

(a)
θ2 = 0 deg
θ2 = − 0.1 deg
θ2 = − 0.2 deg
θ2 = 0.1 deg
θ2 = 0.2 deg
Normalized THz Power [a.u.]
1
0.8
0.6
0.4
0.2
0
−100
−50
0
50
100
Angle [degree]



(b)
Emission Angle [degree]
40
30
20
10
0
−10
−20
−30
−40
−0.2
−0.15
−0.1
−0.05
0
0.05
0.1
0.15
0.2
Incidence Angle of the Laser Beam 2 [degree]
Measurement Result
Theoretical Calculation

large area emitter (LAE) with vertical field E_0

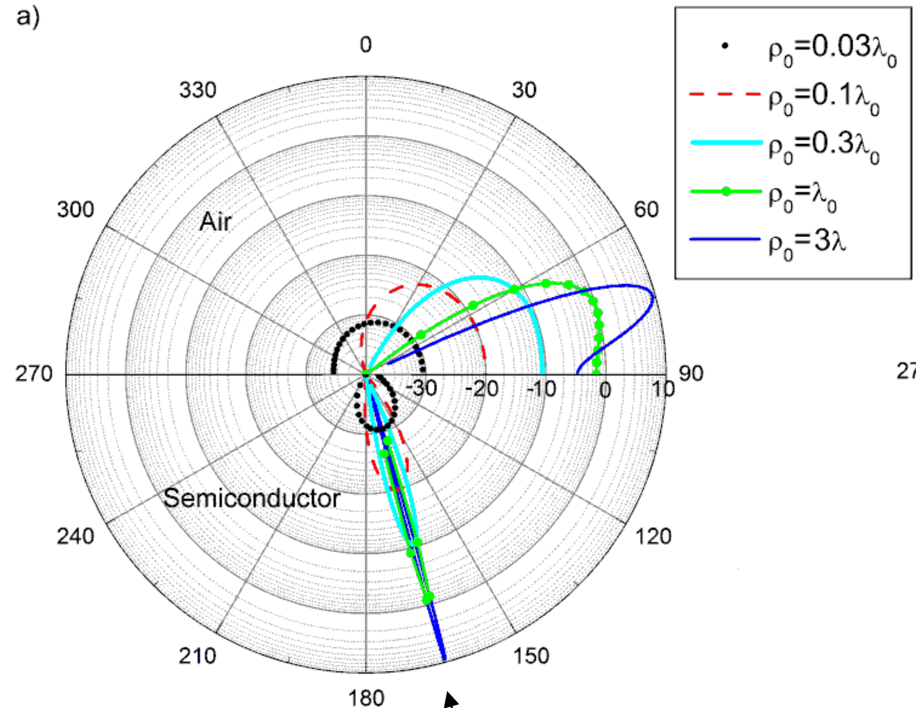
Modification of radiation pattern of a vertical Hertzian dipole in semiconductor, if in proximity to semiconductor/air interface



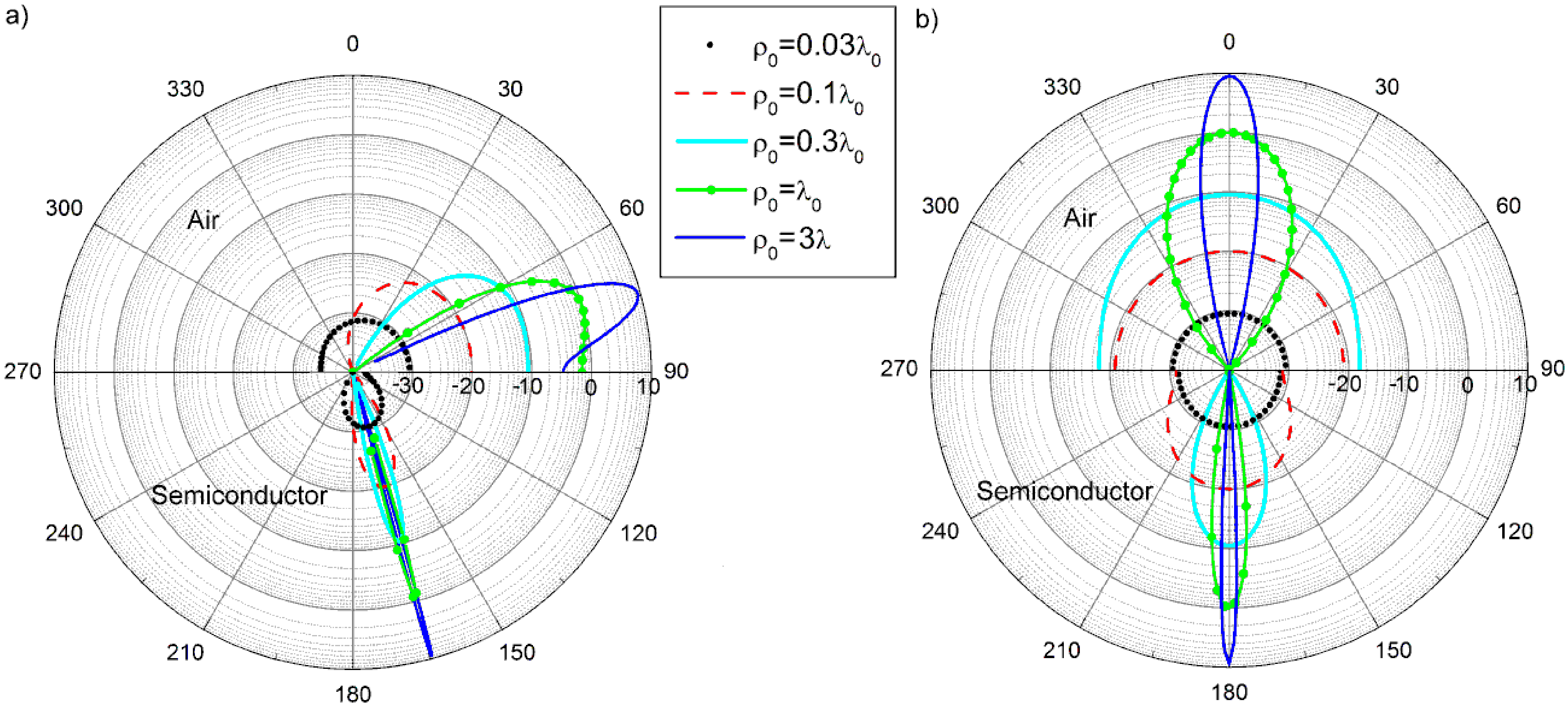
Brewster angle

Maximum of radiation pattern at the Brewster angle!

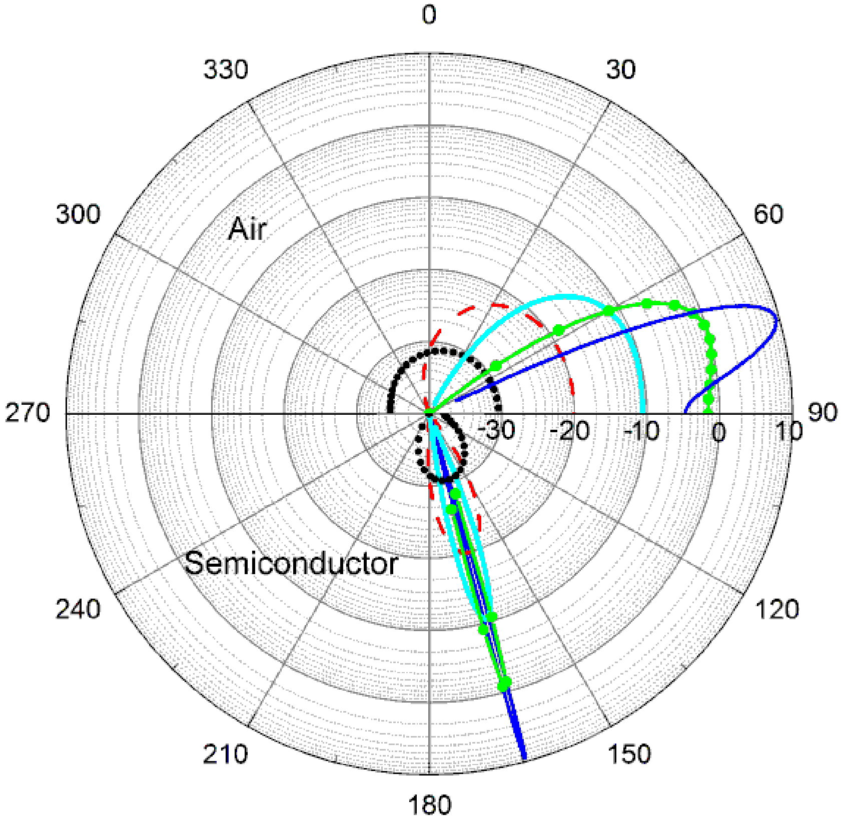
continuous-array factor for Brewster plane

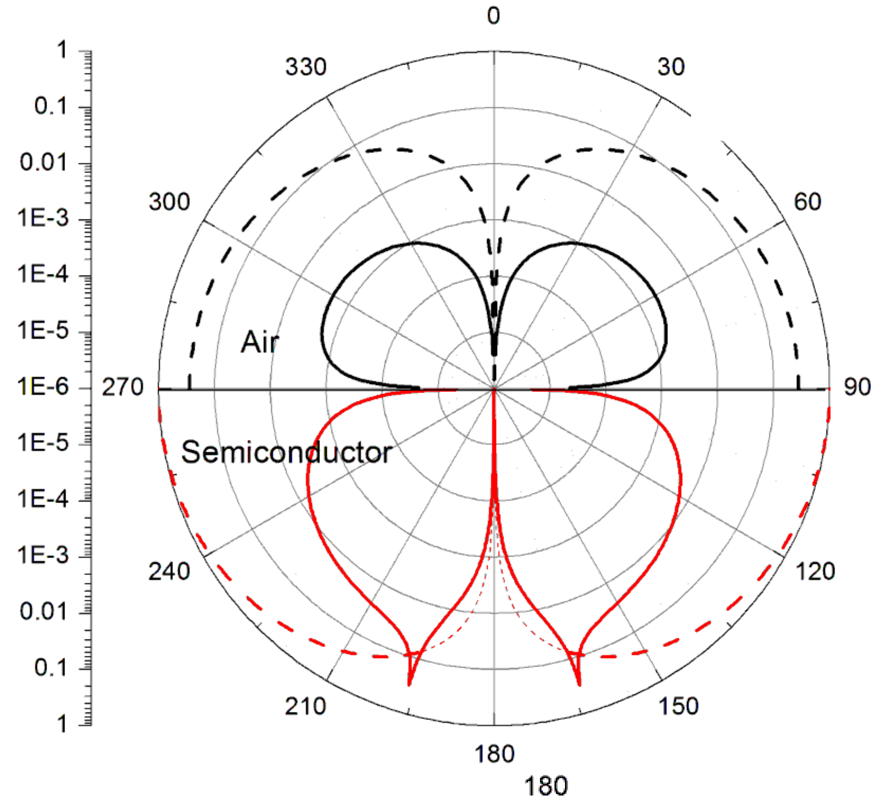


Brewster angle



Array factors of a vertical LAE in the x-zplane (a) and the Brewster-y plane (b) for various excitation spot radii



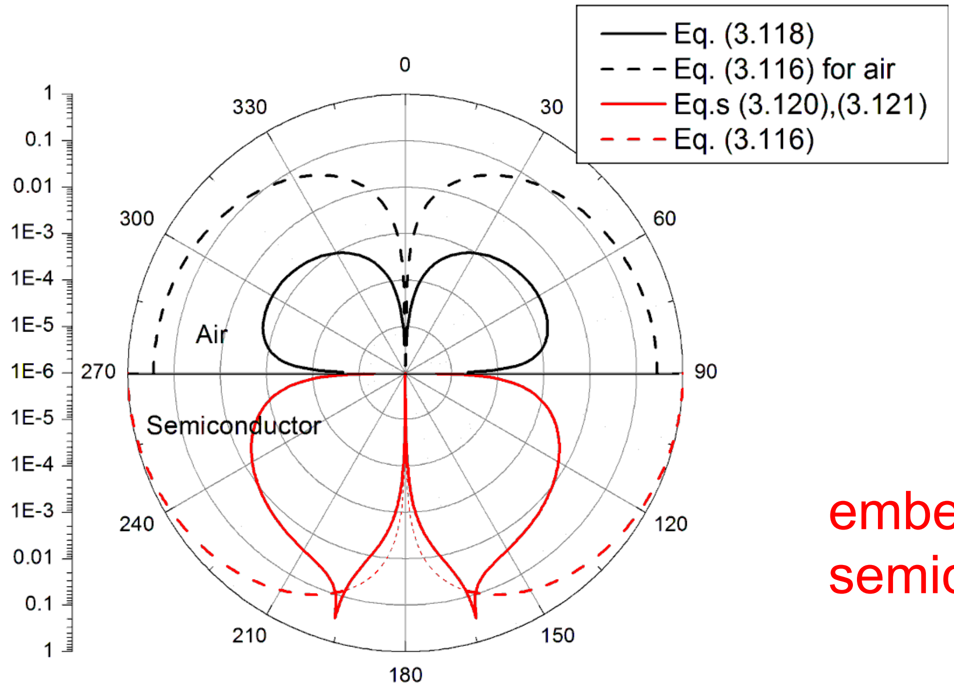


Array factors of a vertical LAE in the x-zplane (a) and the Brewster-y plane (b) for various excitation spot radii

Modification of radiation pattern of a vertical Hertzian dipole in semiconductor, if in proximity to semiconductor/air interface

dipole embedded in air

dipole in semiconductor, in proximity to air

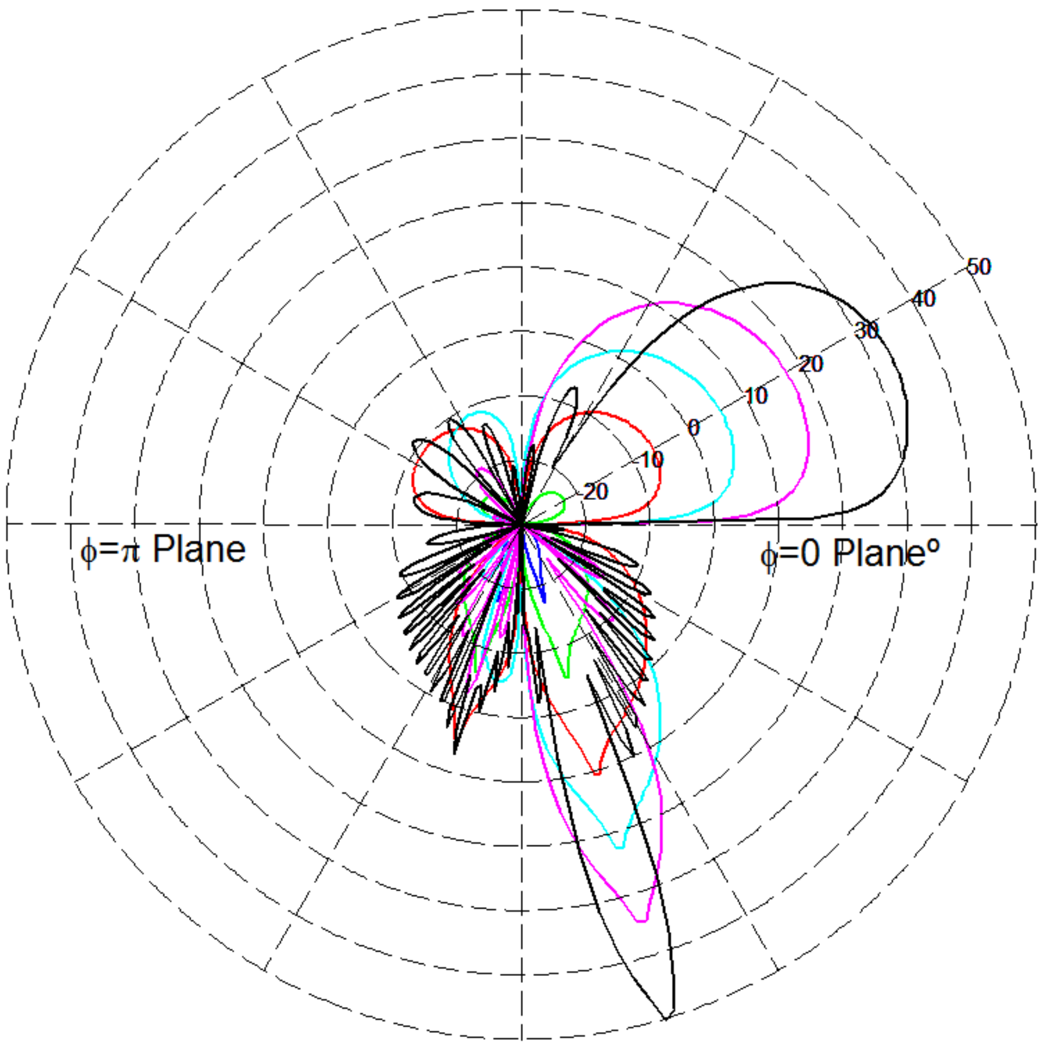


embedded into semiconductor

in semiconductor in proximity to air

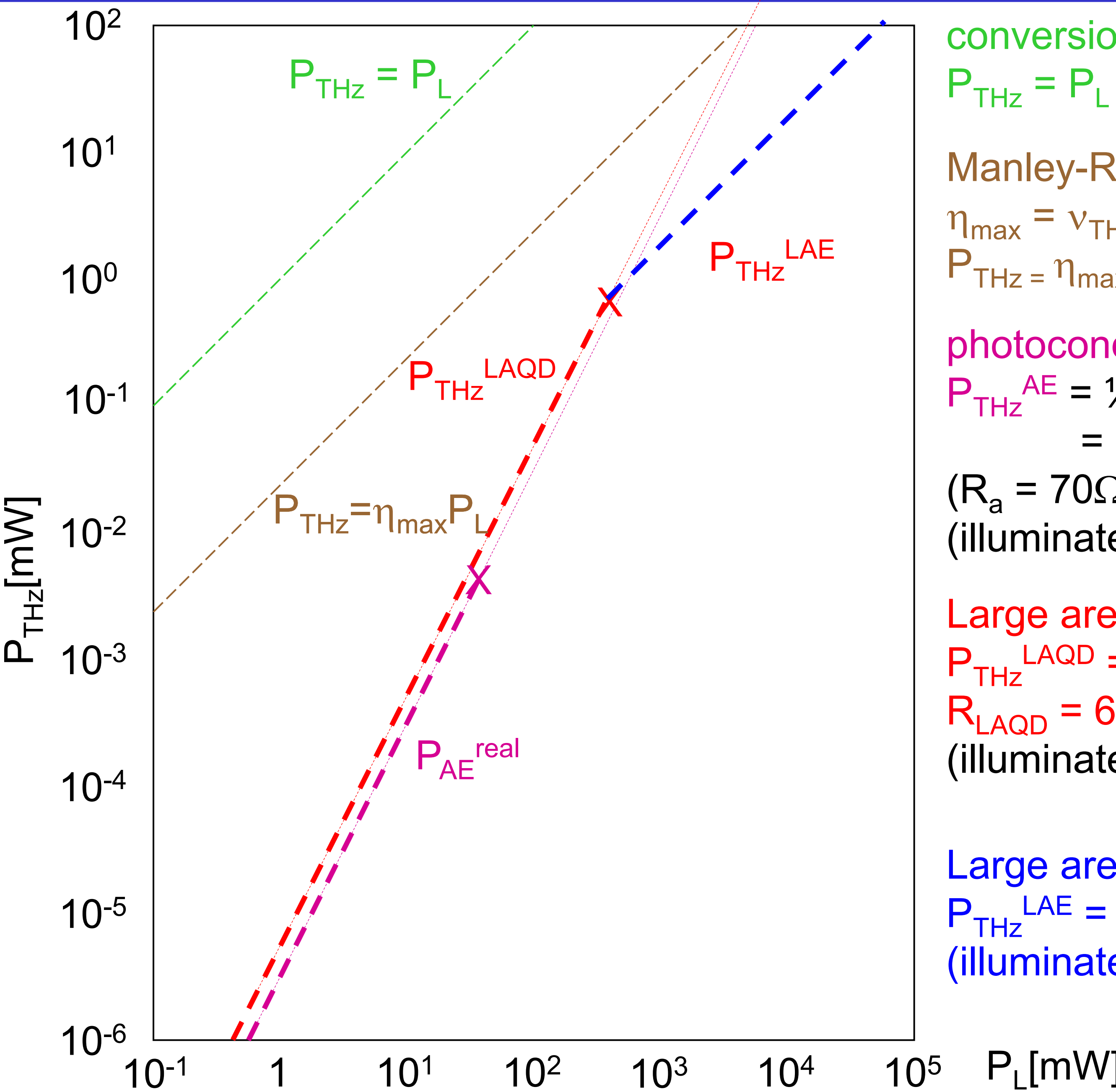
Fig. 3.60: Dashed lines: Power emitted by a vertical Hertzian dipole embedded in air (top) or in a semiconductor with n_{sc} = 3.6. Solid lines: Radiation patterns of the dipole in proximity to the interface to air according to Eqs. (3.116), (3.118), (3.120) and (3.121).

radiation pattern of a vertical LAE at interface to air



Legend	ρ_0	$a=\rho_0/10$
Blue	$0.1\lambda_{sc}$	$0.01\lambda_{sc}$
Green	$0.2\lambda_{sc}$	$0.02\lambda_{sc}$
Red	$0.5\lambda_{sc}$	$0.05\lambda_{sc}$
Cyan	$1\lambda_{sc}$	$0.1\lambda_{sc}$
Magenta	$2\lambda_{sc}$	$0.2\lambda_{sc}$
Black	$5\lambda_{sc}$	$0.5\lambda_{sc}$

THz power vs. laser power for photomixers



conversion efficiency $\eta = 1$
$P_{THz} = P_L$

Manley-Rove (non-linear mixing)
$\eta_{max} = \nu_{THz}/\nu_0$
$P_{THz} = \eta_{max} P_L$

photocond. antenna emitter (AE)
$P_{THz}^{AE} = ½ R_a g^2 (I_{THz}^{id})^2$
$= 3.5x\ 10^{-3}\Omega\ (I_{THz}^{id})^2$;
($R_a = 70\Omega$, $g = \tau_{rec}/\tau_{tr} = 10^{-2}$)
(illuminated area $100\mu m^2$, e.g.)

Large area quasi-dipole (LAQD)
$P_{THz}^{LAQD} = ½ R_{LAQD} (I_{THz}^{id})^2$;
$R_{LAQD} = 6x10^{-3}\Omega$,
(illuminated spot $\pi\rho_c^2 \approx 1000\mu m^2$)

Large area emitter (LAE)
P_{THz}^{LAE} = PTHzLAQD $(r/rc)^2$
(illuminated spot $\rho > \rho_c$

Results on LAQD and LAE THz emitters

so far: none on CW mixing (to our knowledge!)

however, recently, ($t > 2006$): very exciting results on LAEs under pulse operation

Results on LAQD and LAE THz emitters

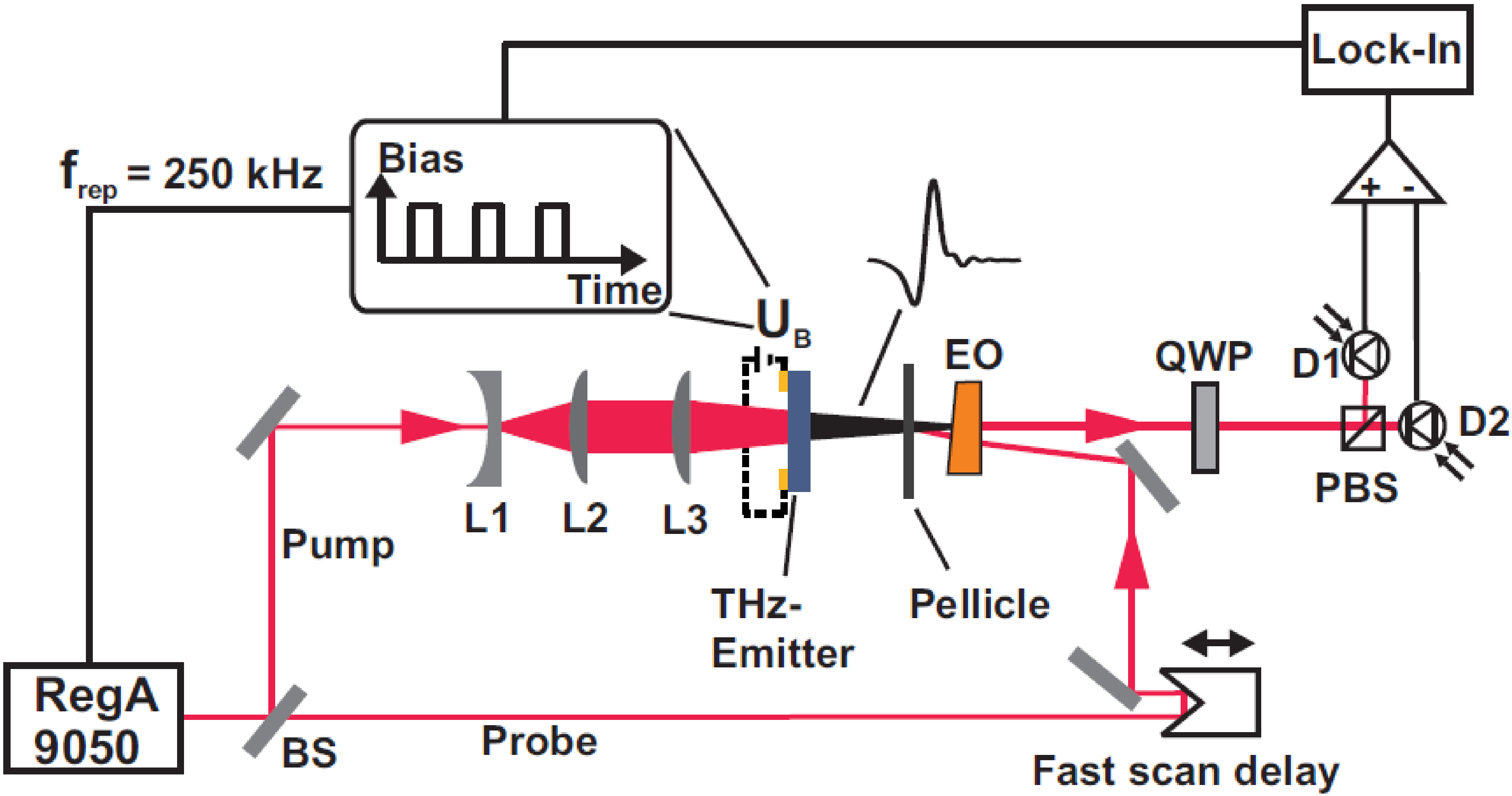
so far: none on CW mixing (to our knowledge!)

however, recently, (t > 2006): very exciting results on LAEs under pulse operation

Main differences between CW mixing and pulse excitation

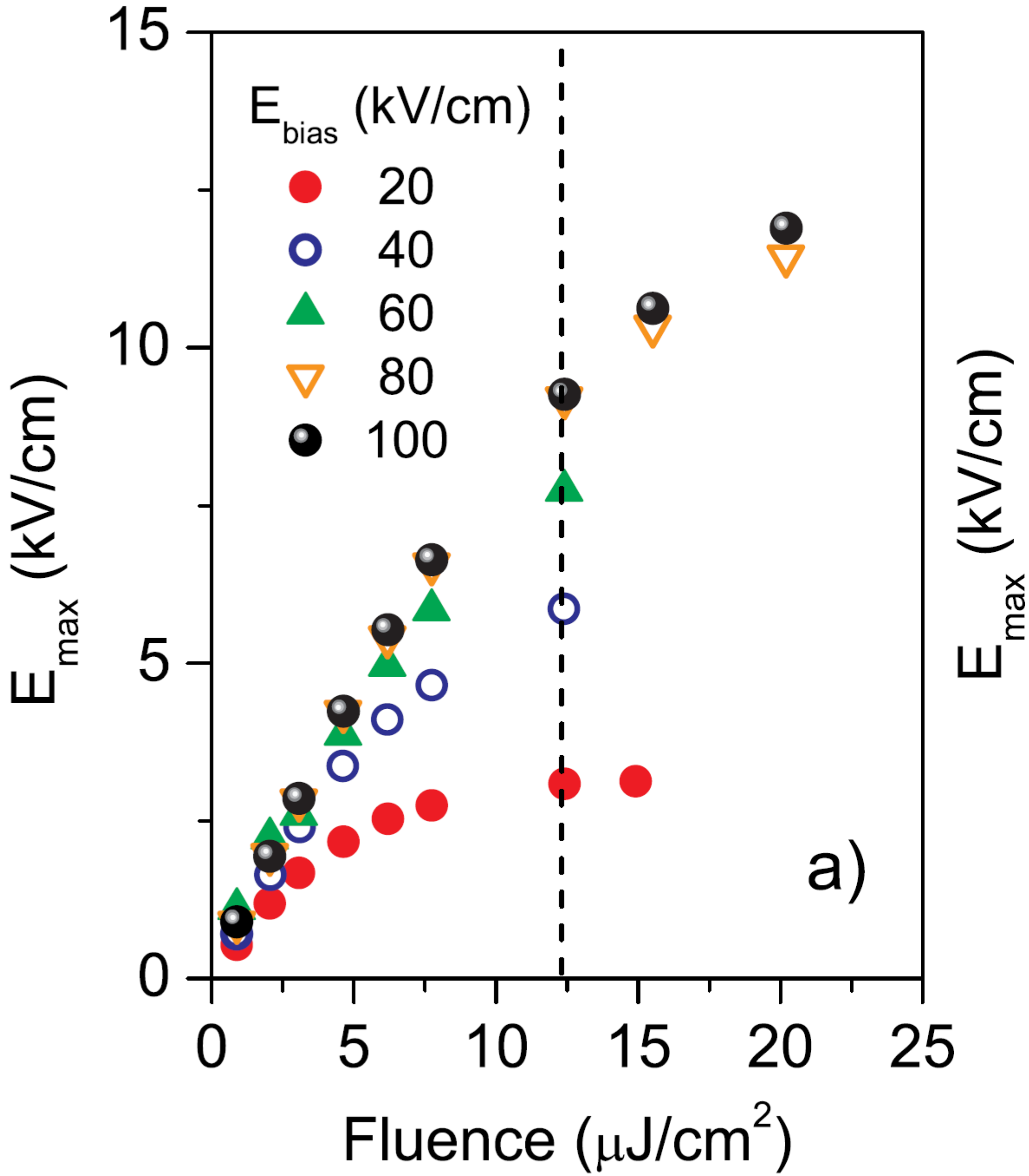
CW mixing	pulse excitation
Extremely narrow band width, tunable Tunable over a wide frequency range	One broad band THz cycle per pulse
100 % duty cycle	duty cycle $\delta = T_{THz}/\tau_{rep} = \nu_{rep}/\nu_{THz} << 1$
P_L^{max} limited by thermal failure threshold P^{th}	More favorable budget regarding thermal failure: *average* laser power $<P_L>^{max} = P^{th}$ $\Rightarrow$ (laser pulse energy)$T_{THz} = \delta^{-1} P^{th} >> P^{th}$ $\Rightarrow P_{THz} \propto (\delta^{-1}P^{th})^2 >>>> P^{th}$
$\Rightarrow P_{THz,CW}$ limited by thermal failure threshold P^{th}	$\Rightarrow <P_{THz}>_{pu} \propto \delta^{-1} P_{THz,CW} >> P_{TH,CW}$

Large area THz emitter (pulsed operation)

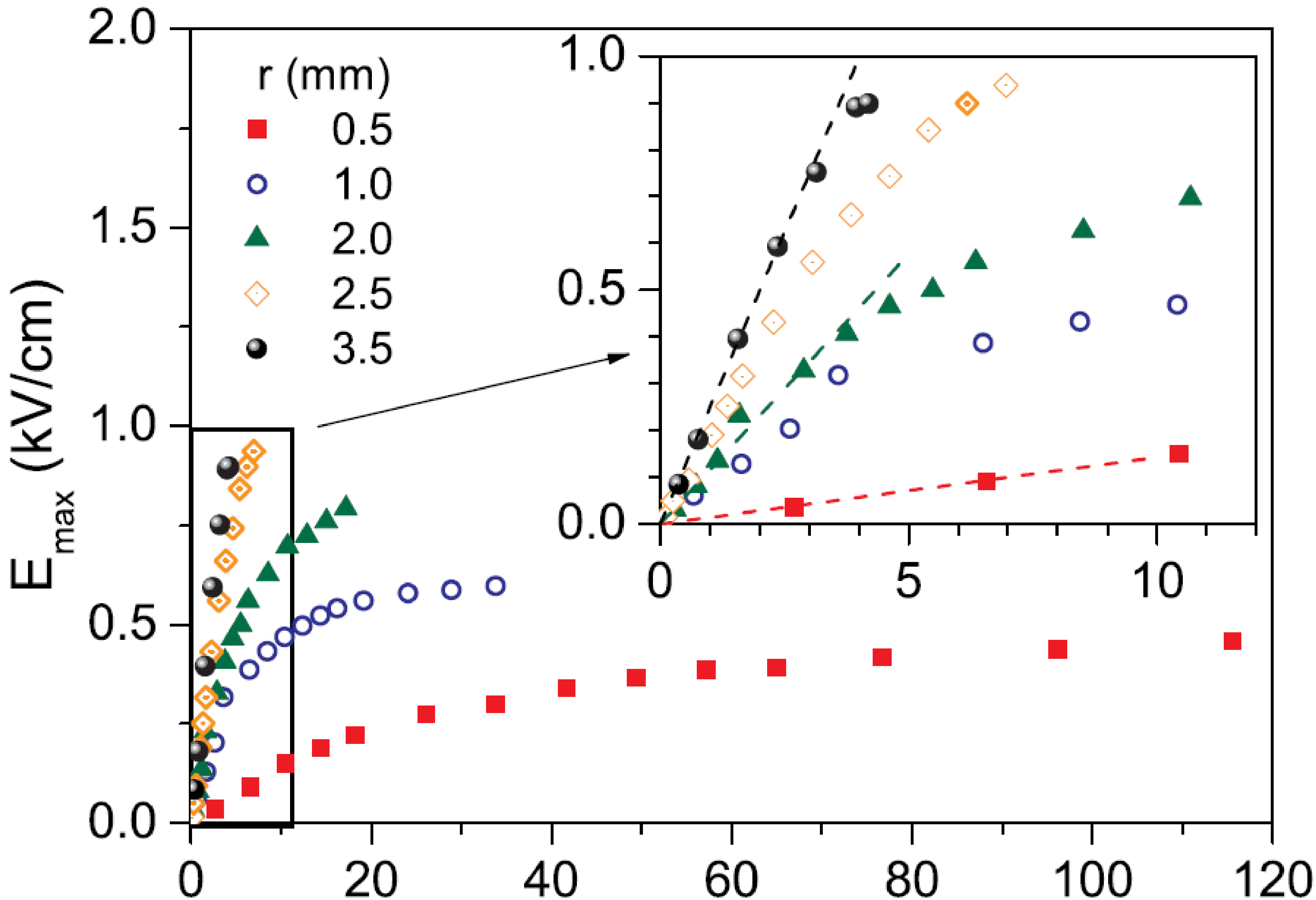


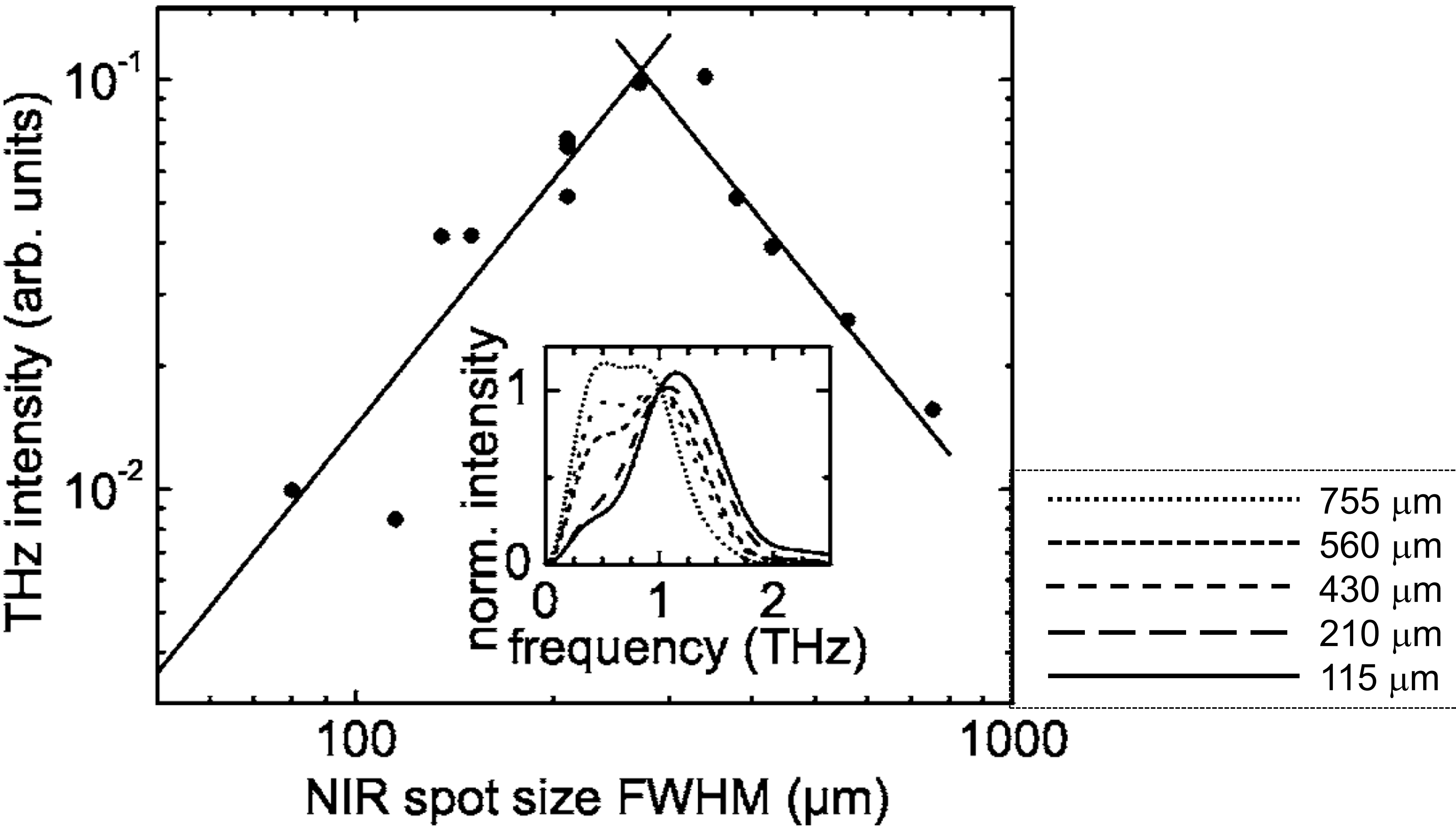
M. Beck, H. Schäfer, G. Klatt, J. Demsar, S. Winnerl, M. Helm and T. Dekorsy, OPTICS EXPRESS 18, 9251 (2010)

Large area THz emitter (pulsed operation)



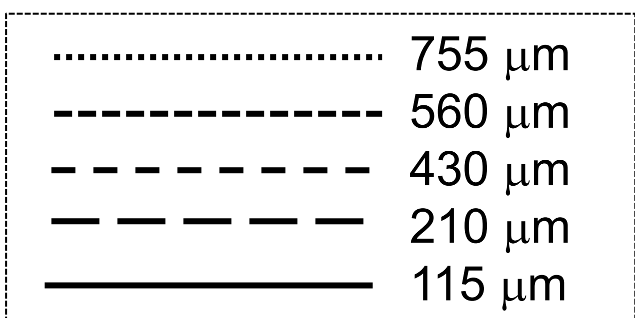
Large area THz emitters





THz intensity (arb. units)
10^{-1}
10^{-2}
100
1000
NIR spot size FWHM (μm)
norm. intensity
0
1
0
1
2
frequency (THz)
755 μm
560 μm
430 μm
210 μm
115 μm

Fig. 3. Dependence of the detected THz intensity (E_{THz}^2) on the size (FWHM) of the exciting NIR spot (double logarithmic scale). Filled circles, measured data; solid lines, guides to the eyes. Inset, THz spectra for various excitation spot sizes normalized to the intensity value at 1 THz; 755 μm (short dotted), 560 μm (dotted), 430 μm (short dashed), 210 μm (dashed), 115 μm (solid).

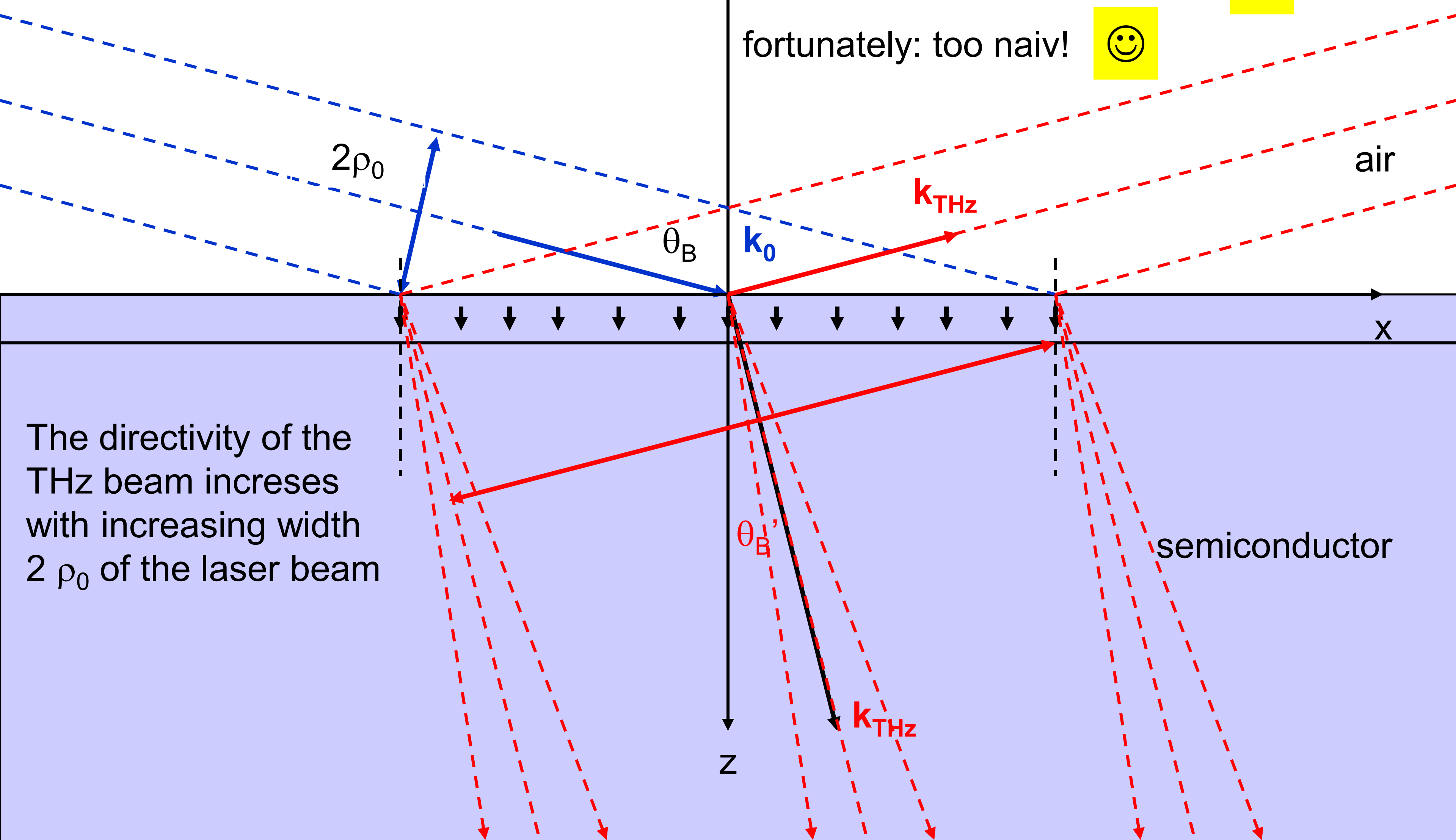


LAE with vertical dipoles with laser beam incidence under Brewster angle θ_B

THz radiation mostly emitted into substrate under (refracted) Brewster angle θ_B' (≈ 15.6°)

expected intensity $\propto \sin^2\theta_B' = 0.072 \Rightarrow$ 7.2% of maximum intensity ☹

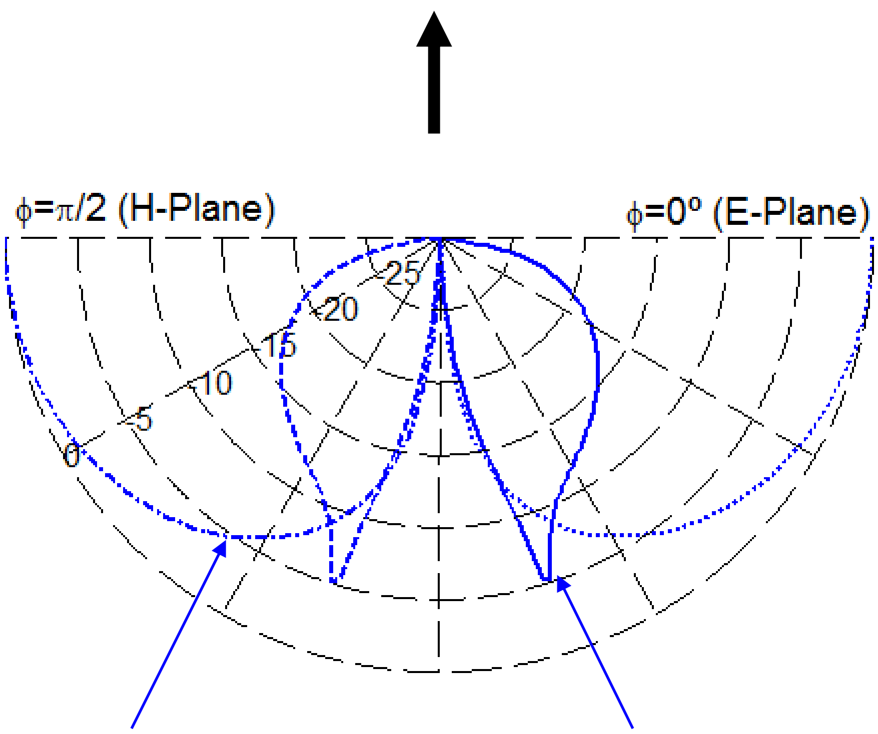
fortunately: too naiv! ☺



The directivity of the THz beam increses with increasing width 2 ρ_0 of the laser beam

radiation pattern of a vertical dipole in InGaAs close to interface to air? *

vertical dipole



embedded in bulk semiconductor

Located at interface semiconductor/air

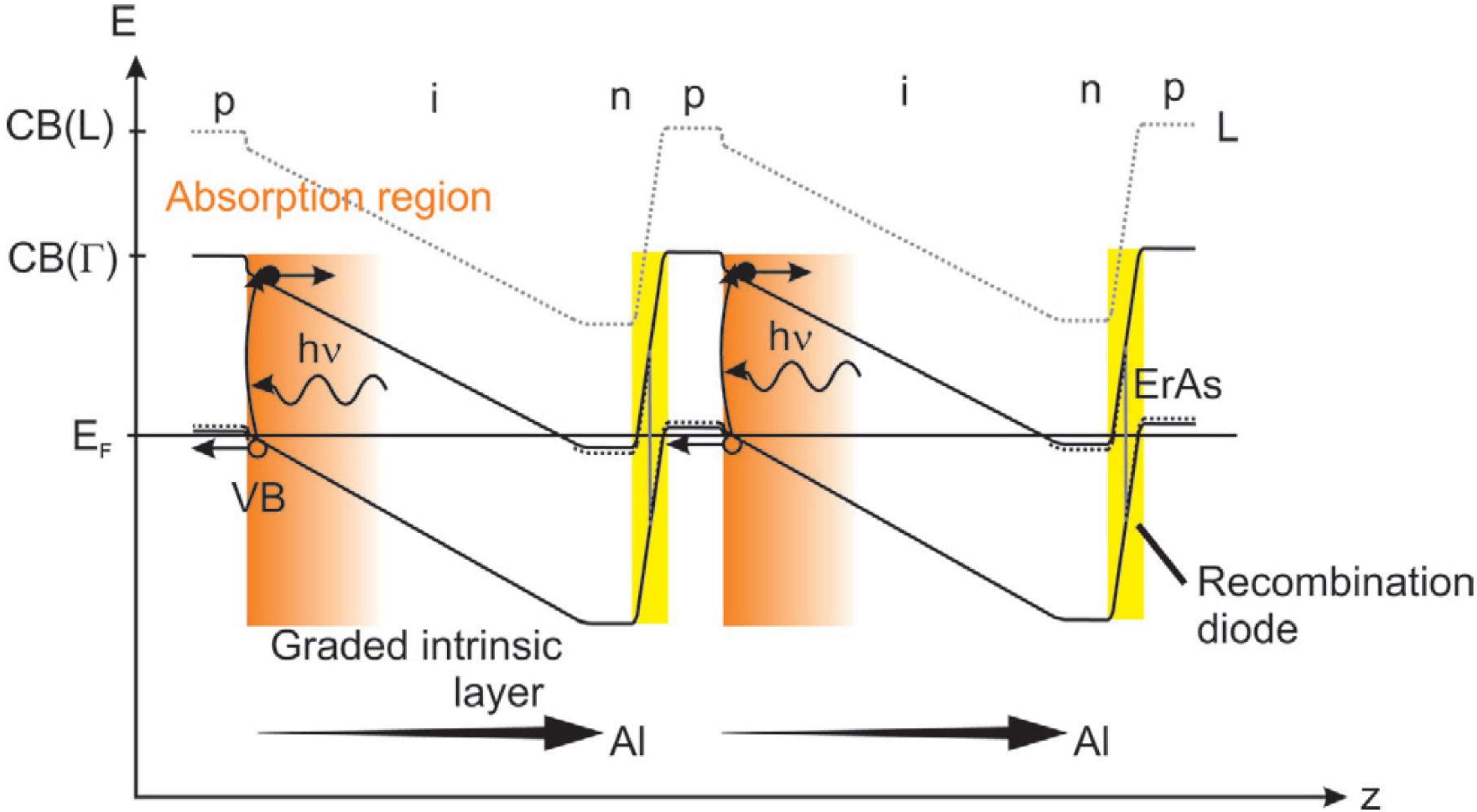
maximum is found at the Brewster angle ☺

At θ_{Br} the intensity increased by factor 4 due to constructive interference with totally reflected beam

29% of P^{LAQD} instead of naively expected 7.2 %!

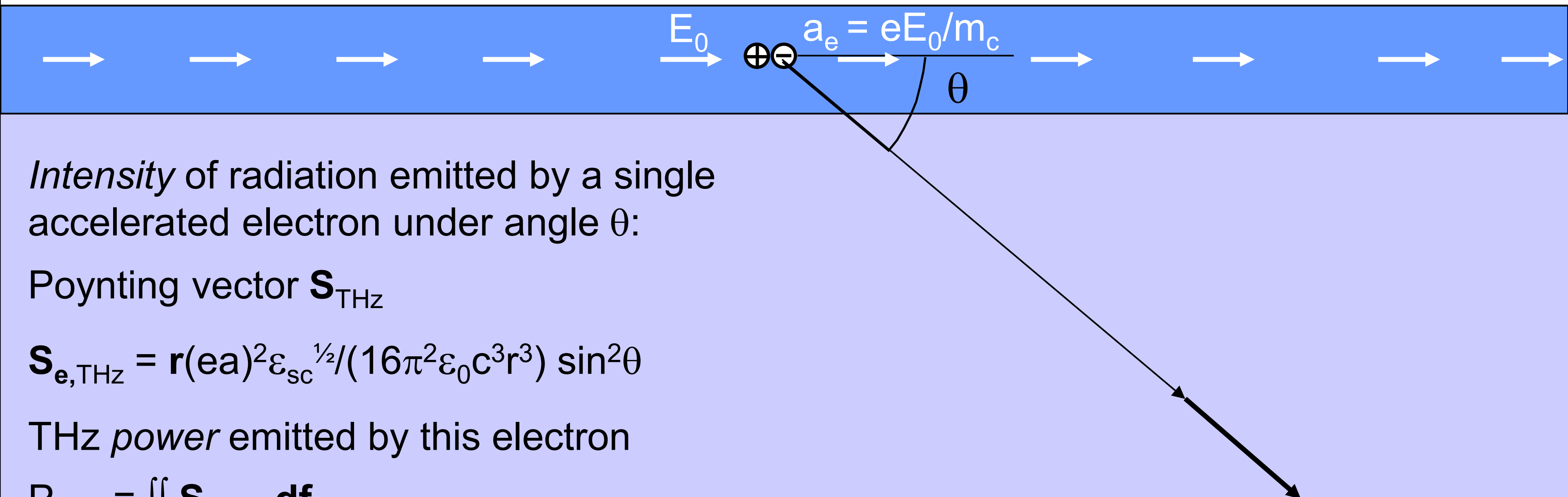
$\Rightarrow$ Ideal condition for operating LAE under Brewster angle excitation!

*L.E. García Muñoz (2012); W. Lukosz, J. Opt. Soc. Am. 67-69 (1977-79).



E
CB(L)
CB(Γ)
E_F
p
i
n
p
i
n
p
L
Absorption region
hν
hν
ErAs
VB
Recombination
diode
Graded intrinsic
layer
Al
Al
z

simplified picture of large area emitter (LAE) – in-plane field E_0



Intensity of radiation emitted by a single accelerated electron under angle θ:

Poynting vector $\mathbf{S}_{THz}$

$$\mathbf{S}_{\mathbf{e},THz} = \mathbf{r}(ea)^2\varepsilon_{sc}^{1/2}/(16\pi^2\varepsilon_0 c^3 r^3)\sin^2\theta$$

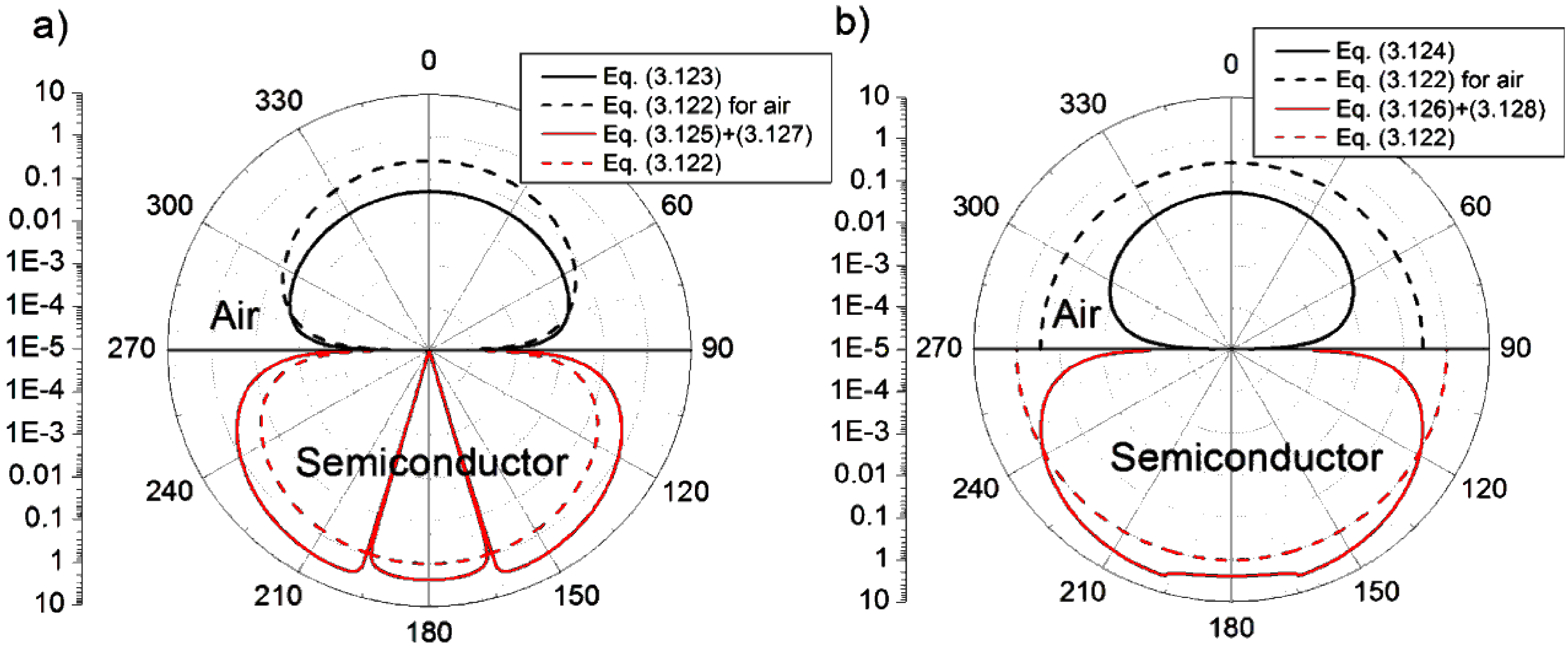
THz *power* emitted by this electron

$$P_{THz} = \iint_{sphere} \mathbf{S}_{e,THz}\mathbf{df}$$

$$P_{e,THz} = [\varepsilon_{sc}^{1/2}/(6\pi\varepsilon_0 c^3)]\,(ea_e)^2$$

Main probleme: the assumption of ballistic acceleration is not realistic for CW-mixing for in-plane E-field scenario
(long lifetimes!, space charge screening!)

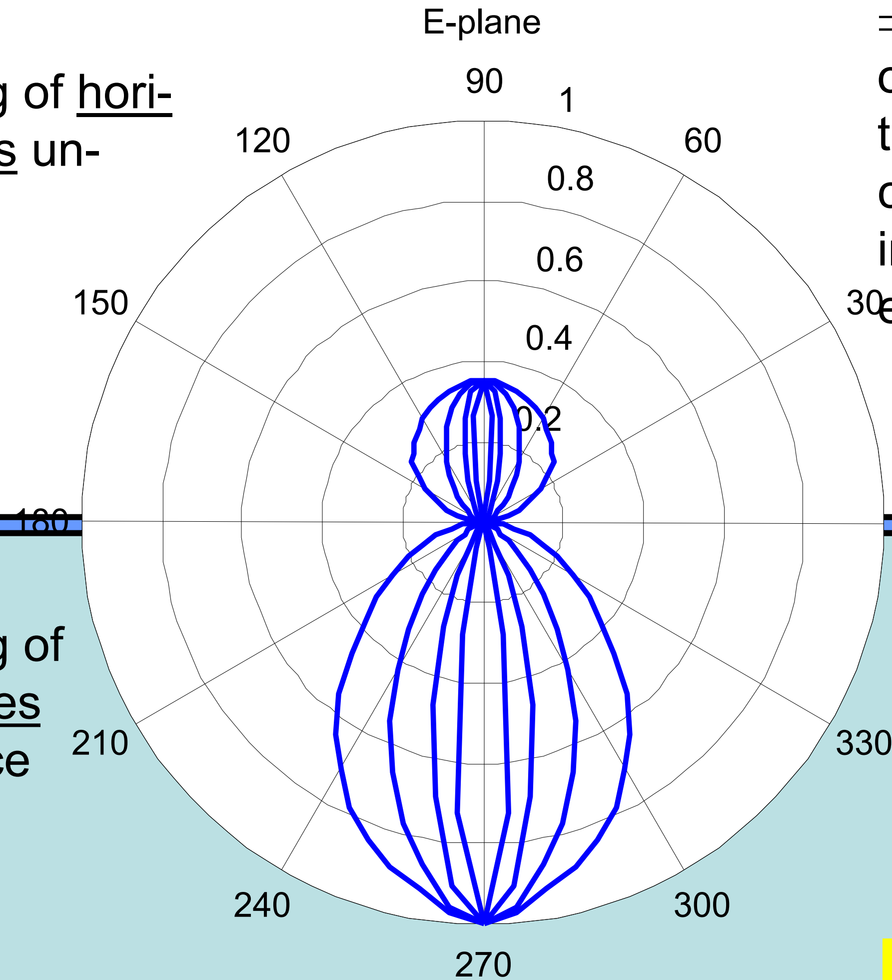
However: realsitic scenario for pulsed excitation in si – GaAs, e.g.



a)
b)
Eq. (3.123)
Eq. (3.122) for air
Eq. (3.125)+(3.127)
Eq. (3.122)
Eq. (3.124)
Eq. (3.122) for air
Eq. (3.126)+(3.128)
Eq. (3.122)
Air
Semiconductor
0
30
60
90
120
150
180
210
240
270
300
330
10
1
0.1
0.01
1E-3
1E-4
1E-5

emission pattern for Gaussian laser beam with $0.2\,\lambda \le \rho_0 \le 2\,\lambda$

radiation pattern for LAE emitter consisting of hori-zontal Hertzian dipoles under normal incidence of the laser light



⇒ maximum intensity of the „array factor“ of the LAE (z-direction) coincides with maximum intensity of the radiating element (z-direction)

☺

what happens for LAE emitter consisting of vertical Hertzian dipoles under normal incidence of the laser light

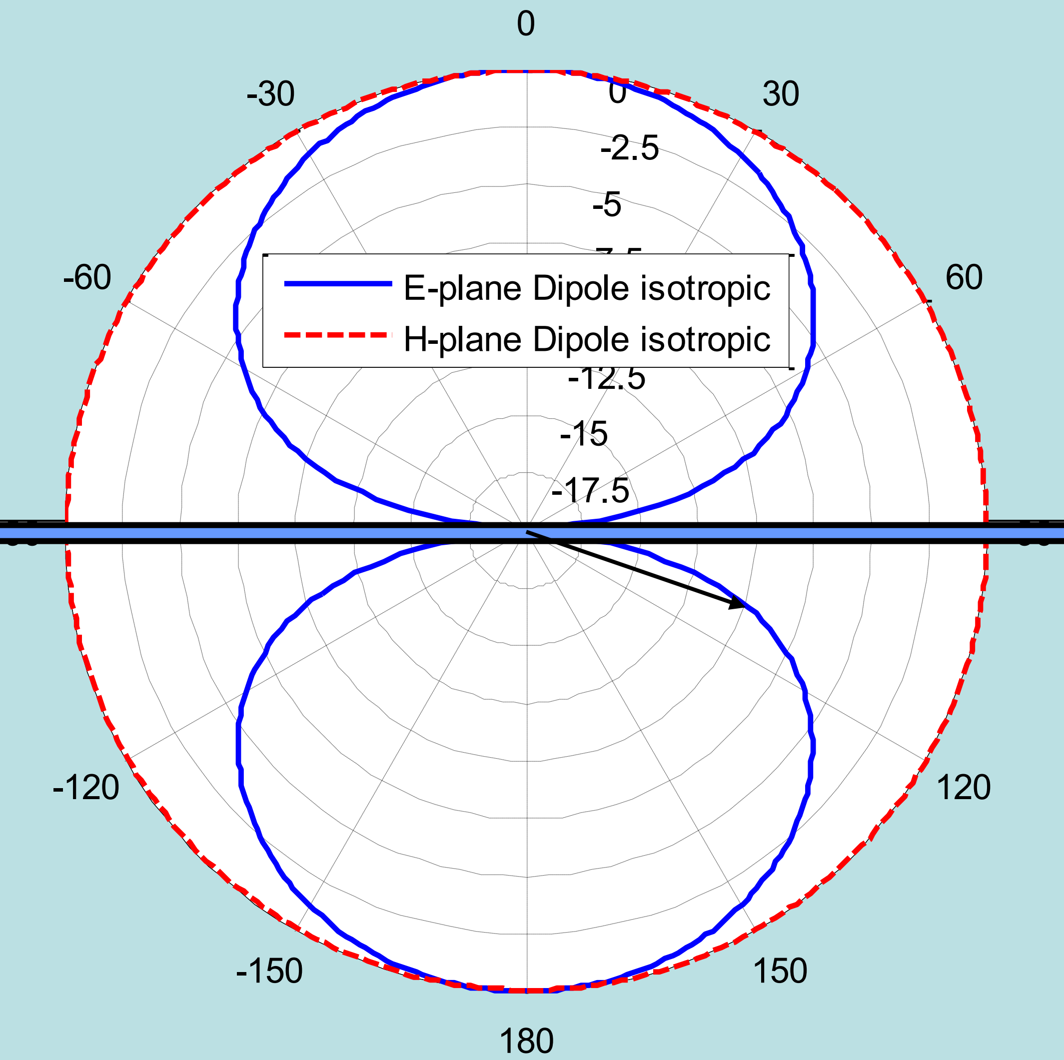
⇒ maximum intensity of the „array factor“ of the LAE (z-direction) coincides with zero of intensity of the radiating element (z-direction)

☹

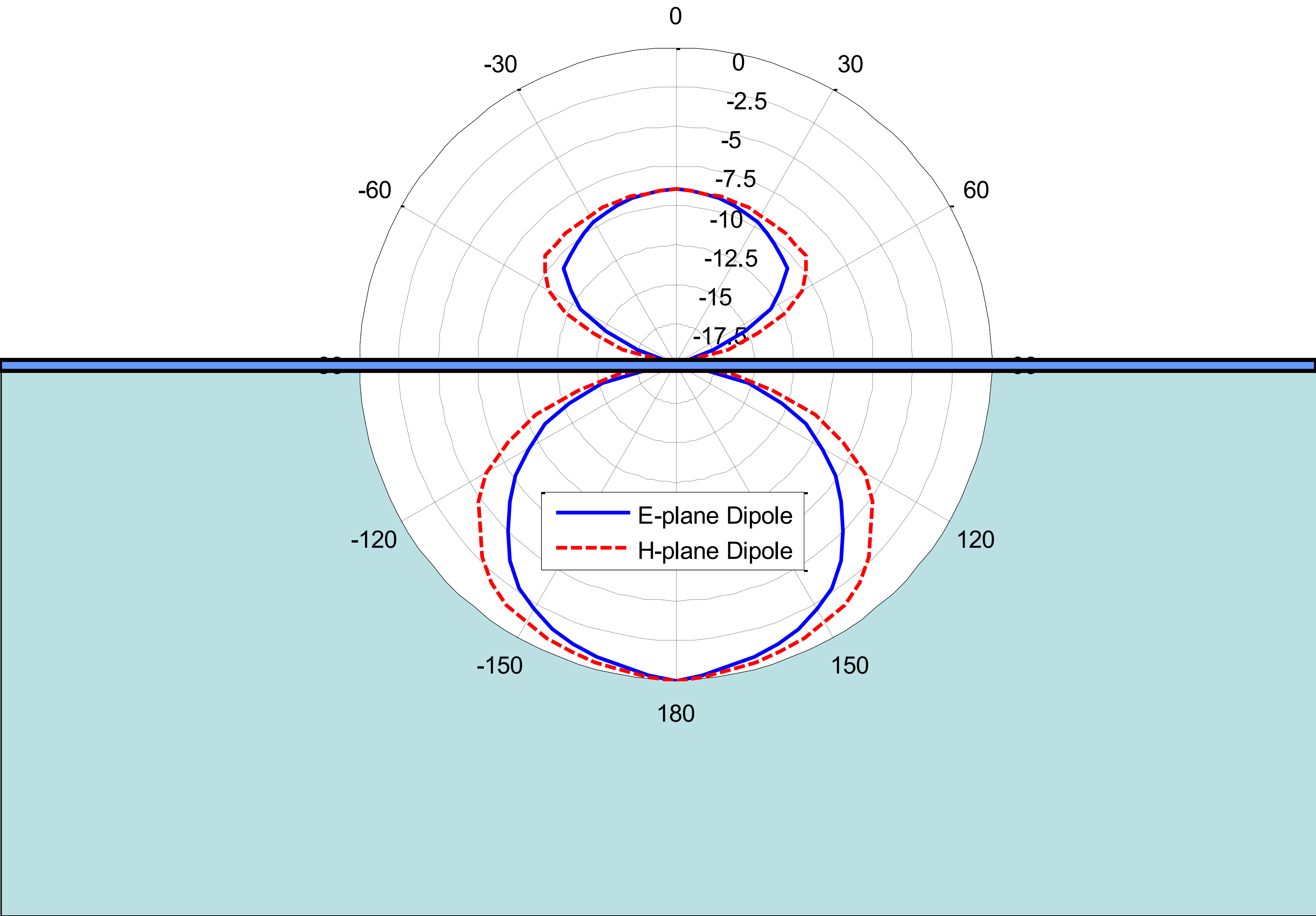
otherwise, vertical dipoles (E-field inz z-direction) appealing for several reasons:
High current-efficiency (p-i-n – oder n-i-pn-i-p – diodes), ballistic transport …)

Are vertical dipoles useful at all?

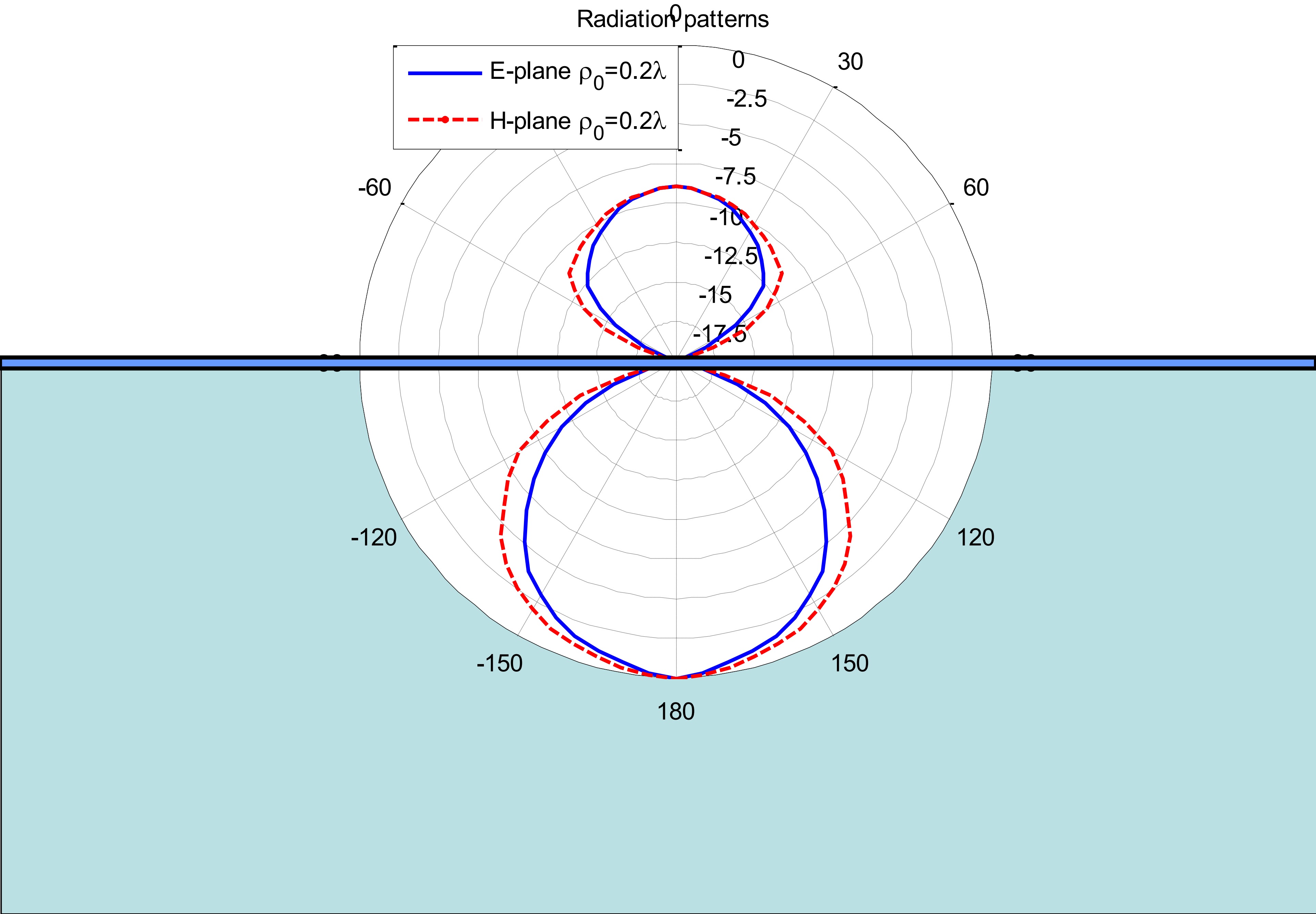
Emission pattern of Hertzian dipole embedded in GaAs



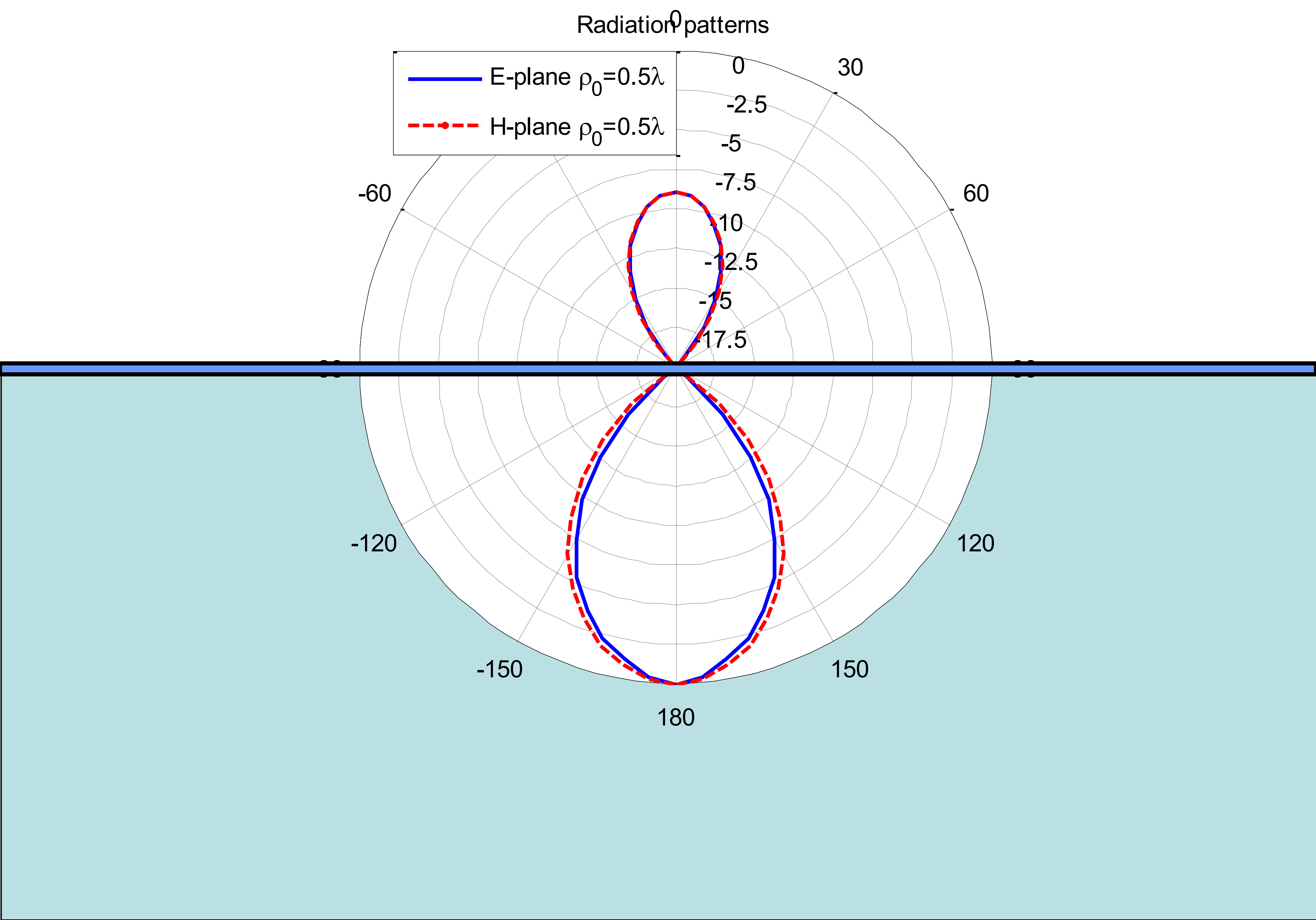
Emission pattern of Hertzian dipole at air/GaAs interface ($\rho_0 << \lambda$)



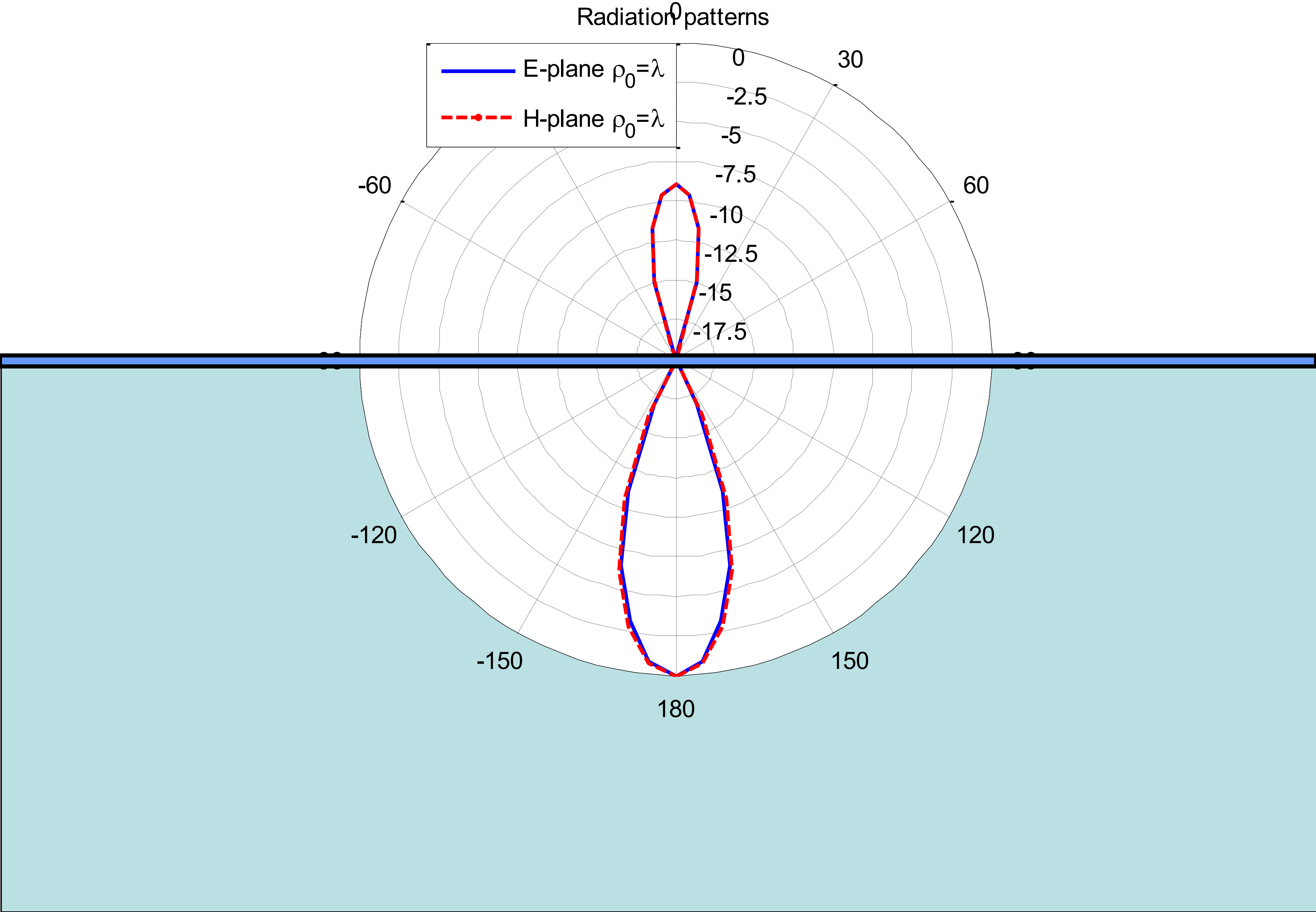
Emission pattern for Gaussian laser beam with ρ_0 = 0.2 λ



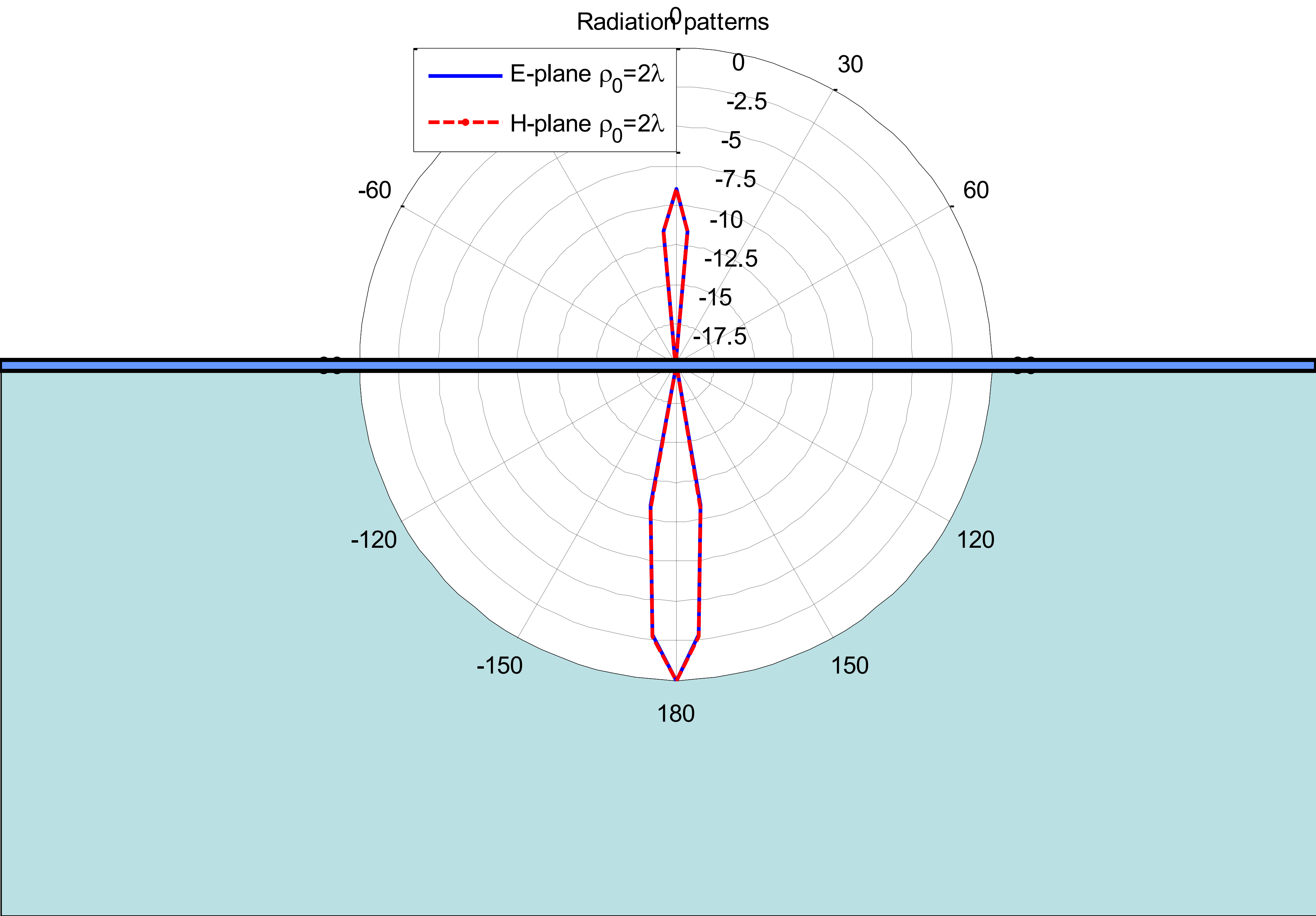
Emission pattern for Gaussian laser beam with $\rho_0 = 0.5\ \lambda$



Emission pattern for Gaussian laser beam with $\rho_0 = 1.0\ \lambda$



Emission pattern for Gaussian laser beam with $\rho_0 = 2.0\ \lambda$



LAQD, for photomixing, simplified(!)

THz power emitted by N coherently accelerated electrons generated at time t in a „large area quasi dipole“ (LAQD)

$P_{THz}^{LAQD}(t) = (1/6\pi)\,[(eNa)_t]^2 \varepsilon_{sc}^{1/2}/(\pi\varepsilon_0 c^3)$

$(eNa)_t$ = charge being ballistically accelerated at the time t $a = eE_0/m_c$

laser power $P_L(t) = P_{L,0}\,[1 + \cos\omega_{THz} t]$; $dN/dt = P_L(t)/h\nu_0$; $I_{ph,0}^{id} = (e/h\nu_0)\,P_{L,0}$

(… some calculation)…   (……nachrechnen!

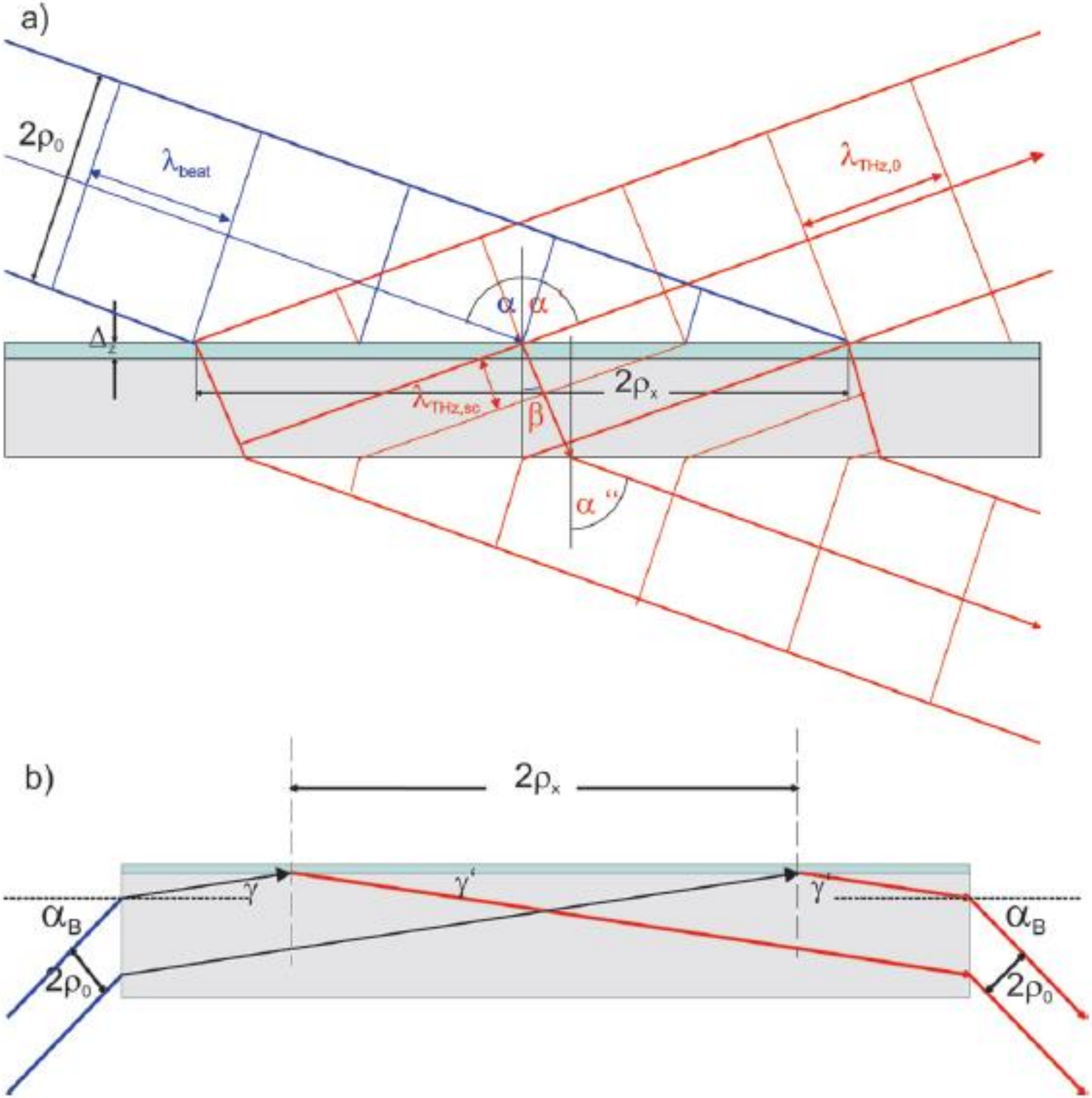
$P_{THz}^{LAQD} = ½\, R_{LAQD}\,(I_{ph,0}^{id})^2$,   with $I_{ph,0}^{id} = (e/h\nu_0)\,P_{L,0}$

with $R_{LAQD} = (2/3\pi)\,\varepsilon_{sc}^{1/2} Z_0 (v_{bal}/c)^2 \approx 6 \times 10^{-3}\,\Omega$; $v_{bal} = 2\times10^8$ cm/s in InGaAs, e.g.)

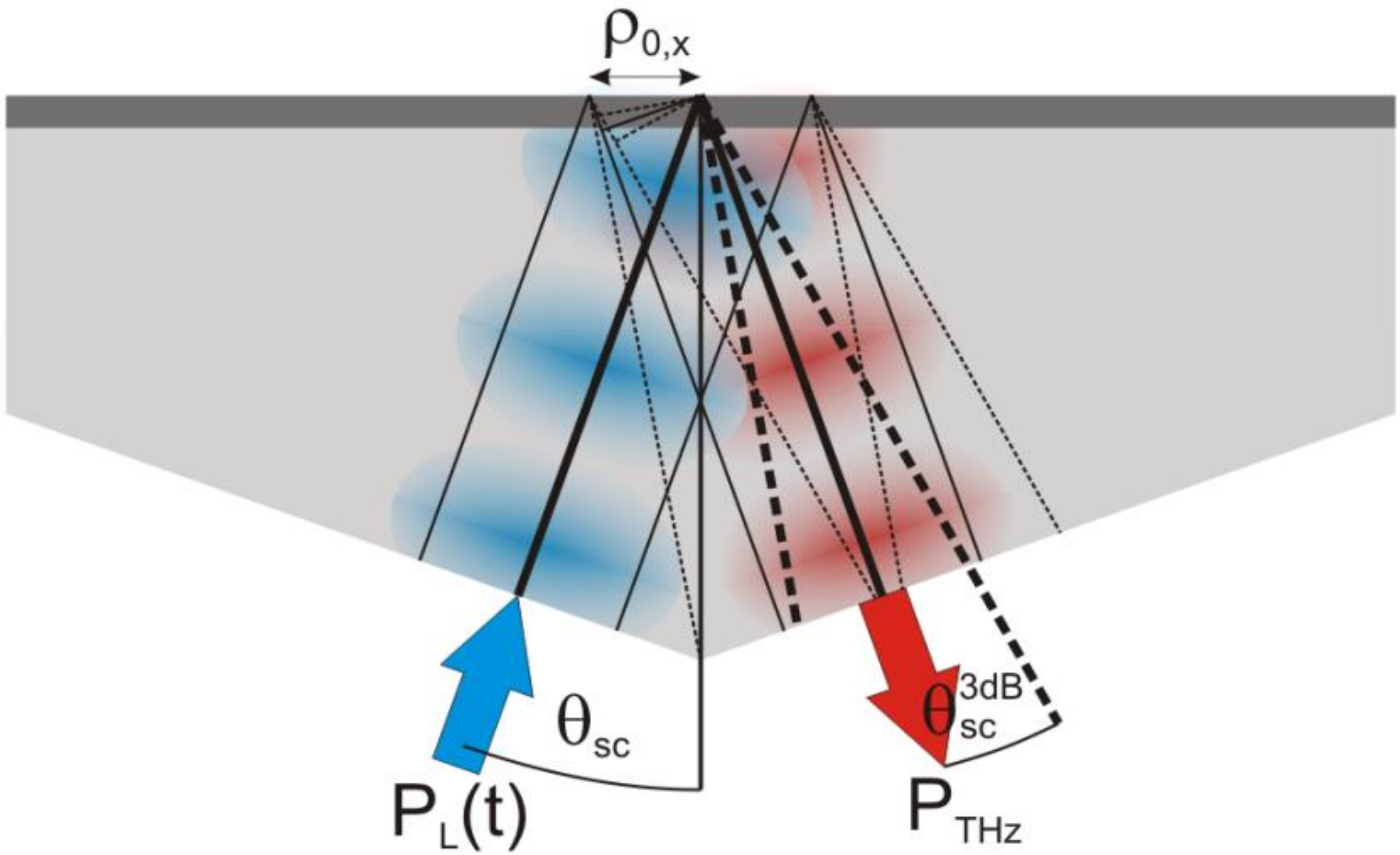
$Z_0 = (\varepsilon_0 c)^{-1} = 377\ \Omega$ = „radiation impedance of vacuum“

$$P_{THz}^{LAQD} = 6 \times 10^{-3}\Omega\,(I_{ph,0}^{id})^2$$

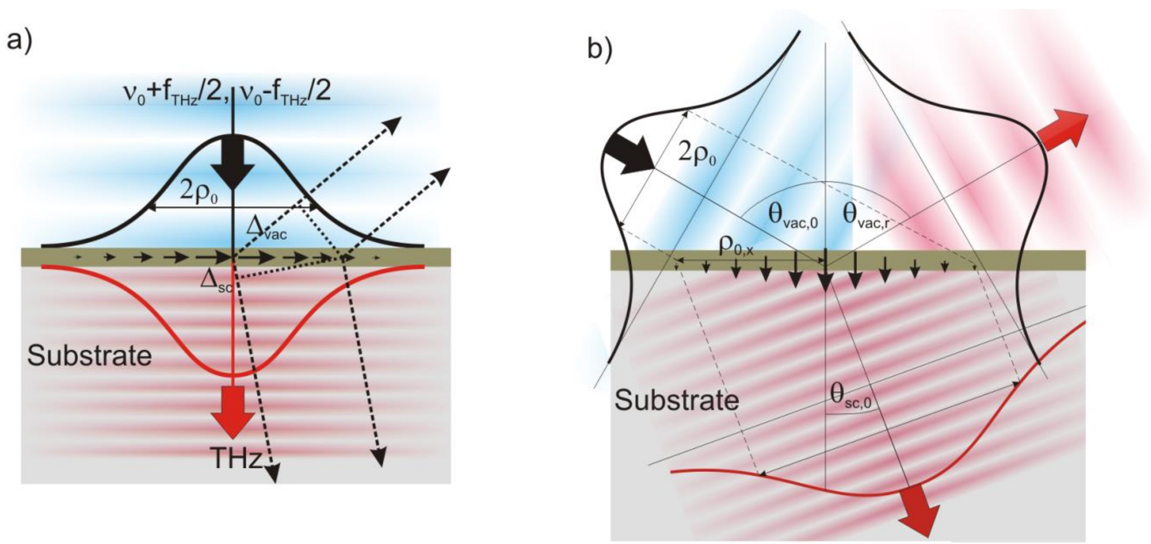
Wichtig: in n-periodischer nipnip-struktur : jedes Photoelektron trägt bei (Nicht wie im AE, wo n Photonen pro one-e – Beitrag zum Photostrom absorbiert werden müssen!)



a)
$2\rho_0$
λ_{beat}
$\lambda_{THz,0}$
α
α'
Δ_z
$\lambda_{THz,sc}$
$2\rho_x$
β
α''
b)
$2\rho_x$
γ
γ'
γ'
α_B
$2\rho_0$
α_B
$2\rho_0$



ρ0,x
θsc
θ3dB sc
PL(t)
PTHz


a)
ν0+fTHz/2, ν0-fTHz/2
2ρ0
Δvac
Δsc
Substrate
THz
b)
2ρ0
θvac,0
θvac,r
ρ0,x
Substrate
θsc,0

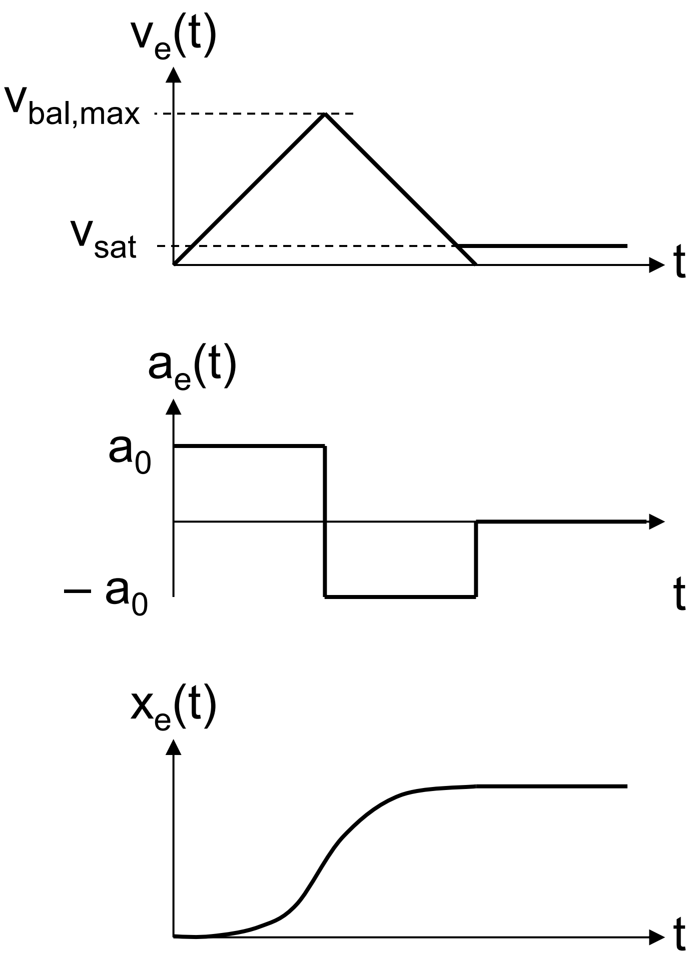
simplified picture of large area emitter (LAE)

Time dependence of $P_{THz}(t)$, $S_{THz}(t) \propto a^2(t)$ (?)

Wichtig: sin für eine Periode
Better: See JAP-rev, Eq.s 107-114

$a_0 = eE_0/m_c$

in (most) III-V sc.s for $E_0 > 5$ kV/cm
"velocity overshoot":



$v_{bal,max} = a_0 T_{THz}/2 \Rightarrow = eE_0 T_{THz}/2m_c$

$\Rightarrow \nu_{THz} = eE_0/(2m_c v_{bal,max})$

≈ 1 THz, for E_0 =10kV/cm in InGaAs

$x(t) = eE_0/4\nu_{THz}m_c[t - \omega_{THz}{}^{-1}\sin\omega_{THz}t]$

≈ 1 THz, for E_0 =10kV/cm in InGaAs

$x(t) = ½\, v_{bal,max}\, t - ½\, v_{bal,max}\omega_{THz}{}^{-1}\sin\omega_{THz}t]$

$x_0 = ½\, v_{bal,max}/\omega_{THz}$

≈ 160 nm @ 1 THz in InGaAs

$v(t) = ½\, v_{bal,max}[1 - \cos\omega_{THz}t]$

$v_0 = ½\, v_{bal,max} \approx 10^8$cm/s in InGaAs

$a(t) = (d/dt)v(t) = -\, ½\, \omega_{THz} v_{bal,max} \sin\omega_{THz}t]$

$a_0 = \omega_{THz} v_0 = \omega_{THz}{}^2 x_0$

$= \omega_{THz} v_{bal,max}/2 = \pi\, 10^{20}$cms^{-2} @ 1THz in InGaAs

Classical electrodynamics approach

Excitation of charge carriers by lasers

either: pulse excitation with fs laser pulses (ν_0) $\Rightarrow P_L(t')$

$\Rightarrow$ transient current pulse (ps time scale) $\Rightarrow I_{ph}(t,) = \int r(t-t')P(t')dt'$ (?)

$\Rightarrow$ single cycle broad-band THz pulses $\Rightarrow P_{THz}(\omega_{THz}) = f(r(t))$ (?)

or: „photomixing“

two CW lasers ($\nu = \nu_0 \pm ½\, \nu_{THz}$) $\Rightarrow P_L(t) = P_{L,0}\,[1+\cos(2\pi\nu_{THz}t]$

$\Rightarrow$ carrier generation rate modulated with ν_{THz} $\Rightarrow dN/dt = \eta_{ph}(P_L(t)/h\nu_0)$

$\Rightarrow$ photocurrent modulated with ν_{THz} $\Rightarrow I_{THz}(t) = g\eta(\nu_{THz})\eta_{ph}e(P_{L,}(t)/h\nu_0)$

$\Rightarrow$ narrow-band CW THz emission, $\Rightarrow P_{THz}(t) \propto \eta_{geo} I_{THz}{}^2(t) \propto P_{L,0}{}^2$

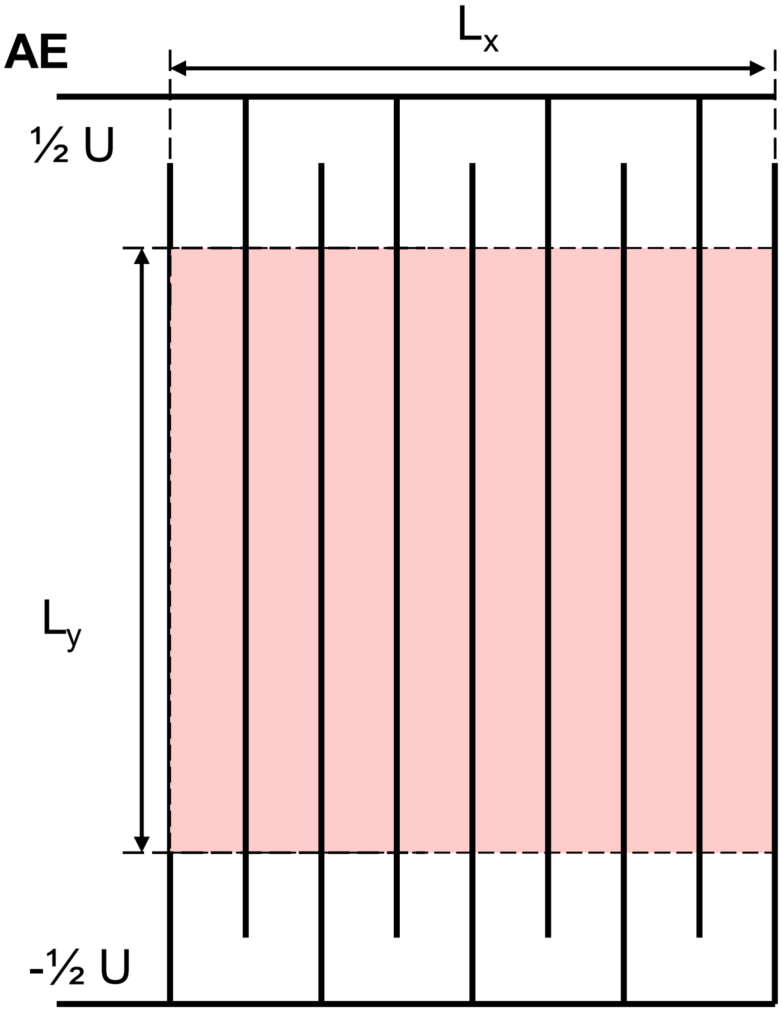
$\Rightarrow$ easily tunable, if lasers tunable

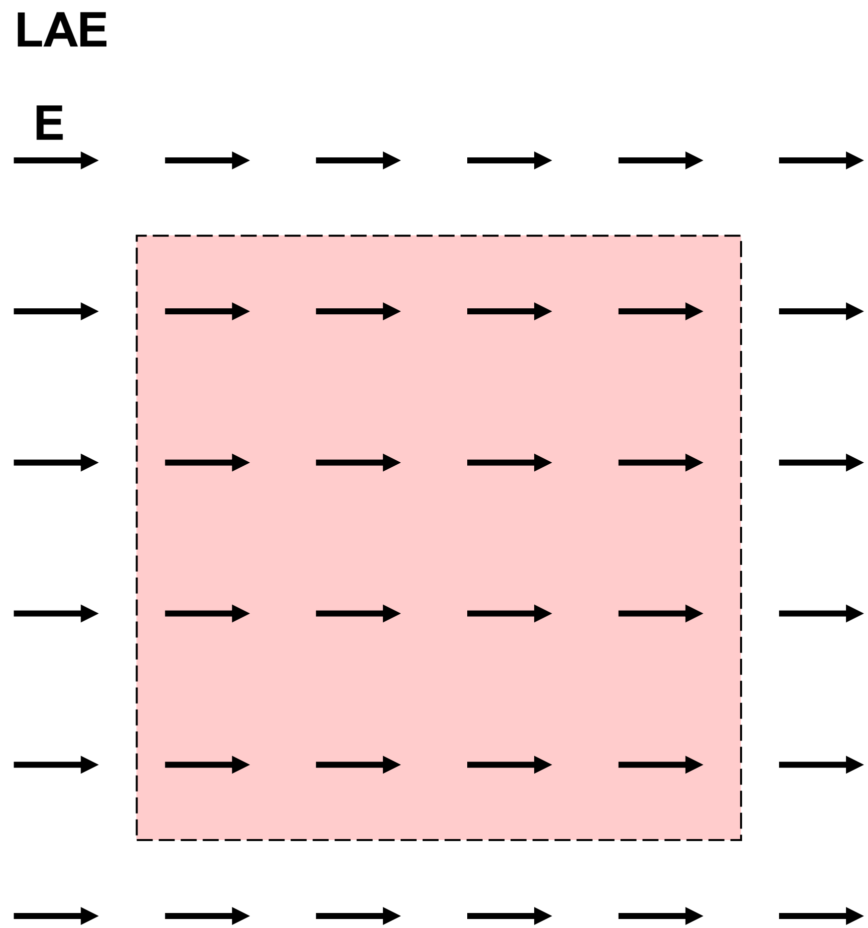
emitters exhibit strong frequency dependence of emitted power, radiation …

$\Rightarrow$ discussion simpler for (narrow band) photomixers than for pulsed sources

$\Rightarrow$ most of our discussions for CW photomixers

comparison AE vs. LAE (for photomixing, simplified)





$E = U/d$ $\quad dN/dt = P_L/h\nu_0$ $\quad N = (dN/dt)\tau_{rec}$

$n = N/(L_xL_y)$ $\quad j = en\mu E$ $\quad I = j\, L_y\,(L_x/d) = g\, I_{ph}^{id}$

$I_{ph}^{id} = (eP_L/h\nu_0)$

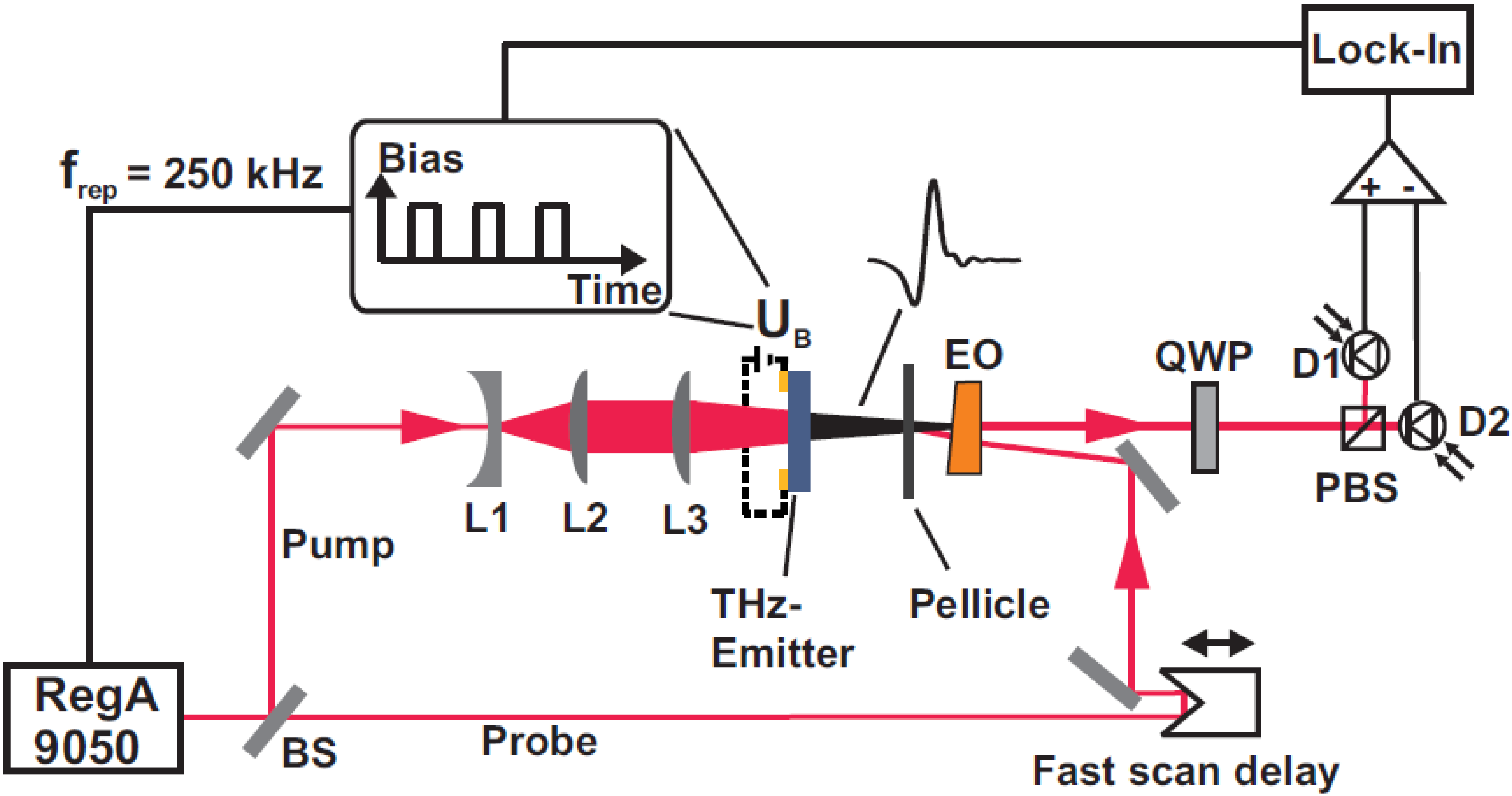
$j = env;\ v = \mu E$ $\quad \iint j dxdy = eNv$

$(d/dt)\iint j dxdy = e(d(dt)(Nv) = eA$

$A = (d(dt)(Nv)$

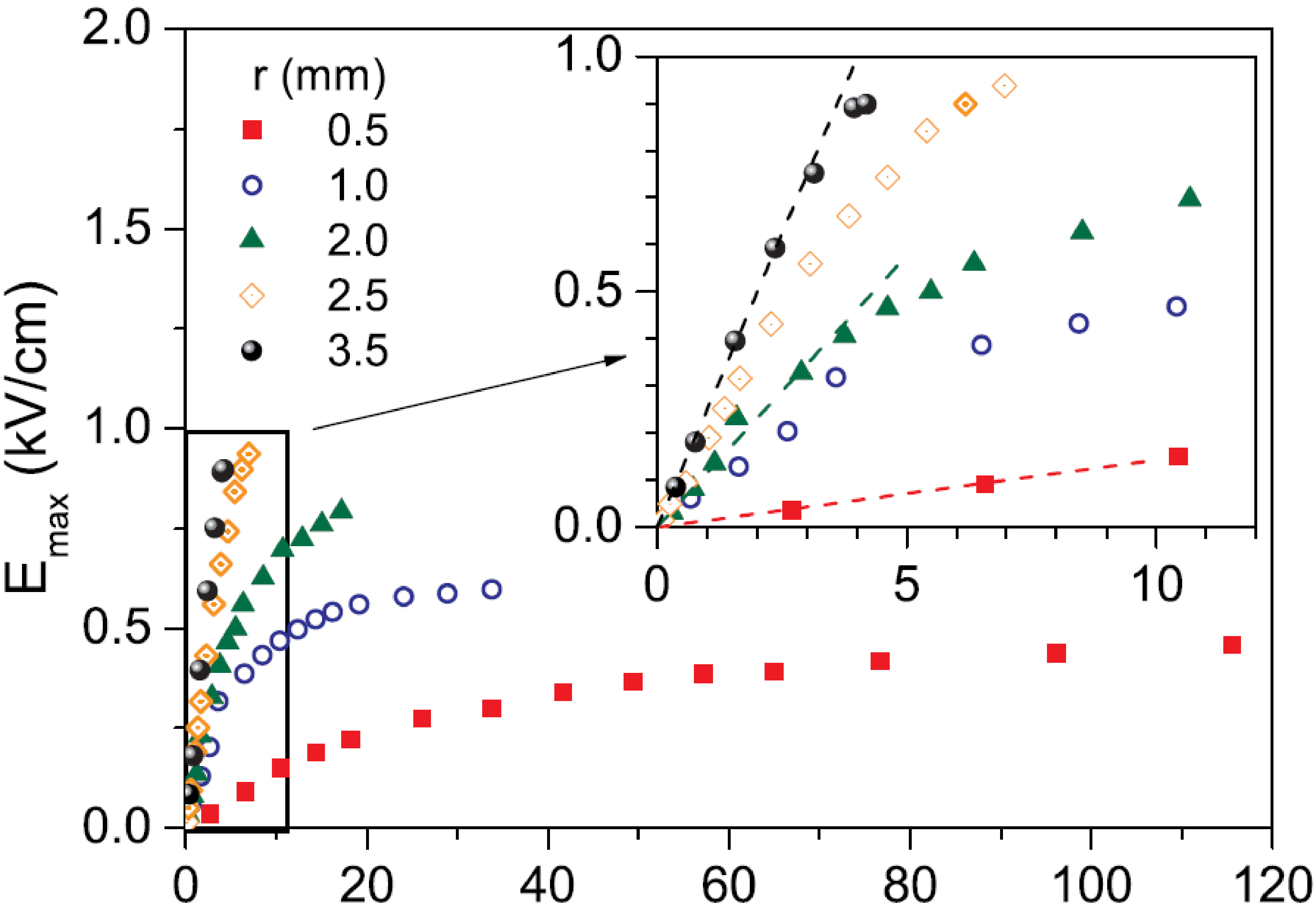
„photocond. gain“ $g = (\tau_{rec}/\tau_{tr}) = \tau_{rec}(\mu eU/d^2) \approx 10^{-2}$, e.g. $\quad A$ = „makroscopic pseudo accel.“

Large area THz emitters

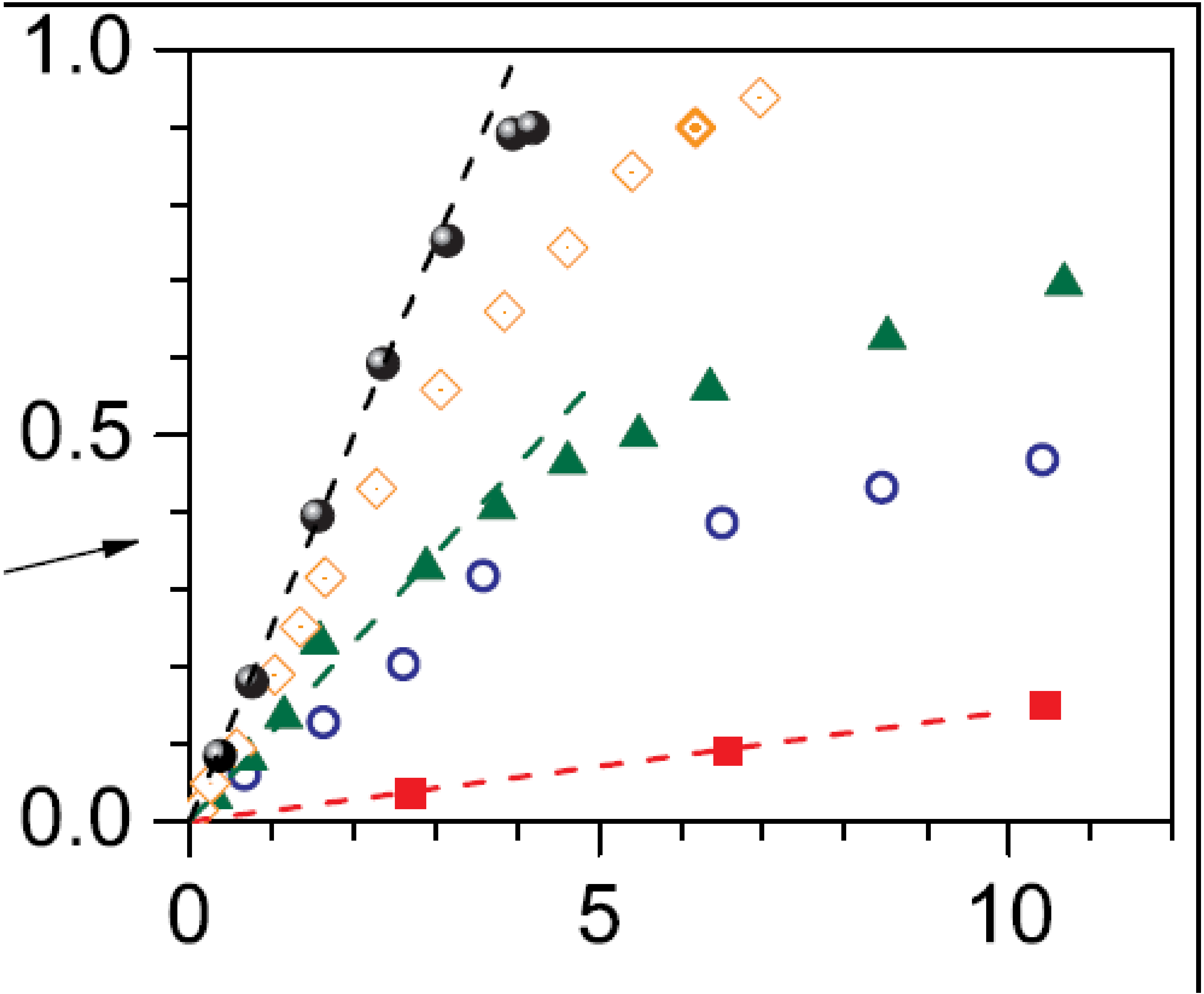


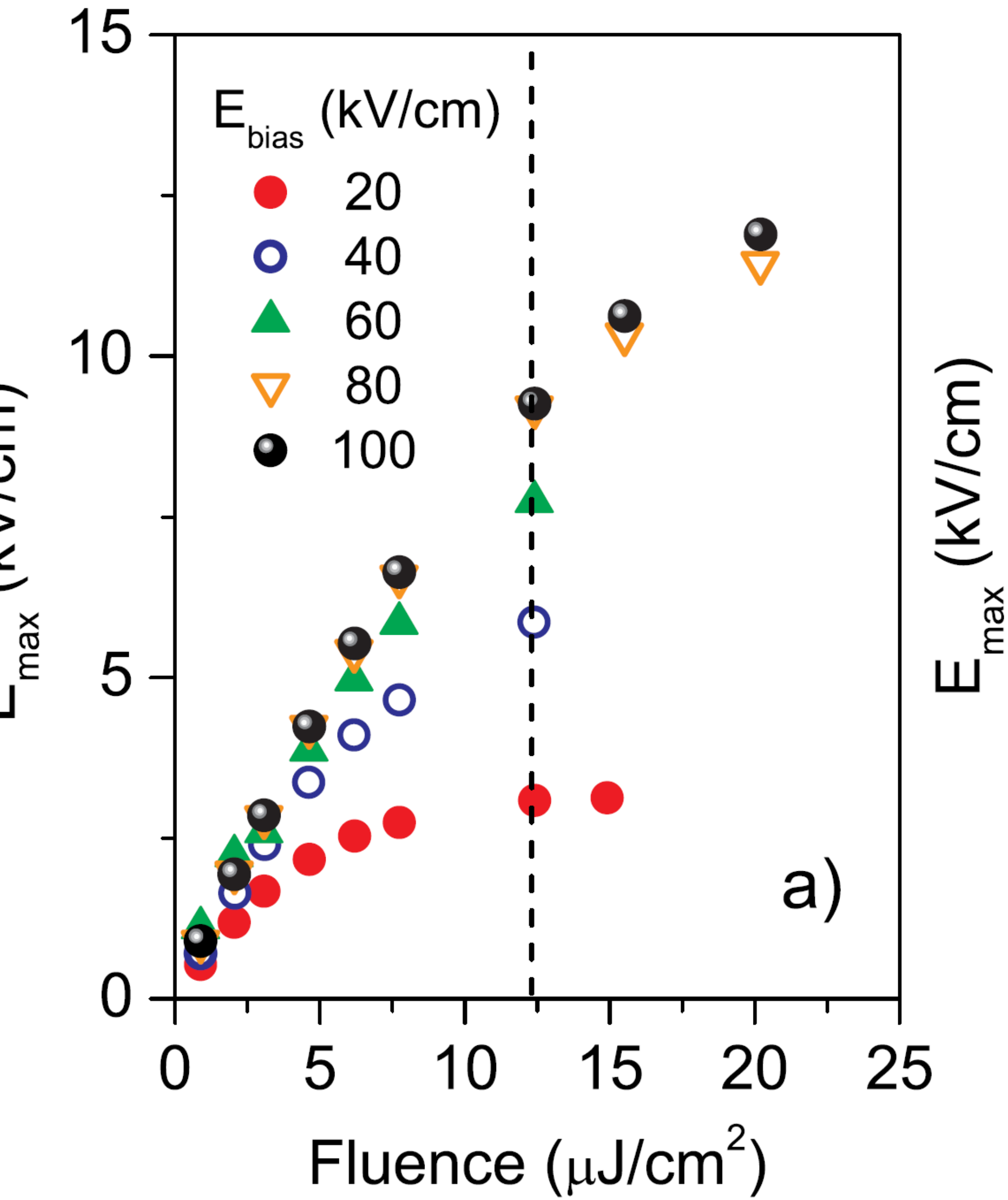
M. Beck, H. Schäfer, G. Klatt, J. Demsar, S. Winnerl, M. Helm and T. Dekorsy, OPTICS EXPRESS 18, 9251 (2010)

Large area THz emitters

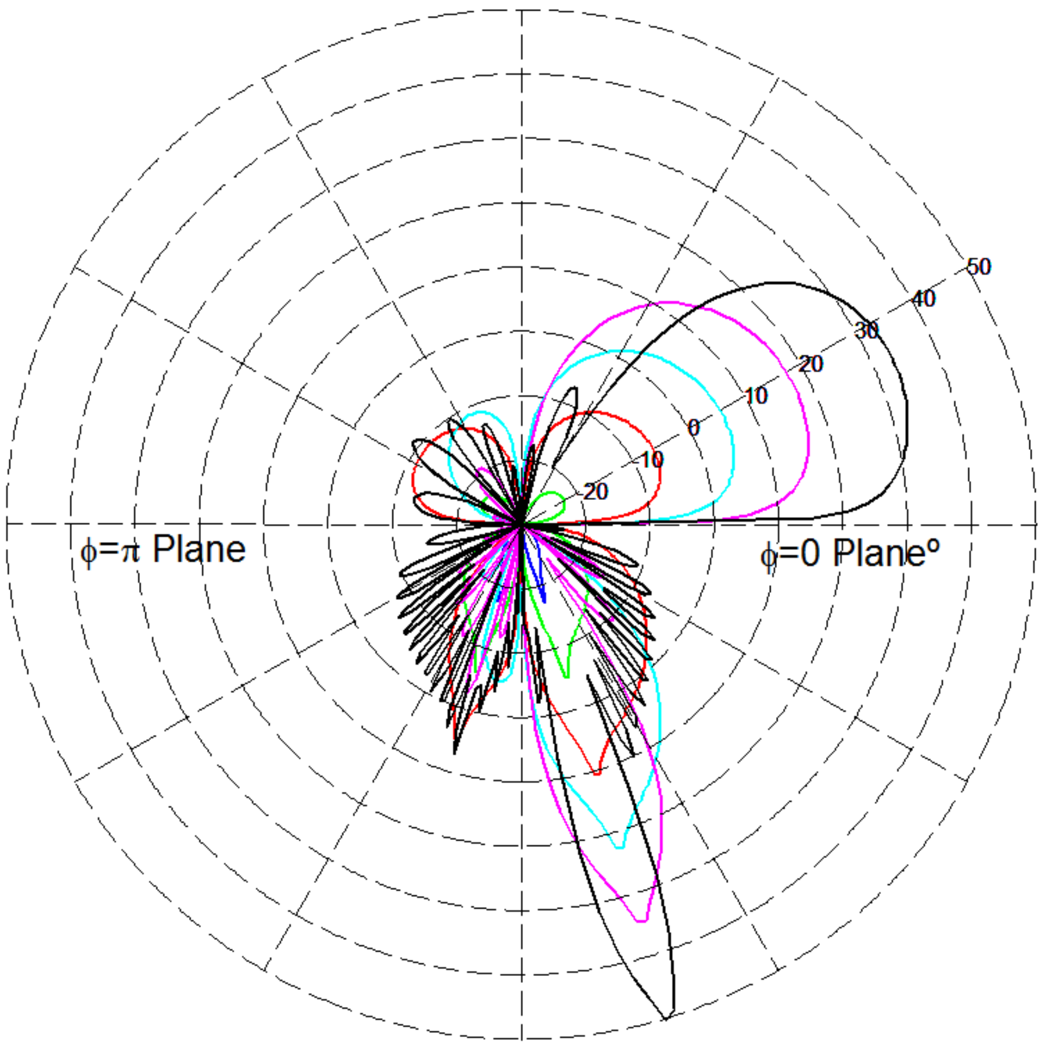


Large area THz emitters





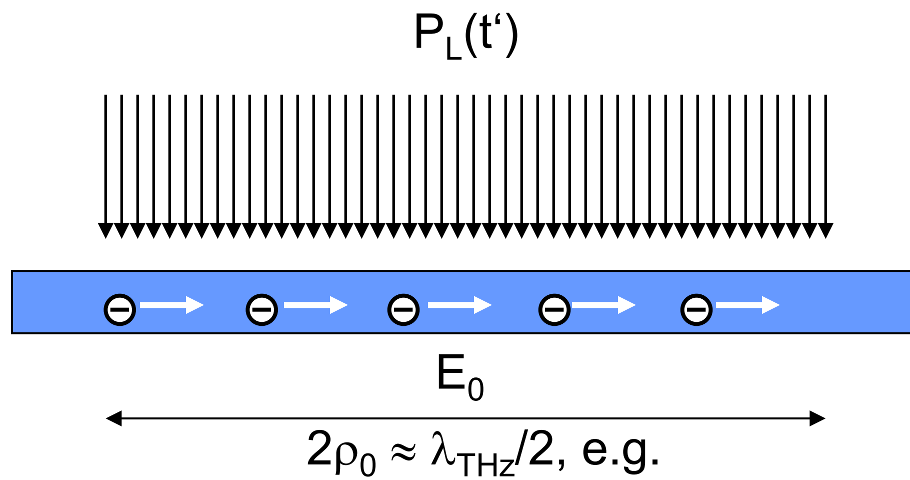
15
10
5
0
E_{bias} (kV/cm)
20
40
60
80
100
a)
0
5
10
15
20
25
Fluence (μJ/cm^2)
E_{max} (kV/cm)



Legend	ρ_0	$a=\rho_0/10$
Blue	$0.1\lambda_{sc}$	$0.01\lambda_{sc}$
Green	$0.2\lambda_{sc}$	$0.02\lambda_{sc}$
Red	$0.5\lambda_{sc}$	$0.05\lambda_{sc}$
Cyan	$1\lambda_{sc}$	$0.1\lambda_{sc}$
Magenta	$2\lambda_{sc}$	$0.2\lambda_{sc}$
Black	$5\lambda_{sc}$	$0.5\lambda_{sc}$

alternative principle of CW-THz generation: photomixing without antenna?

THz radiation emitted directly by the laser induced-carriers, due to the acceleration by the DC electric field E_0 in the sc



$\Rightarrow$ topic of this talk:
large area emitter (LAE)