Compact room temperature operating terahertz transcievers

Optical Communications Technical Group Webinar

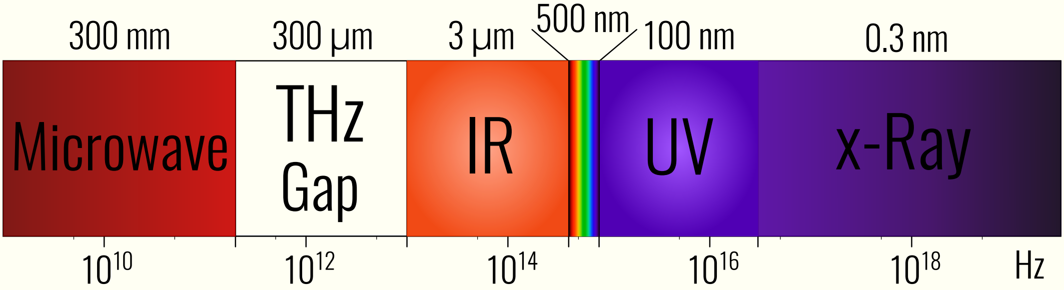
Andrei Gorodetsky, Dr. Sc.
a.gorodetsky@bham.ac.uk

January 19, 2022

Outline

- What is THz radiation
- Features of THz radiation
- Applications of THz radiation
- What we are looking for
- Existing THz sources
- How to make these sources better
- What's next

Terahertz radiation

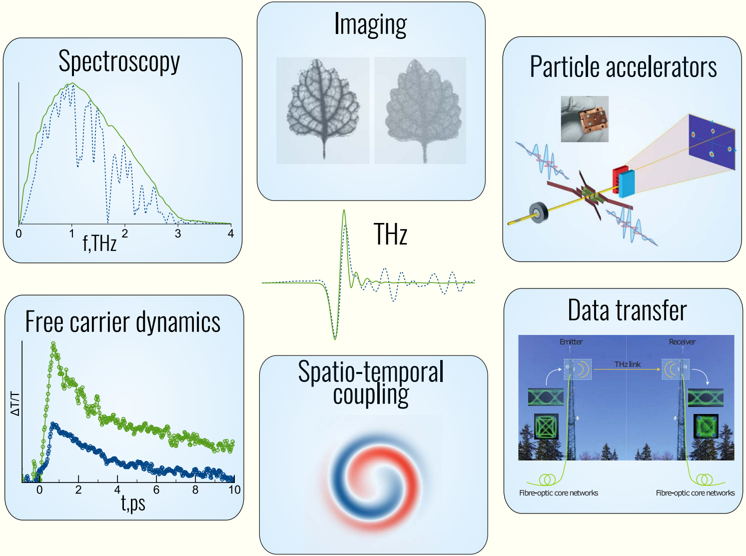


0.1–10 THz ~ 0.1-110 ps ~ 30-3000 μm ~ 3.33-333 cm^{-1} ~ 0.4-40 meV

THz features

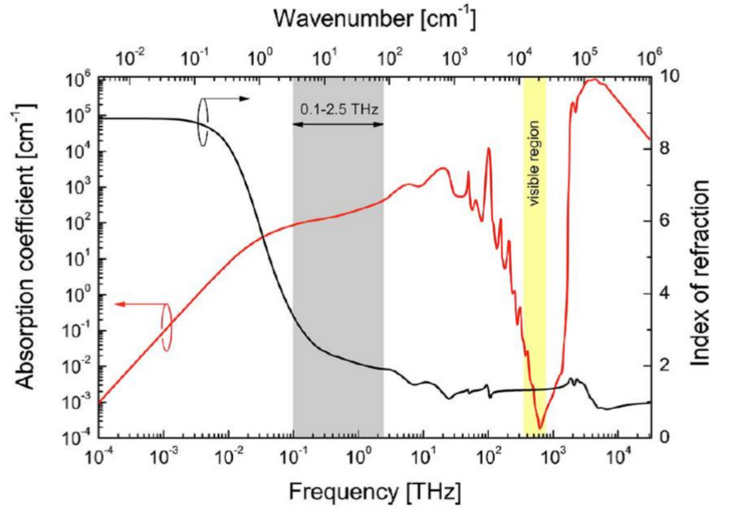
- Non-ionising
- Plastic/wood/clothes/skin etc are transparent for THz radiation
- Wavelength is small (compared to microwave)
- Ultrafast
- Spectral resolution

THz applications



W. L. Chan, et al, Reports Prog. Phys. 70, 1325 (2007), T. Nagatsuma et al, Nat. Photonics 10, 371 (2016),
D. Zhang et al, Nat. Photonics 12, 336 (2018), M. Kulya et al, Appl. Opt. 58, A90 (2019).

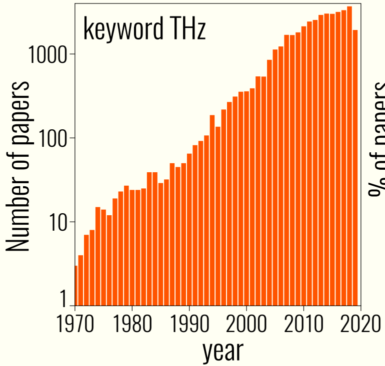
Atmospheric THz transmission

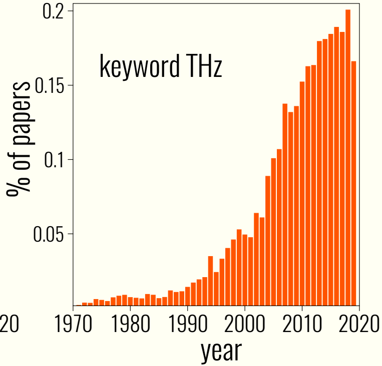


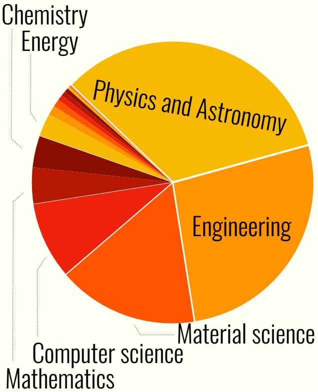
Broadband spectroscopy of bulk water, U. Moller, et. al., JOSA B, 26 (9) A113 (2009)

Terahertz radiation

Interest towards THz







History

Short Electromagnetic Waves of Wave-length up to 82 Microns.

Up to the present date, short electromagnetic waves have been generated only by the method of the Hertz vibrator. This method offers very serious difficulties when we try to produce electromagnetic waves of the smallest possible length, as the vibrator burns out very soon, so that the amount of the energy and the length of the waves produced do not remain constant, and also as the length of the waves decreases slowly, if the dimensions of the vibrator are diminished, when we approach the region of the very shortest waves. The experiments of many investigators who have tried to fill the interval between the short electromagnetic waves of Lebedew and the long heat-

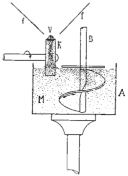


Fig. 1.—Paste radiator.

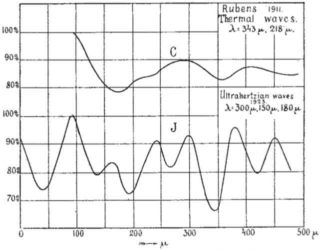
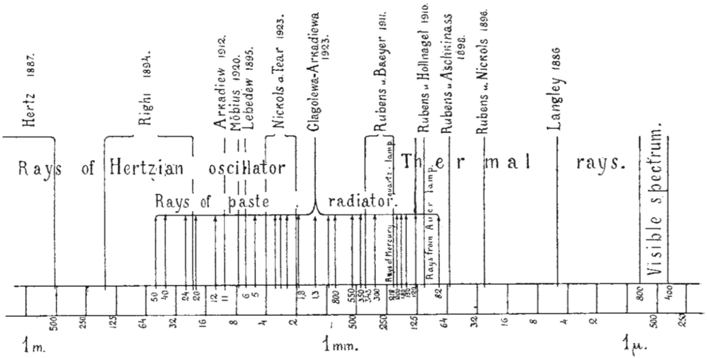
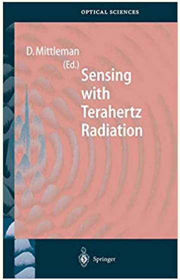


Fig. 2.—Interference curves: C, Rubens and Baeyer heat-waves; T, electromagnetic waves, obtained by the author.

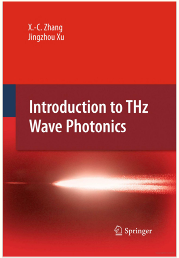


A. Glagolewa-Arkadiewa, Nature 113, 640 (1924).

Books on THz

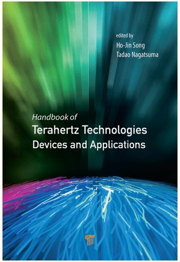


D. Mittleman, 2003

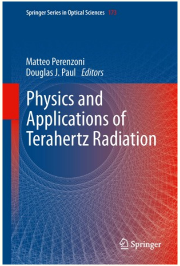


X.-C. Zhang, 2010

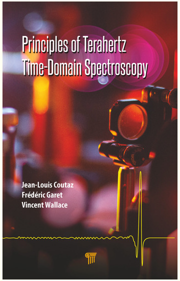
D. Saeedkia 2013



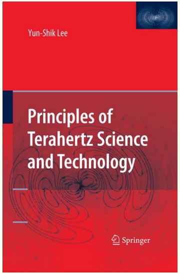
T. Nagatsuma 2015



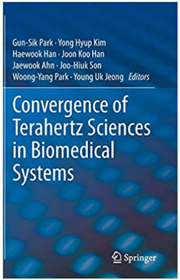
M. Perenzoni, 2014



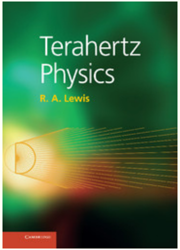
J. L. Coutaz, 2019



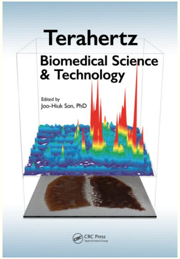
Y.S. Lee, 2009



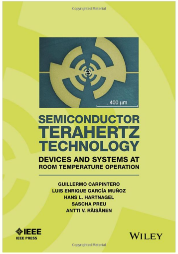
S.G. Park, 2012



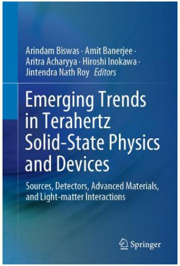
R.A. Lewis, 2013



J.H. Son, 2020



G. Carpintero, 2015



A. Banerjee, 2020

What is sought after (at least within this talk)

THz sources that are:

- Compact ($\sim$ handheld)
- Efficient ($\sim$ mW of power)
- Room temperature operating (to allow handheldness)
- (Ideally) integrated

Terahertz sources

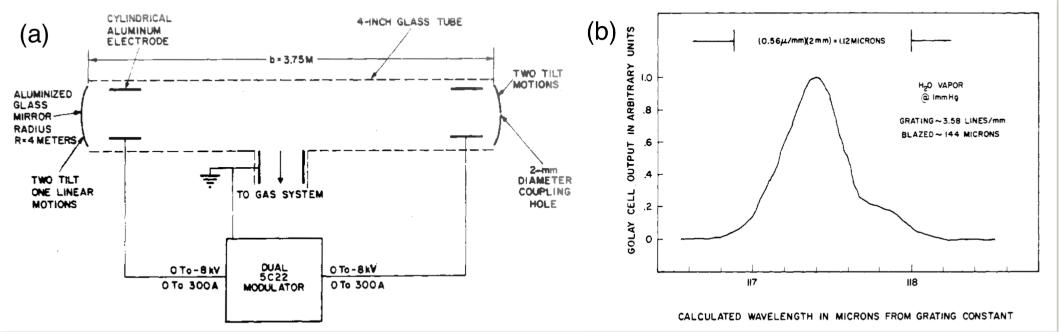
Direct THz sources

- CO_2 laser pumped gas lasers
- Free electron lasers
- Quantum cascade lasers

Conversion THz sources

- Photoconductive antennas
- Unbiased photoconductors
- Nonlinear crystals
- Electronic sources
- Laser filaments
- Nonlinear mixing of IR QCLs
- Spintronic emitters

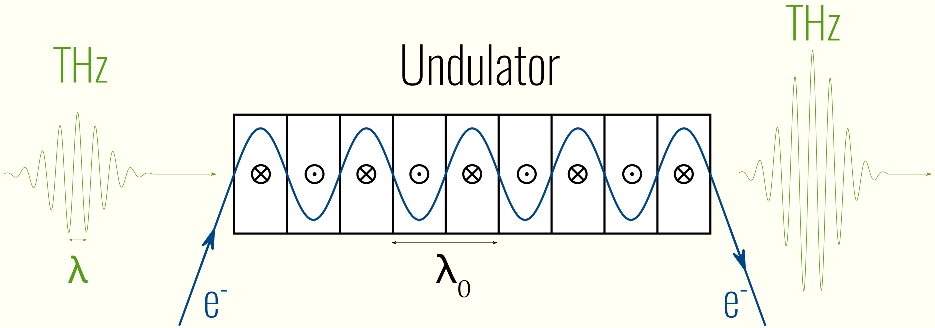
CO_2 laser pumped gas lasers



- hydrogen cyanide
- water vapour
- several meters long

D. Akitt et al Proc. IEEE 54, 4. p 547– 551 (1966)

Free electron lasers

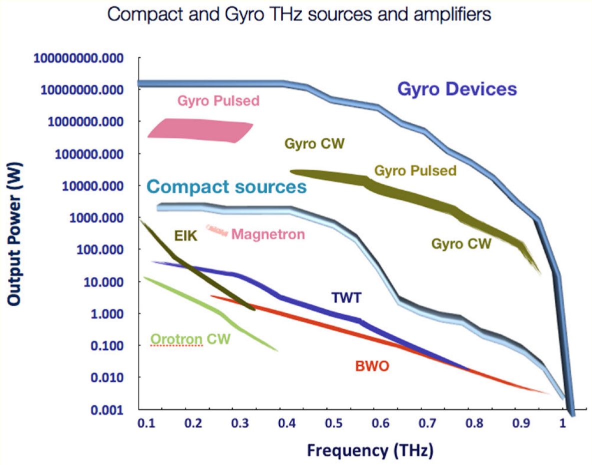


$\lambda = \frac{\lambda_0 \left(K^2+1\right)}{2\gamma^2}$, $E = (\gamma - 1)mc^2$ – beam energy, $K = \frac{eB\lambda_0}{2\pi mc^2}$ – coupling parametre.

- 17 THz FELs in 2017
- takes a building

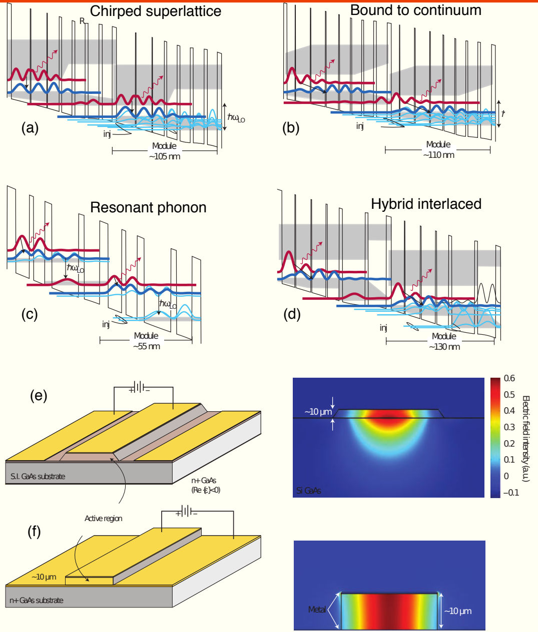
P. J. Neyman et al, Proc. of International Free Electron Laser Conference (FEL'17)

Electronic sources



- low frequency
- most still bulky

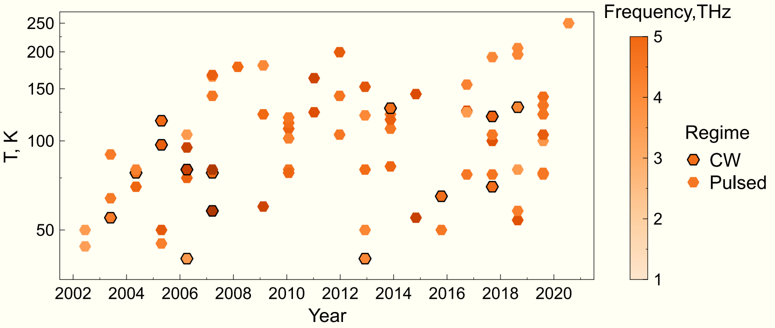
Quantum cascade lasers

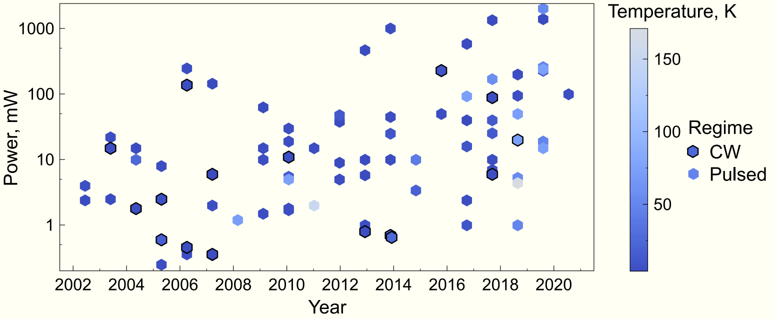


- Requires cooling
- Hard to get <2 THz

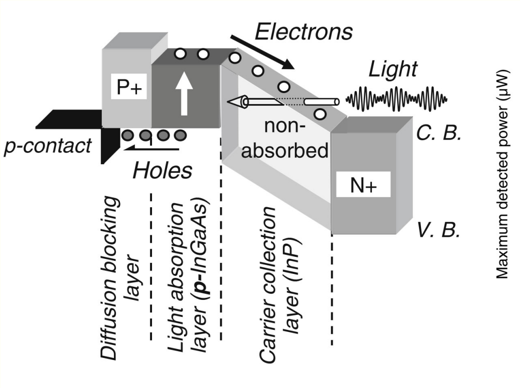
B. S. Williams Nat. Photonics, 1 (9) pp.517–525 (2007)

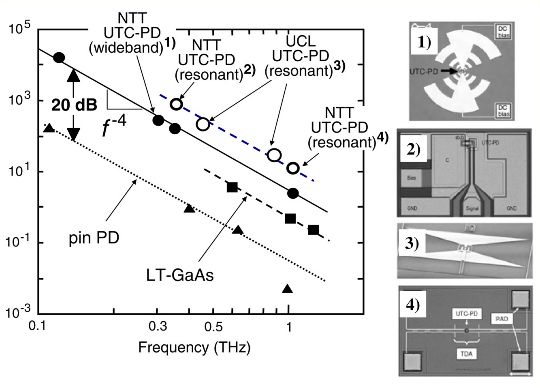
Quantum cascade lasers





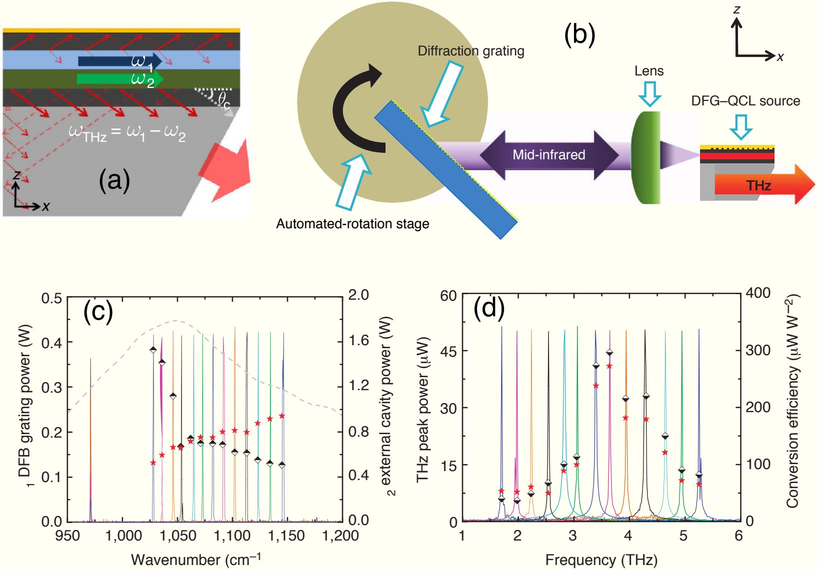
CW diode generation





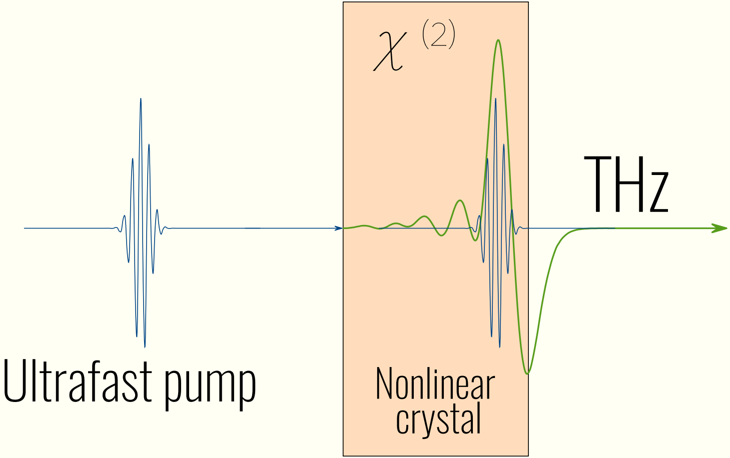
T. Kleine-Ostmann and T. Nagatsuma, J. Infrared, Millimeter, Terahertz Waves 32, 143 (2011)

IR QCL mixing



K. Vijayraghavan et al, Nat. Commun. 4(1) p2021 (2013)

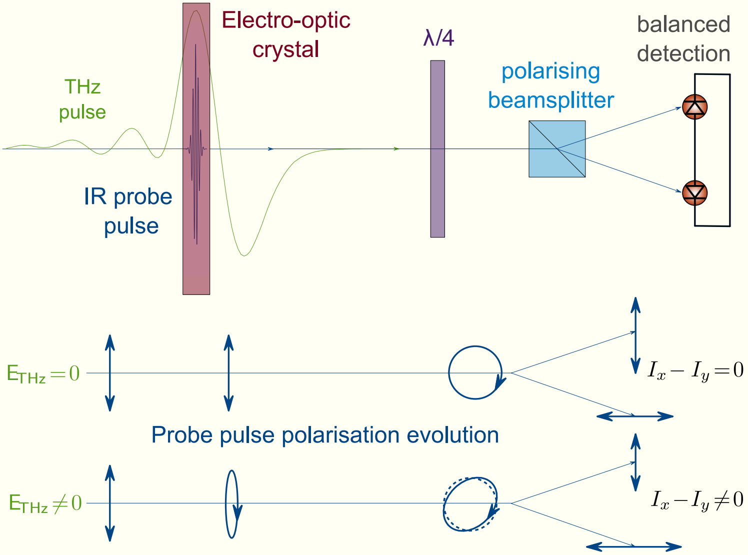
Nonlinear crystal



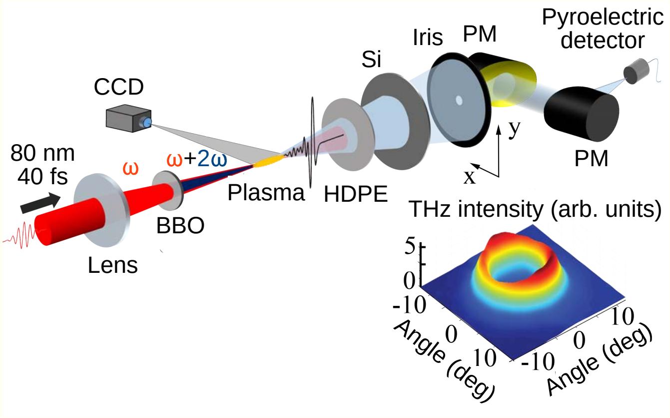
- Low conversion efficiency
- Spectral bandwidth is limited by phase matching
- Efficiency is limited by phase matching
- Nonlinear source $\Longrightarrow$ requires high pump

$$P(\omega_{THz}) \sim \chi^{(2)} E(\omega_1) E(\omega_2) \sim \chi^{(2)} |E_0|^2$$

Detection in nonlinear crystal



Laser filament

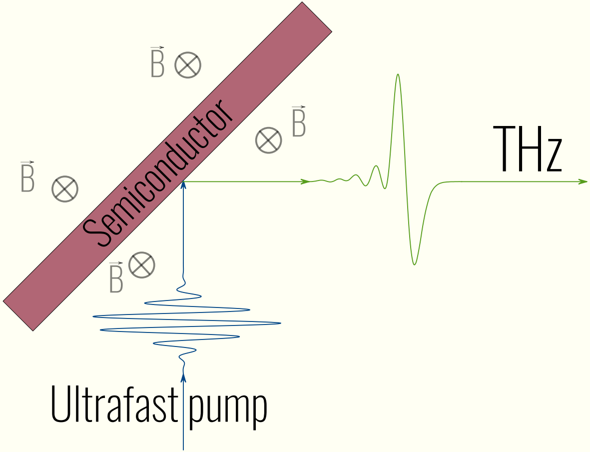


$$\left(\frac{\partial^2}{\partial t^2} + \nu_c \frac{\partial}{\partial t} + \omega_{pe}^2\right)\vec{E} = -4\pi\left(\vec{\Pi} + \frac{\partial \vec{J_e}}{\partial t} + \frac{\partial^2 \vec{P}}{\partial t^2}\right)$$

- Low conversion efficiency
- Broad spectrum
- Filament requires very high pump
- Better works at 3 μm pump
- Nonlinear source $\Longrightarrow$ requires high pump

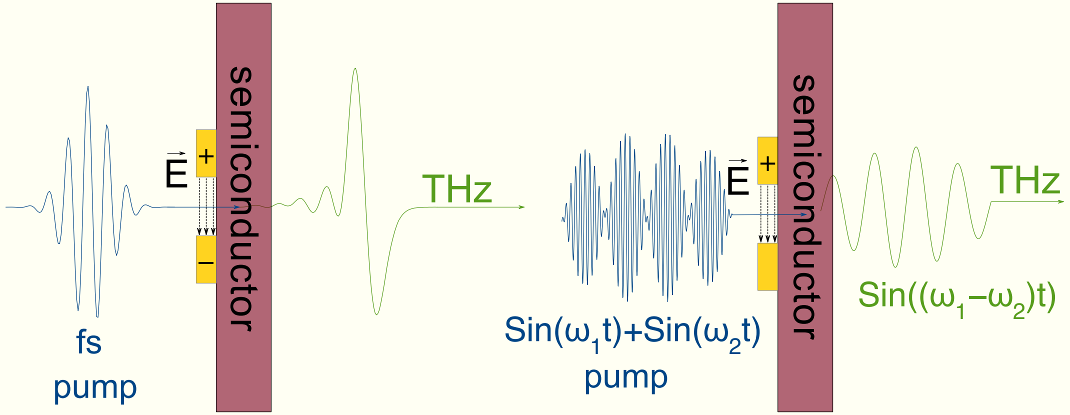
$\vec{J_e}$ – current density $\vec{P}$ – Kerr polarisation, $\omega_{pe} = 2\pi\sqrt{\frac{e^2 N_e}{\pi m}}$ – electron frequency, $\vec{\Pi}$ - pondermotive forces

Unbiased semiconductor

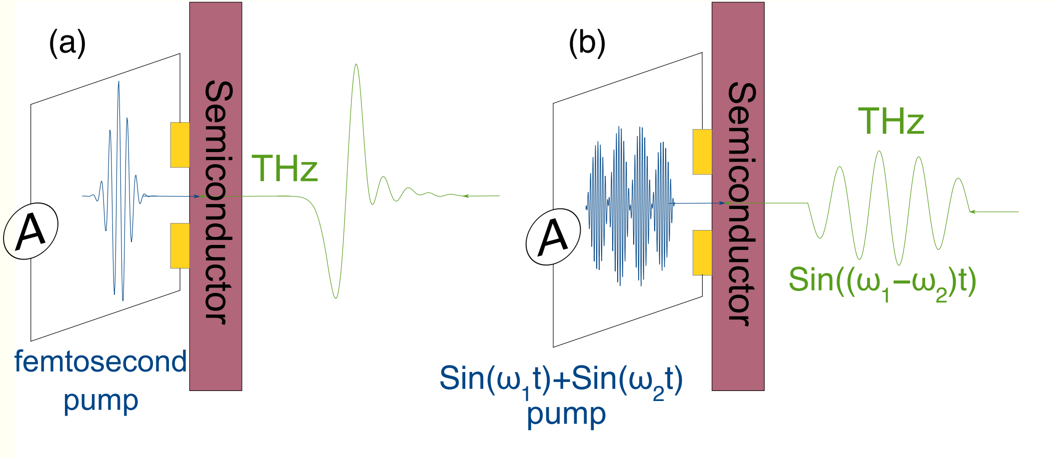


- Low conversion efficiency
- Bulky if magnets are used
- Spectral width is limited by lifetimes

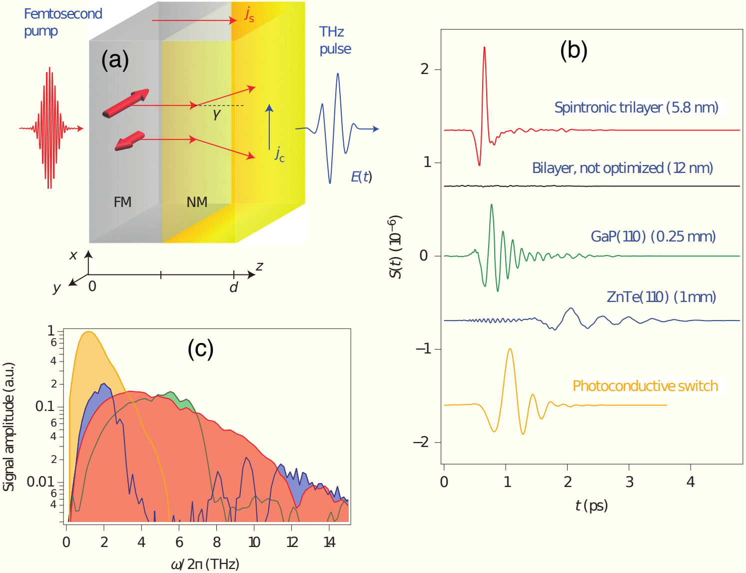
Photoconductive antenna (PCA)



PCA Detection



Spintronic emitter



T. Seifert et al, Nat. Photonics, 10 (7) pp 483–488 (2016.)

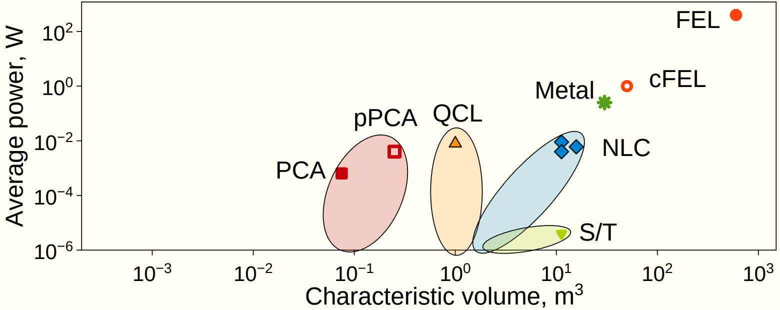
Terahertz Radiation – Generation

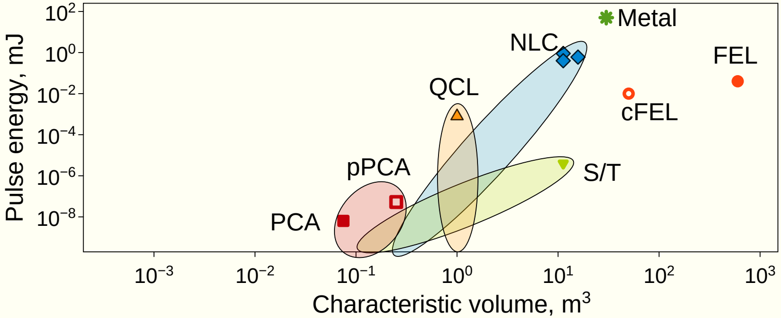
Method	Room Temp?	Compact?	Tunable?	Power range	Freqs, THz
CO_2 pumped Gas lasers	✓	✗	✗	mW	2–3
FEL	✗	✗	✓	W	1–100
Nonlinear crystals	✓	✗	✓	nW-mW	0.1–10
Laser filaments	✓	✗	✓	mW-W	0.1–30
Quantum cascade lasers	✗	✓	✓	mW-W	2–6
IR QCL mixing	✓	✓	✓	nW-μW	2–6
Electronic sources	✓	✗	✗	mW	0.1–0.7
CW optoelectronic diodes	✓	✓	✗	mW	0.1–0.7
Unbiased photoconductors	✓	✗	✗	nW-μW	0.1–2
Photoconductive antennas	✓	✓	✓	nW-mW	0.1–5
Spintronic emitters	✓	✗	✓	nW-μW	0.2–40

Obvious obstacles

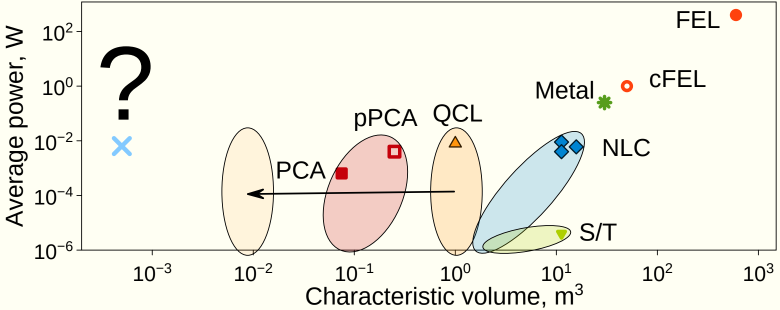
- Most transceivers are bulky
- Most transceivers are not efficient / have frequency tradeoff
- Larger part of transceivers are both bulky and not efficient
- QCL transceivers require significant cooling (i.e. are bulky)

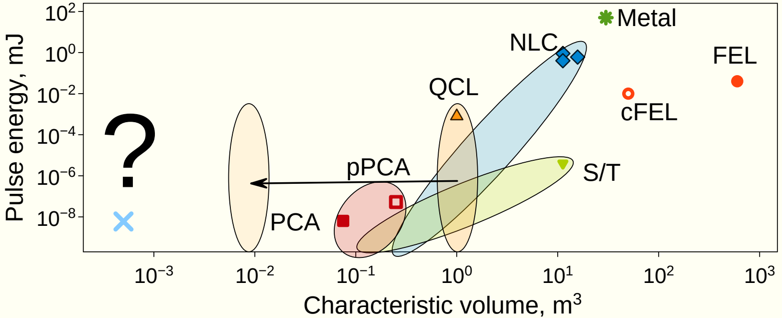
THz sources - power vs size



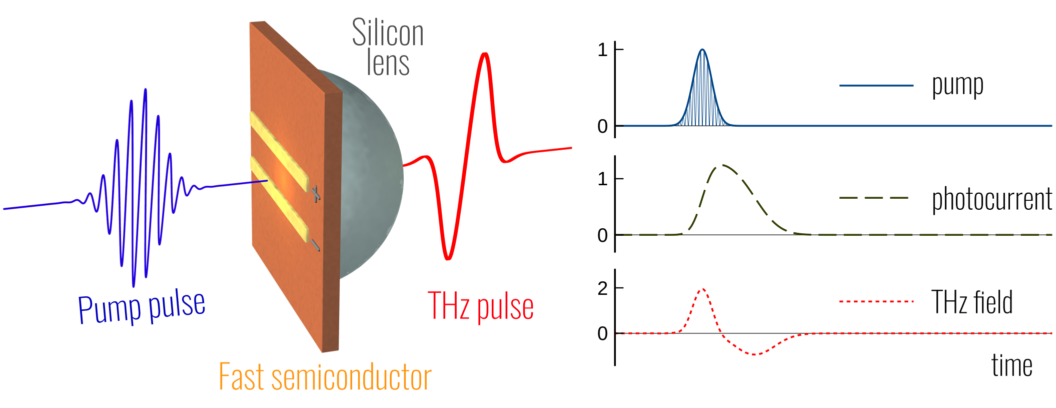


THz sources - power vs size





Photoconductive antenna (PCA)



$$E(z,t) = -\frac{A}{4\pi\varepsilon_0 c^2 z}\cdot\frac{dJ}{dt} = -\frac{A}{4\pi\varepsilon_0 c^2 z}\cdot\left(qv\frac{\partial n}{\partial t} + qn\frac{\partial v}{\partial t}\right)$$

PCA substrates

800 nm pump (Ti:Sapphire)

- SI GaAs
  + mobility
  - lifetimes
  - thermal stability
- LT GaAs
  - mobility
  + lifetimes
  - thermal stability
- LT GaAs on quartz
  - mobility
  + lifetimes
  + thermal stability

1550 nm pump (Telecom)

- Doped InGaAs
  = mobility
  + lifetimes
  - thermal stability
- InGaAs/InAlAs Heterostructures
  + mobility
  + lifetimes
  - thermal stability
- ErAs/InGaAs Heterostructures
  + mobility
  = lifetimes
  - thermal stability

1000-1200 nm pump

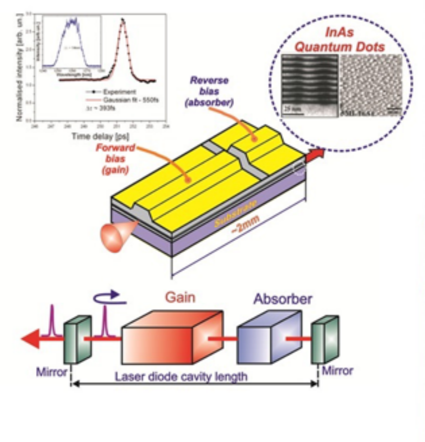
- GaInAsBi
  + mobility
  - lifetimes
  - thermal stability
- GaBiAs
  - mobility
  + lifetimes
  - thermal stability
- InAs/GaAs QD heterostructures
  + mobility
  + lifetimes
  + thermal stability

How PCA setups can be more efficient and compact?

- Pumping by compact lasers can be enabled.
- Higher thermal stability
- Higher photocurrent
  - Higher photoelectronic efficiency
  - Higher mobility
- Higher rate of the photocurrent change
- Light reflection can be lowered
- More absorption in surface layer

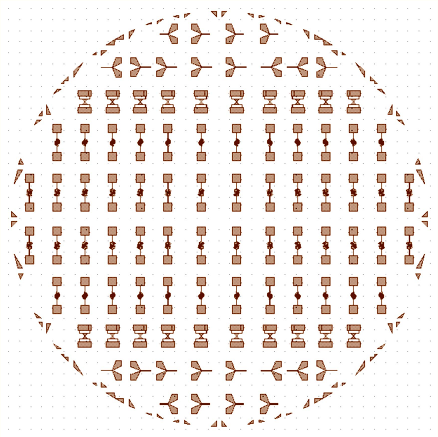
Quantum Dot Lasers

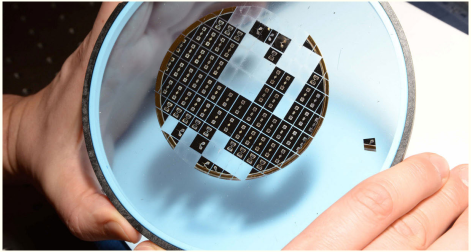
- near-IR (1 –1.3 μm) spectral region
- output peak power over 40 W
- tunability over 200 nm
- pulse duration less than 400fs

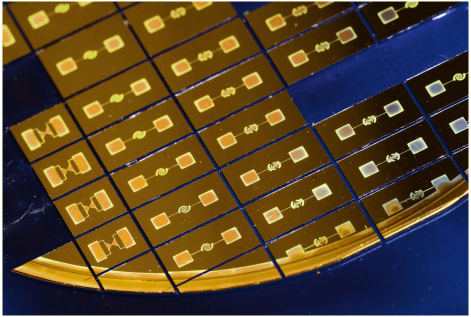


Rafailov, E. U., Cataluna, M. A., Sibbett, W. (2007). Mode-locked quantum-dot lasers. Nature Photonics, 1(7), 395–401

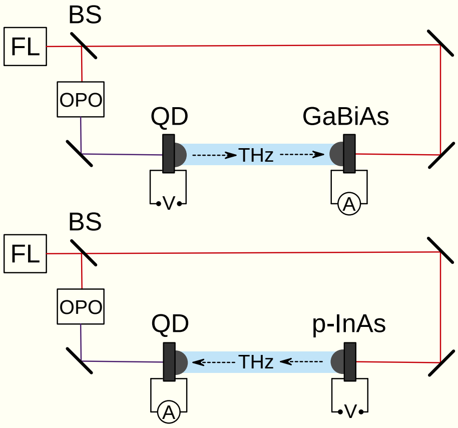
QDPCA Samples

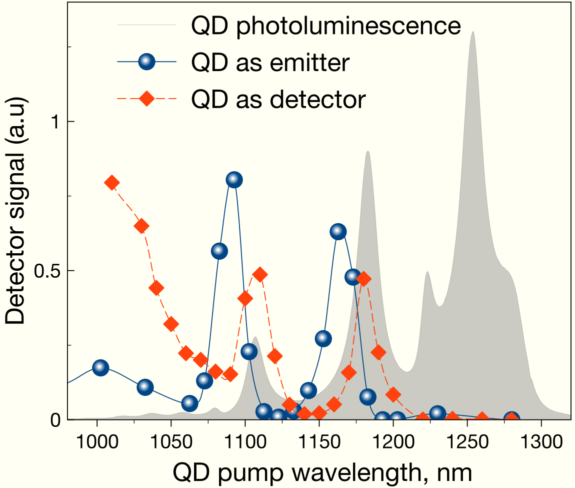






Resonant Pump Pulsed THz Generation





R. R. Leyman, **A. Gorodetsky**, N. Bazieva, G. Molis, A. Krotkus, E. Clarke and E. U. Rafailov *Quantum Dot Materials for Terahertz Generation Applications* // Laser and Photon. Rev., vol. 10, no. 5, pp. 772–779 (2016)

THz superradiance from QD based substrates

THz Superradiance from a GaAs: ErAs Quantum Dot Array at Room Temperature

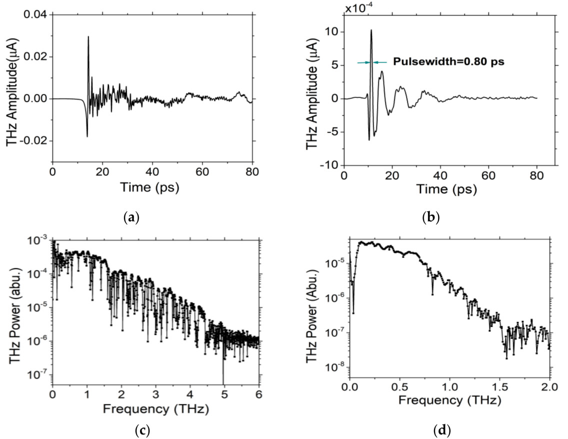
Weidong Zhang [1,2,*], Elliott R. Brown [1,2,*], Andrea Mingardi [1], Richard P. Mirin [3], Navid Jahed [4] and Daryoosh Saeedkia [4]

1. Departments of Physics and Electrical Engineering Wright State University, Dayton, OH 45435, USA
2. TeraPico, LLC, Beavercreek, OH 45431, USA
3. Applied Physics Division, National Institute of Standards and Technology, Boulder, CO 80305, USA
4. TeTech S, Suite 3, 170 Columbia, W. Waterloo, Ontario, ON N2L 3L3, Canada

* Correspondence: wzzhang@fastmail.fm (W.Z.); elliott.brown@wright.edu (E.R.B.); Tel.: +1-937-344-9712 (E.R.B.)

Received: 22 June 2019; Accepted: 22 July 2019; Published: 26 July 2019

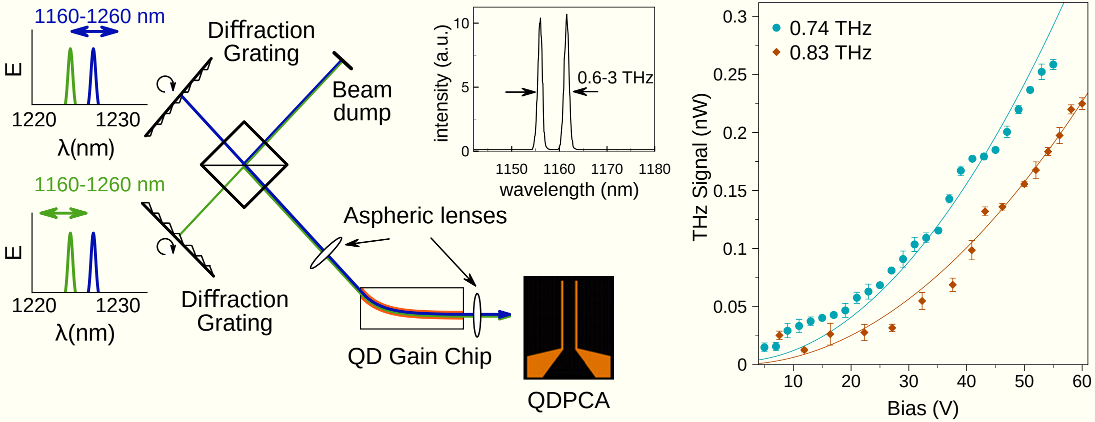
check for updates



A record of ∼117 μW pulsed THz power was obtained, with a 1550 nm-to-THz power conversion efficiency of ∼0.2%

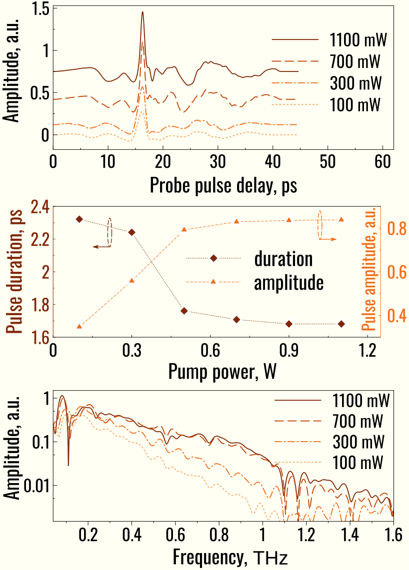
W. Zhang, E. R. Brown, A. Mingardi, R. P. Mirin, N. Jahed, and D. Saeedkia, Appl. Sci. 9, 3014 (2019).

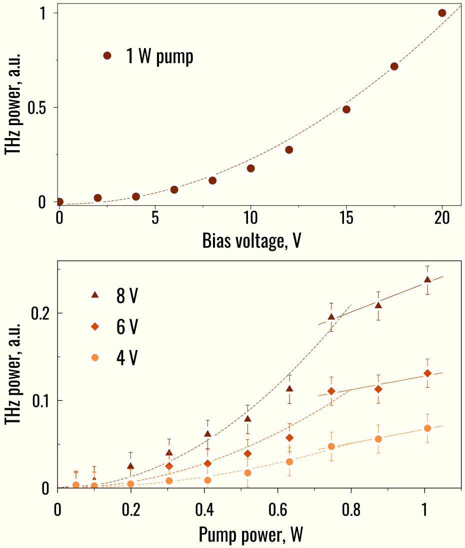
Resonant Pump CW THz Generation



K. A. Fedorova, **A. Gorodetsky**, E. U. Rafailov *Compact All-Quantum-Dot Based Tunable THz Laser Source*//IEEE J. Sel. Top. Quant. Electron. vol. 23, no. 4, pp. 1-5 (2016)

High breakdown tolerance



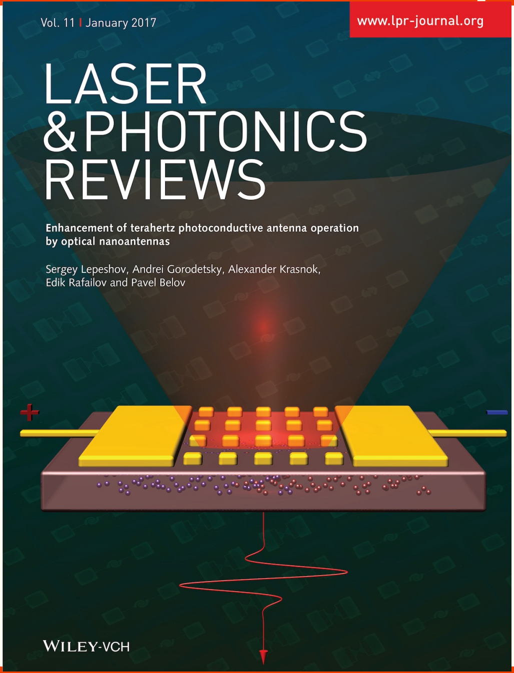


A. Gorodetsky, I.T. Leite, E. U. Rafailov *Operation of quantum dot based terahertz photoconductive antennas under extreme pumping conditions* // Appl. Phys. Lett. 119, 111102 (2021); doi: 10.1063/5.0062720

How PCA setups can be more efficient and compact?

- Pumping by compact lasers can be enabled. ✓
- Higher thermal stability ✓
- Higher photocurrent ✓
  - Higher photoelectronic efficiency ✓
  - Higher mobility ✓
- Higher rate of the photocurrent change ✓
- Light reflection can be lowered
- More absorption in surface layer

Hybrid PCA Review Paper

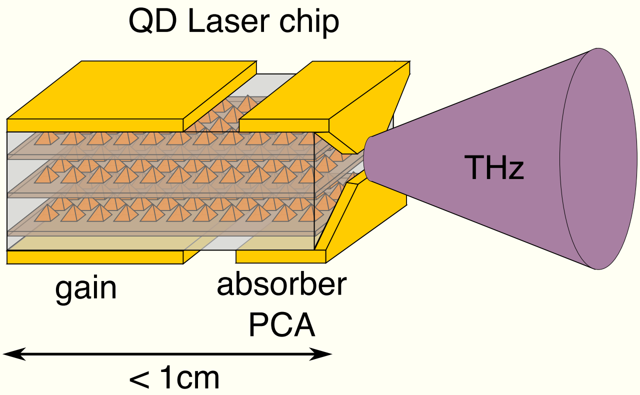


S. Lepeshov, A. Gorodetsky, A. Krasnok, E. Rafailov, and P. Belov,

Enhancement of terahertz photoconductive antenna operation by optical nanoantennas.

Laser and Photonics Reviews,
vol. 11, no. 1, pp. 1600199 (2017)

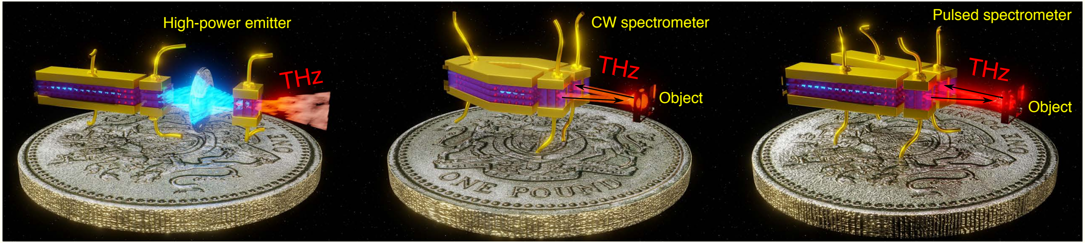
Outlook



- Intracavity generation - all intracavity power used for pumping
- Naturally occurring modelocking
- Extreme compactness
- High reprate

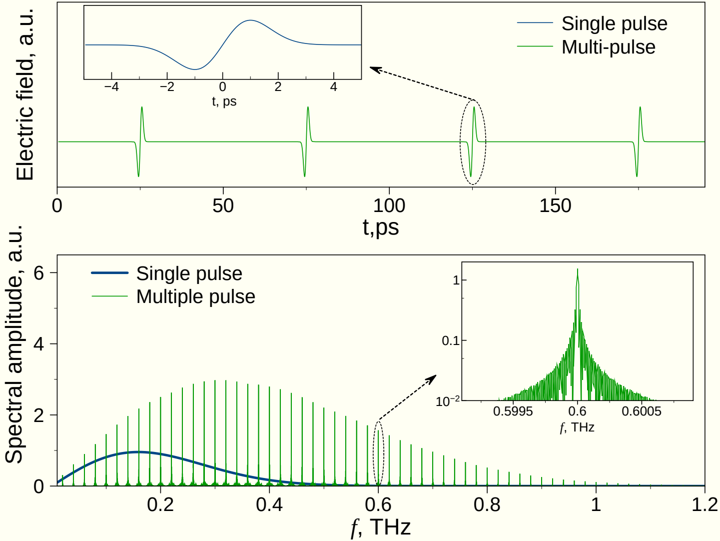
Outlook

- On-chip compact THz systems



Outlook

- Frequency combs for ultrafine spectroscopy



Conclusion

Compact CW low frequency setups

- UTC photodiodes

All-rounder

- Telecom pumped InGaAs PCAs

Super compact all-rounder

- QD pumped QD PCAs

High frequency CW

- IR QCL waveguide mixer

Acknowledgements and Contacts

Acknowledgements

MagicPlot

RFBR
RUSSIAN FOUNDATION FOR BASIC RESEARCH

UKRI
Engineering and Physical Sciences Research Council

Contacts

kadavr.spb.ru

andrei@itmo.ru

drGorodetsky