THz Optoelectronics research group

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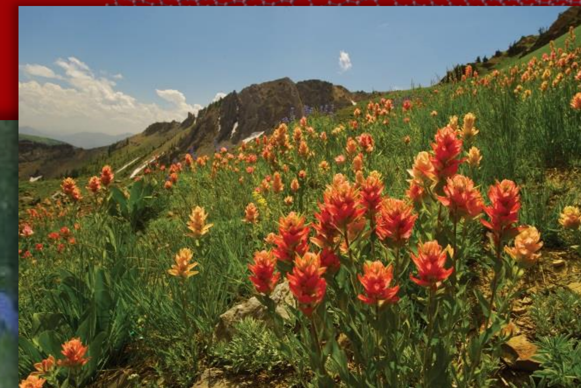
www.terahertzoptoelectronics.org

THz optoelectronics research group @ UofU



THz optoelectronics research group @ UofU

Dr. Berardi Sensale-Rodriguez (PI)
PhD Electrical Engineering,
University of Notre Dame (USA)

Graduate students:

Sara Arezoomandan (PhD-ECE)
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University of Tehran (Iran)

Hugo Condori (PhD-ECE)
MSc. Electrical Engineering,
Montana State University (USA)

Mehdi Hasan (PhD-ECE)
MSc. Electrical Engineering,
University of New Mexico (USA)

Athena Shahrabi (PhD-MSE)
BS. Materials Science and Engineering,
Sharif University (Iran)

Alumni:

Kai Yang (MSc-CS, 2014)

Graduate students:

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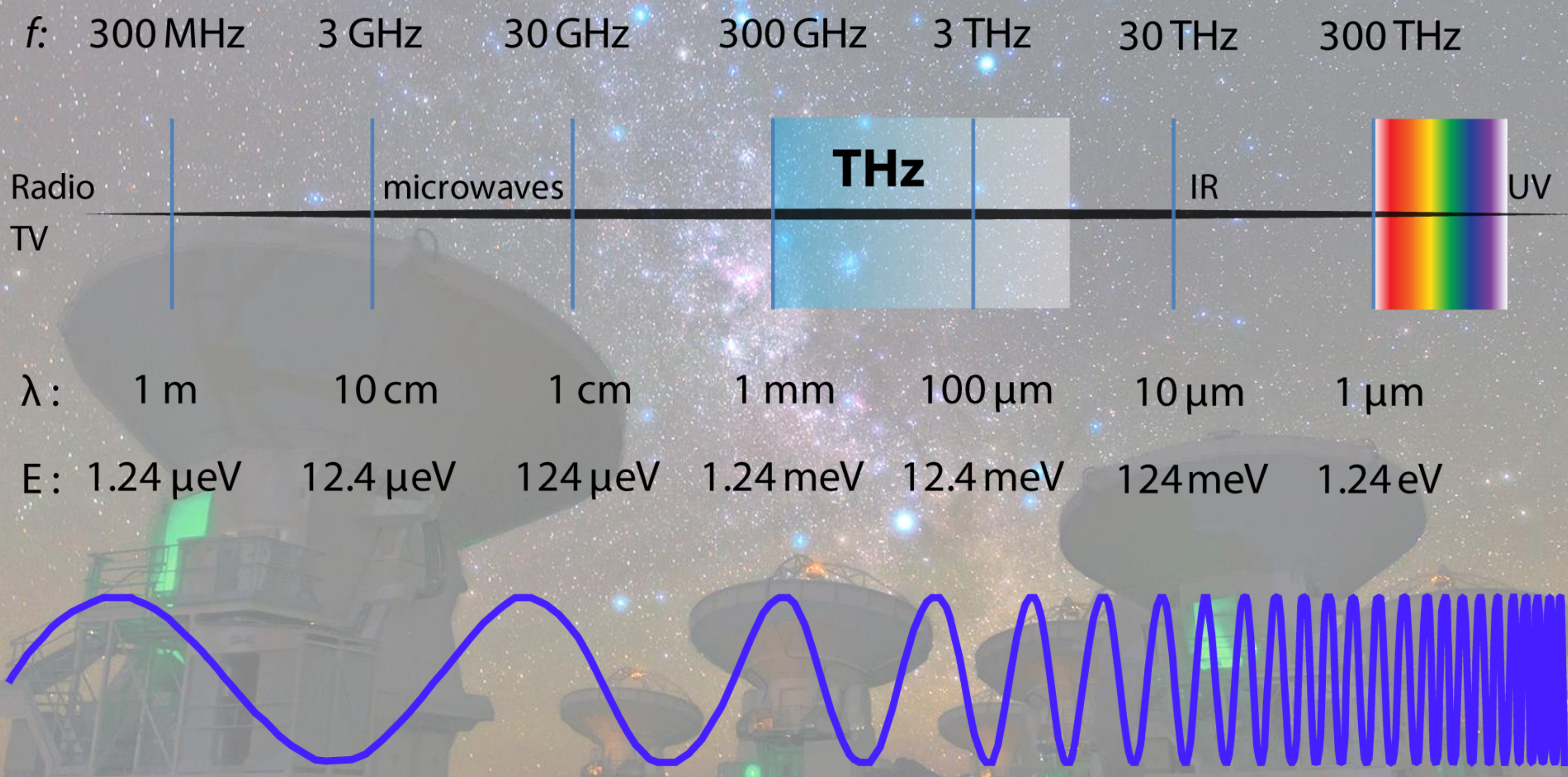
MSc. Electrical Engineering,
Beijing JiaoTong University (China)

Phrashant Gopalan (PhD-ECE)
MSc. Electrical Engineering,
University of Pennsylvania (USA)

Alumni:

James Hirst (MSc-ECE, 2015)

The THz frequency range



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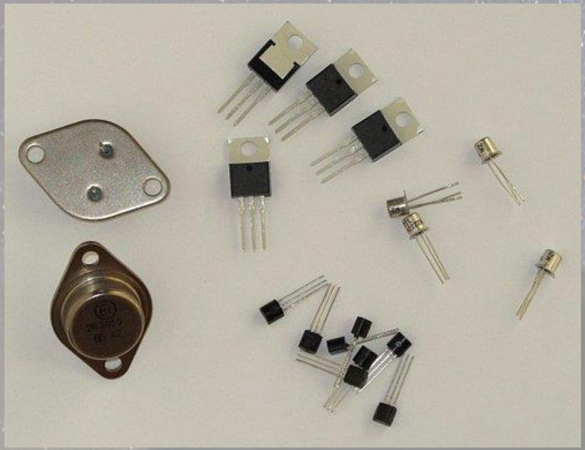
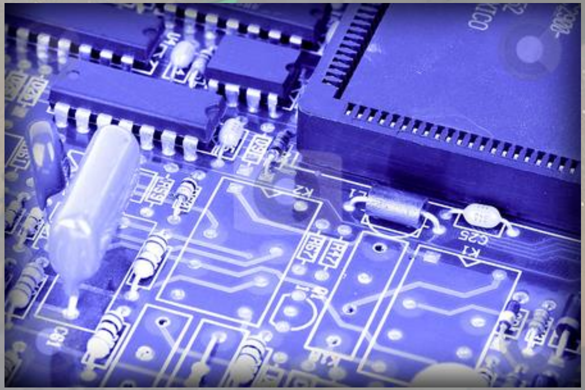
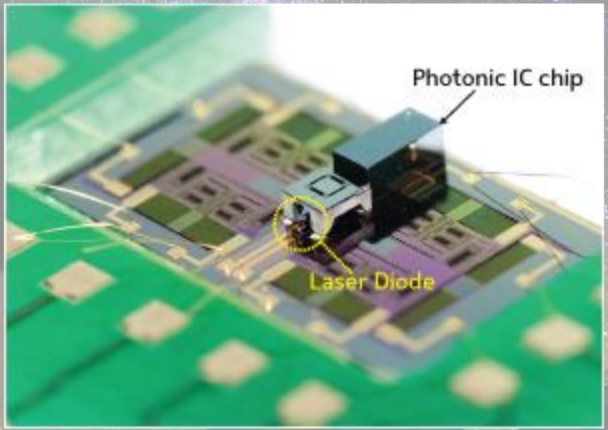
Radio waves vs. optical waves

Today… RF electronics and optical devices

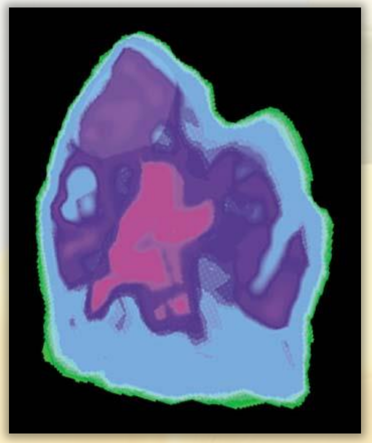






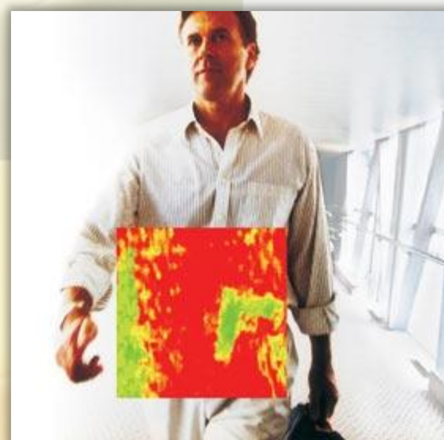
Applications of THz waves

Medical imaging



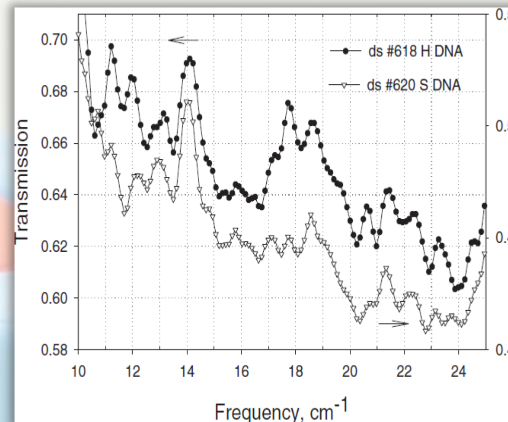
http://thznetwork.net/

Security

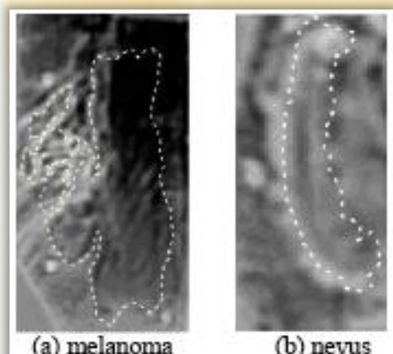


http://thznetwork.net/

Spectroscopy

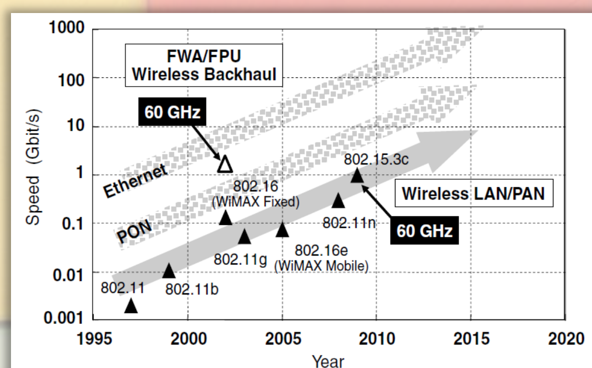


Chem. Phys. Lett., vol. 320, no. 42, (2000)

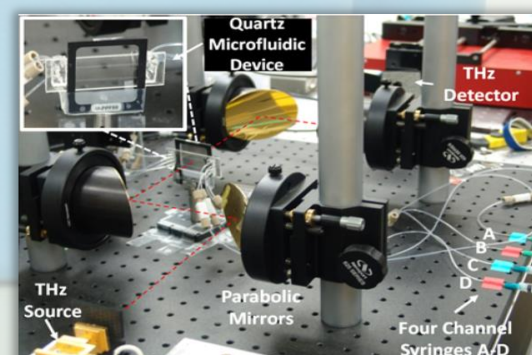


IEEE Eng. Med. Biol. Conf., 199-200, (2005)

Communications



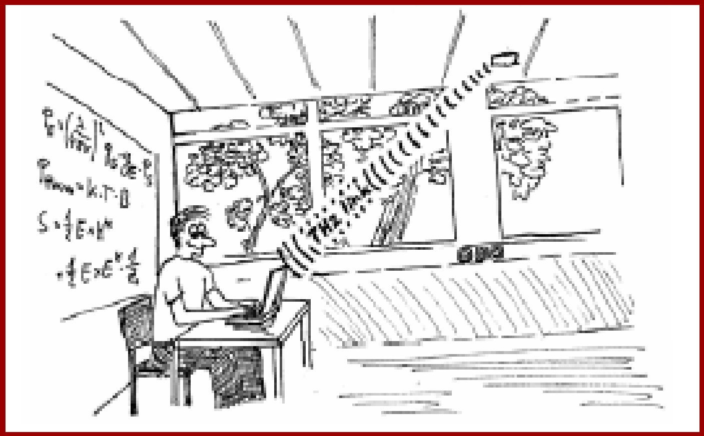
J. Infrared Milli. Terahz. Waves 32, 143 (2011)



Pathak et al. *IRMMWTHz-2012*

The THz gap

Let’s suppose we want to build a THz band communications link…



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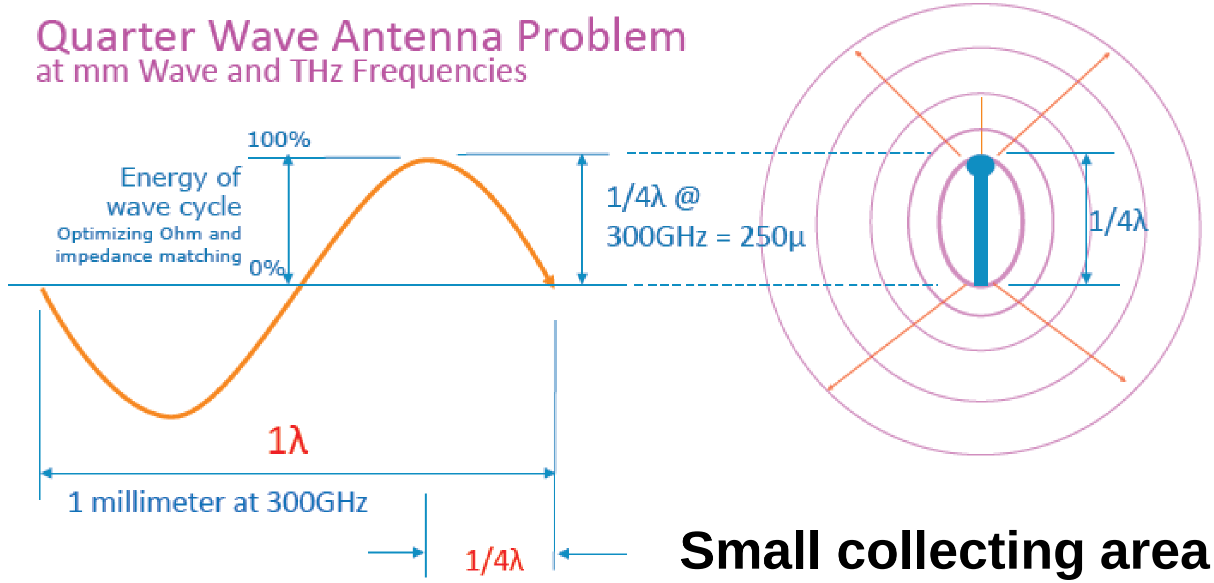
The THz gap

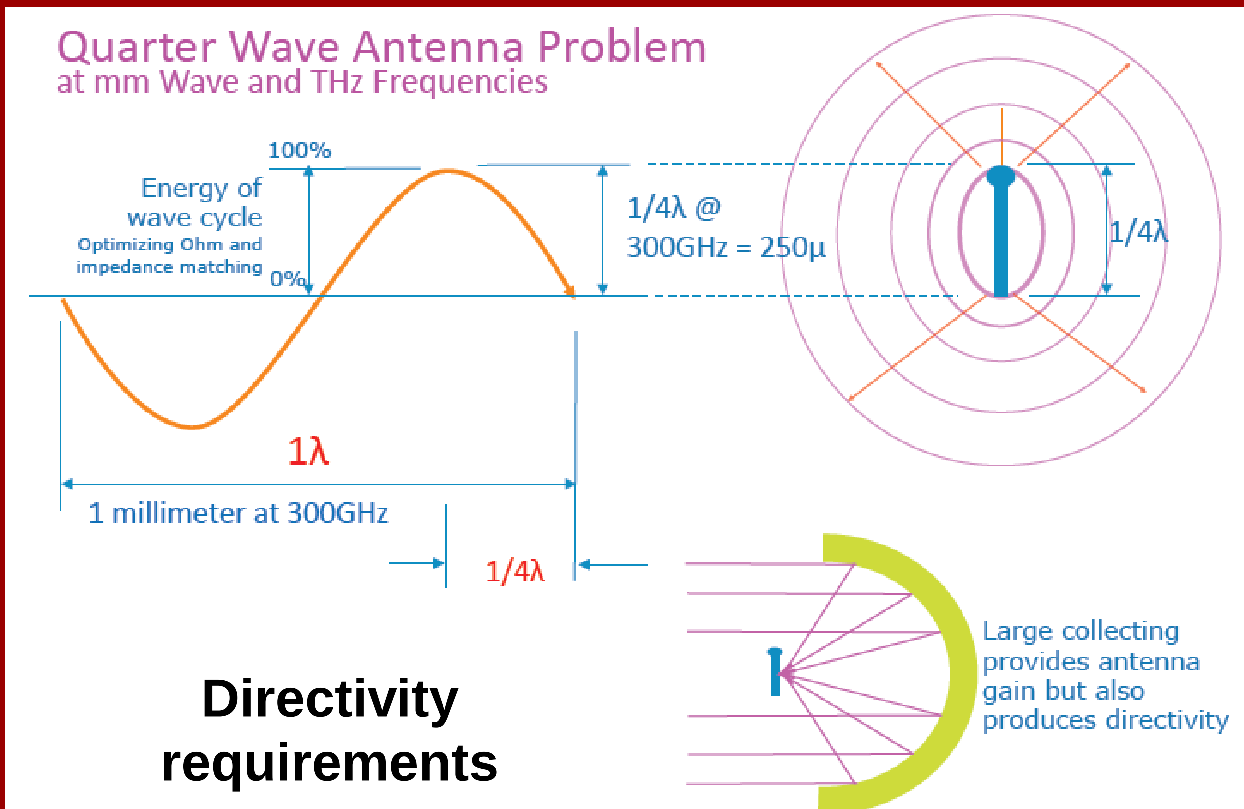


At 300 GHz (1mm wavelength)
The maximum omni-directional
antenna size is 250 microns.....
For a receiver this is a very
small signal collecting area!

Small collecting area due to small antenna size

www.ieeeusa.org/communications/ia/files/Britz-FCC-19Dec2011.pdf

The THz gap



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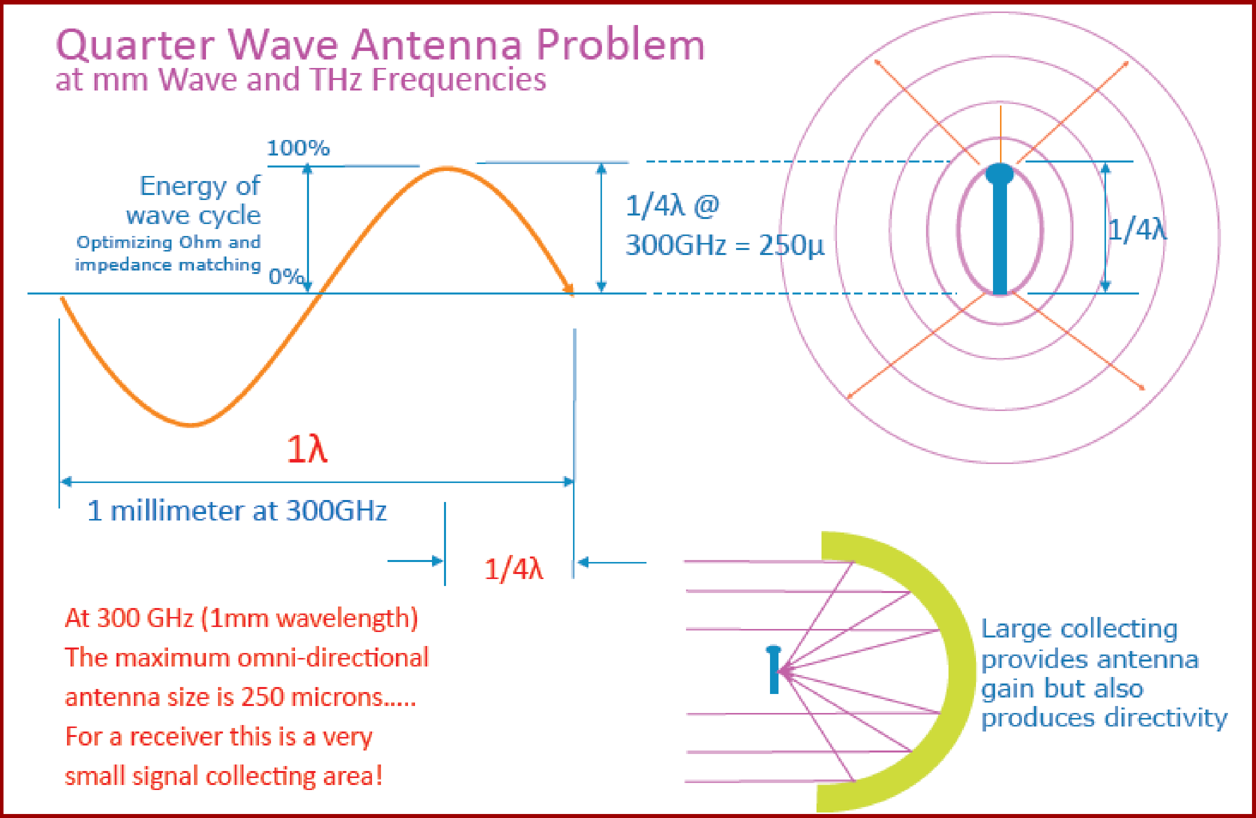
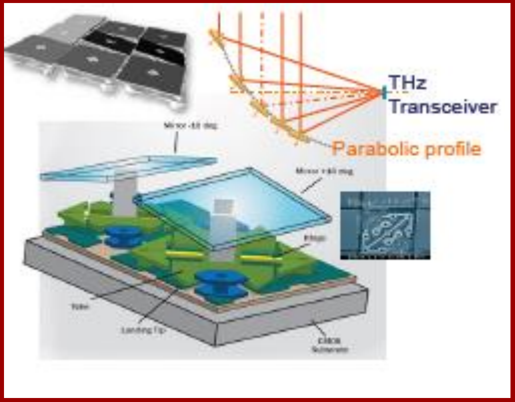
The THz gap



www.ieeeusa.org/communications/ia/files/Britz-FCC-19Dec2011.pdf

Challenge:

beam steering is needed in order to establish communication links!



The THz gap

Need for devices capable of controlling the properties of transmitted/reflected THz beam

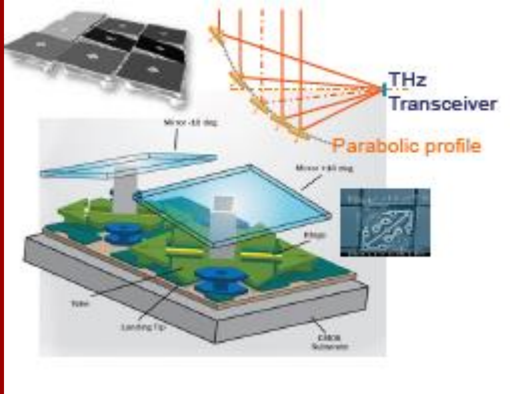
“Local properties” ➔ metamaterials

Which properties?

Amplitude & Phase

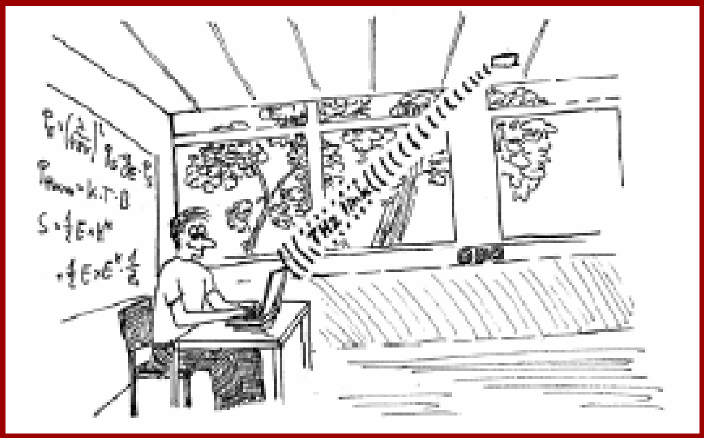
<u>Challenge:</u>

beam steering is needed in order to establish communication links!



The THz gap

Let’s suppose we want to build a THz band communications link…



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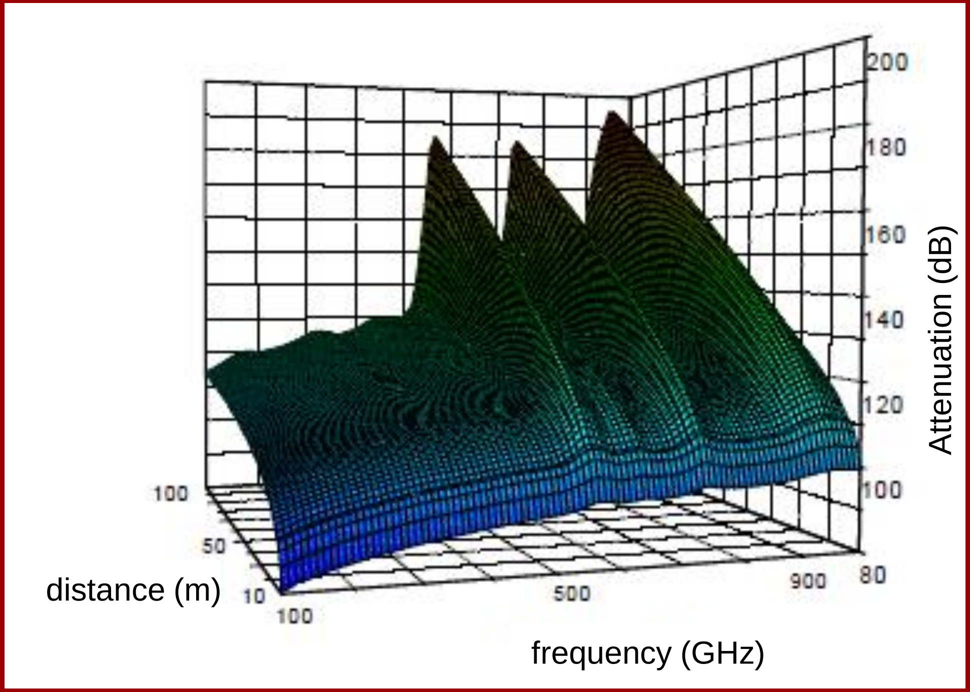
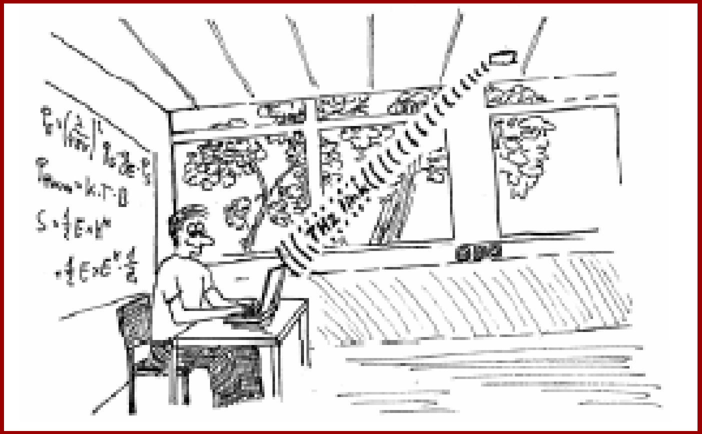
The THz gap

Loss in THz communication links





~100dB power attenuation @ 10 m from the source! Need for powerful enough sources to counteract these losses!

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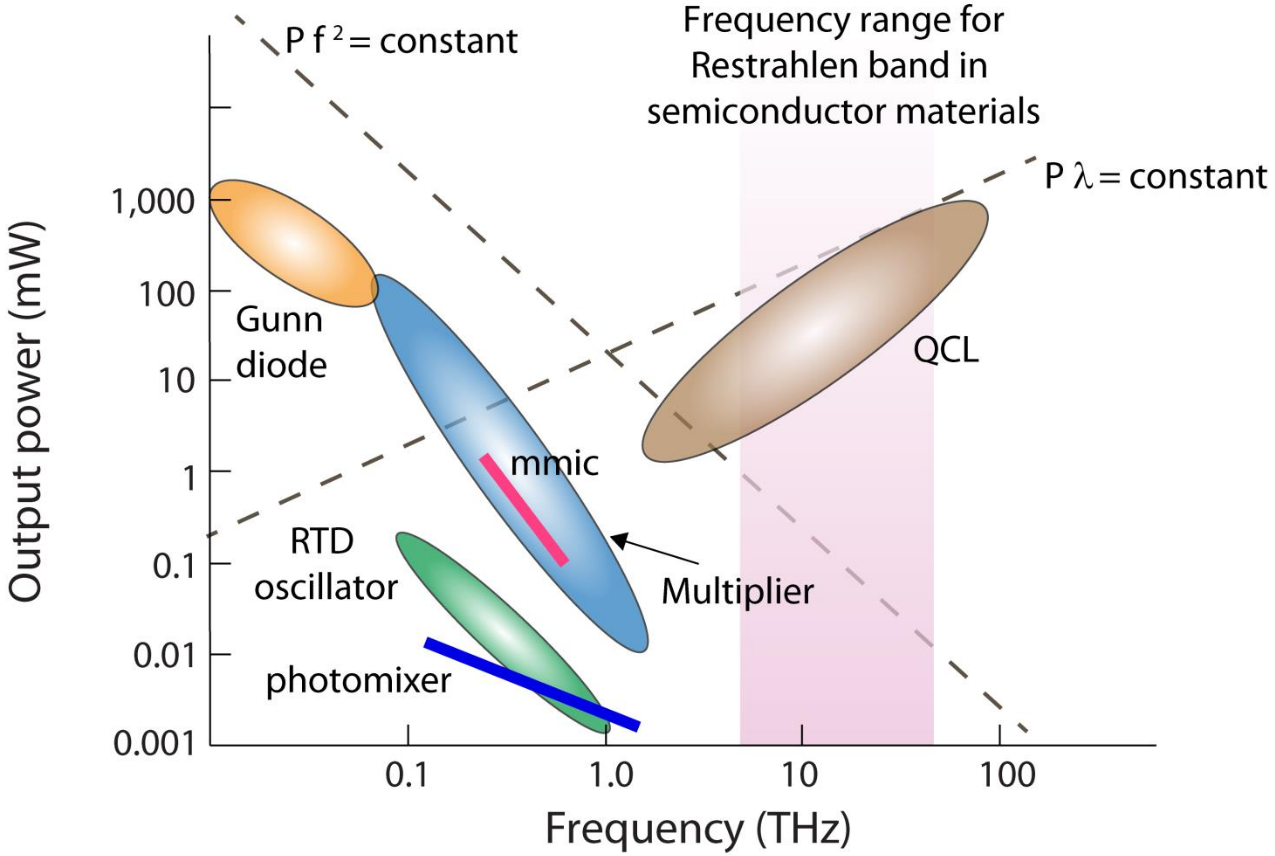
The THz gap

Device efficiency drops at THz frequencies…



The THz gap

Need for devices:

- Efficiently **operating at RT**
- Capable of **actively manipulating** THz waves (modulators, switches, active filters, active lenses,…)
- Capable of **responding to THz frequencies** (amplifiers, oscillators, detectors, switches,…)
- Other needs: integration, measurement techniques, interface, etc.

Deep-subwavelength THz metamaterials

Motivation

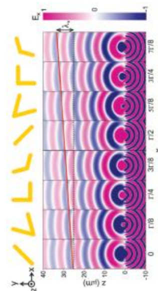
- Realize beam shaping employing reconfigurable metamaterial phase shifters.
- *What are the best metamaterial geometries?*

Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction

Nanfang Yu,[1] Patrice Genevet,[1,2] Mikhail A. Kats,[1] Francesco Aieta,[1,3] Jean-Philippe Tetienne,[1,4] Federico Capasso,[1*] Zeno Gaburro[1,5*]

generalized Snell's law of refraction

$$\sin(\theta_t)n_t - \sin(\theta_i)n_i = \frac{\lambda_o}{2\pi}\frac{d\Phi}{dx}$$



For beam shaping applications, an ideal metacell geometry should simultaneously provide:

(i) large phase modulation (PM),
(ii) large transmittance (T),
(iii) small unit-cell to wavelength ratio (L/λ_p).

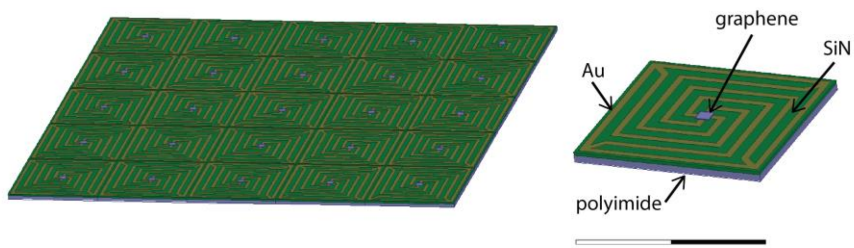
Two figures of merit related to (i), (ii), and (iii) can be defined:

$$foM_1 = \frac{PM \times T}{[360°] \times [100\%]} \qquad foM_2 = \frac{L}{\lambda_P}$$

Appl. Phys. A
DOI 10.1007/s00339-014-8693-8
Applied Physics A
Materials Science & Processing

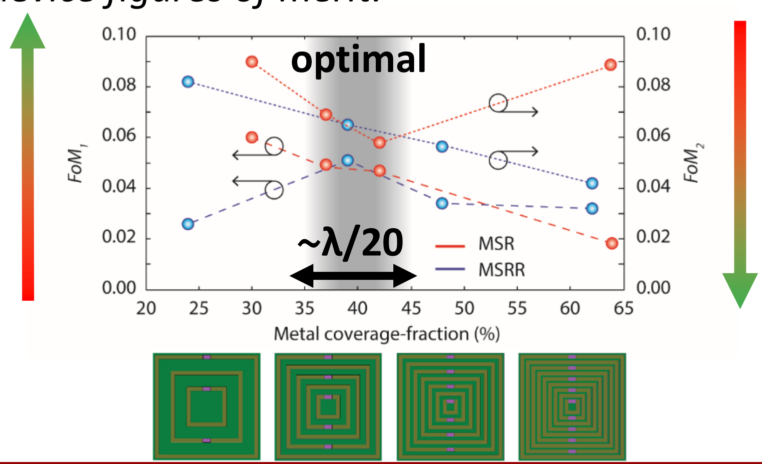
Graphene-based electrically reconfigurable deep-subwavelength metamaterials for active control of THz light propagation

Sara Arezoomandan · Kai Yang · Berardi Sensale-Rodriguez



We showed (Applied Physics A, 2014) that active deep-subwavelength metamaterials can provide better tradeoffs than the previous art in terms of the figures of merit.

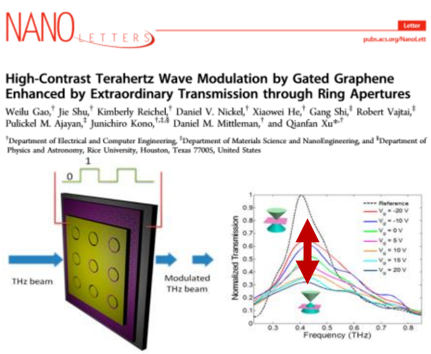
Later on (Scientific Reports, 2015), we identified that the *metal coverage fraction is a key parameter, which should be optimized, affecting the device figures of merit.*



Reconfigurable THz filters

Motivation

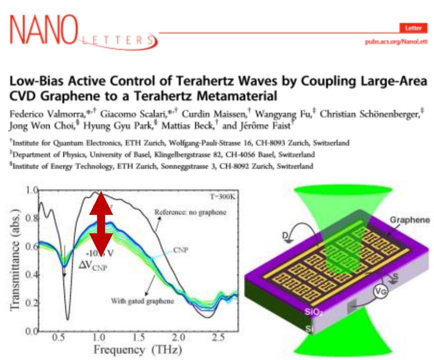
- Employing a *uniform graphene layer* as the active element in metamaterial THz filters (as in previous works) *modulates well the transmission amplitude at resonance, but does not shift the resonance in frequency.*
- *Propose a device structure that can behave as a reconfigurable filter.*


NANO LETTERS

High-Contrast Terahertz Wave Modulation by Gated Graphene Enhanced by Extraordinary Transmission through Ring Apertures

Weilu Gao, Jie Shu, Kimberly Reichel, Daniel V. Nickel, Xiaowei He, Gang Shi, Robert Vajtai, Pulickel M. Ajayan, Junichiro Kono, Daniel M. Mittleman, and Qianfan Xu

Department of Electrical and Computer Engineering, Department of Materials Science and NanoEngineering, and Department of Physics and Astronomy, Rice University, Houston, Texas 77005, United States


NANO LETTERS

Low-Bias Active Control of Terahertz Waves by Coupling Large-Area CVD Graphene to a Terahertz Metamaterial

Federico Valmorra, Giacomo Scalari, Curdin Maissen, Wangyang Fu, Christian Schönenberger, Jong Won Choi, Hyung Gyu Park, Mattias Beck, and Jérôme Faist

Institute for Quantum Electronics, ETH Zurich, Wolfgang-Pauli-Strasse 16, CH-8093 Zurich, Switzerland
Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland
Institute of Energy Technology, ETH Zurich, Sonneggstrasse 3, CH-8092 Zurich, Switzerland

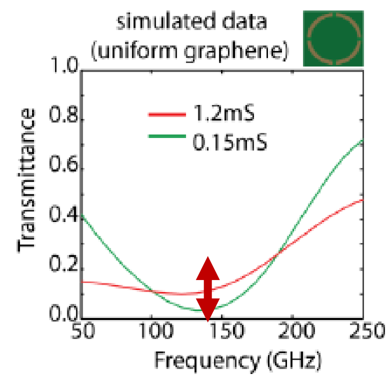
We demonstrated (Appl. Phys. Lett., 2014) that *by employing optimally patterned graphene in metamaterials, rather than uniform graphene, when altering its conductivity, the resonance frequency can be shifted.*

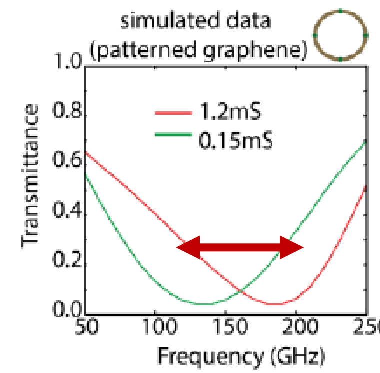
APPLIED PHYSICS LETTERS **105**, 093105 (2014)

Graphene-based tunable metamaterial terahertz filters

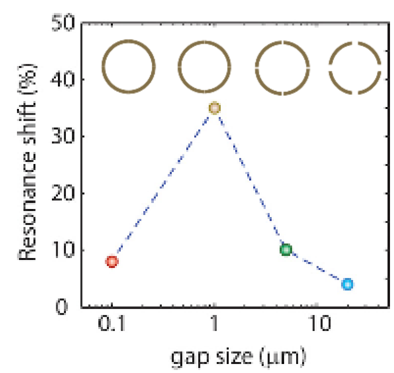
Kai Yang, Shuchang Liu, Sara Arezoomandan, Ajay Nahata, and Berardi Sensale-Rodriguez[a)]
Department of Electrical and Computer Engineering, The University of Utah, 50 S. Central Campus Dr., Salt Lake City, Utah 84112, USA

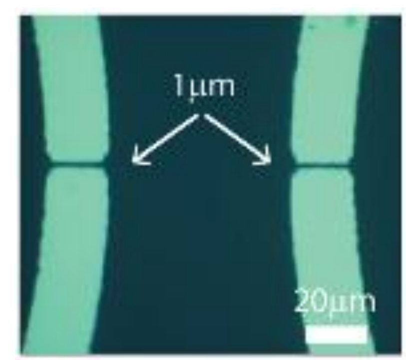
Transmittance versus frequency, when the graphene conductivity is altered, for a SRR metamaterial structure containing: (left) uniform graphene, and (right) patterned graphene)





The key parameter to optimize, is the SRR gap size, there is an optimal giving the largest resonance shift.



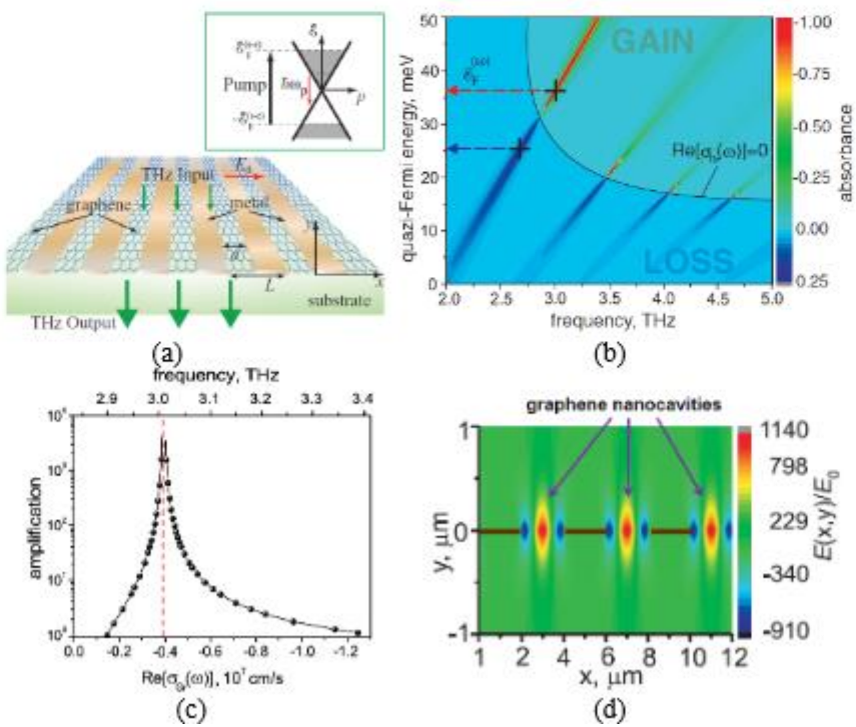


THz/far-IR sources

Graphene Active Plasmonics for Superradiant Terahertz Lasing

T. Otsuji [a], T. Watanabe [a], S.A. Boubanga Tombet [a], A. Satou [a], A.A. Dubinov [b], V. Popov [c], V. Ryzhii [a]
[a] Research Institute of Electrical Communication, Tohoku University, Sendai, 9808577 Japan
[b] Institute for Physics of Microstructures, Russian Academy of Sciences, Nizhny Novgorod, Russia
[c] Kotelnikov Institute of Radio Engineering and Electron. (Saratov Branch), RAS, Saratov, Russia

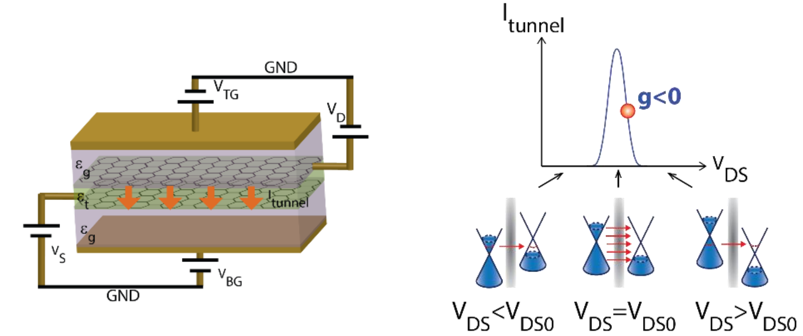
THz lasing in plasmonic structures



APPLIED PHYSICS LETTERS 103, 123109 (2013)

Graphene-insulator-graphene active plasmonic terahertz devices

Berardi Sensale-Rodriguez[a)]
Department of Electrical and Computer Engineering, The University of Utah, Salt Lake City, Utah 84112, USA



THz amplification in plasmonic devices