Research of anapole modes in ring-shaped subwavelength periodic structures fabricated on thin free-standing metal film

Surya R. Ayyagari(1), Alexey Basharin(2), Simonas Indrišiūnas(3), Daniil Pashnev(1), Vytautas Janonis(1), Polina Kuzhir(2), Guillaume Ducournau(4),, and Irmantas Kašalynas(1)

(1) Terahertz Photonics Laboratory, Center for Physical Sciences and Technology (FTMC), Vilnius, Lithuania
(2) University of Eastern Finland (UEF), Center for Photonics Sciences, Joensuu, Finland
(3) Laser Microfabrication Laboratory, Center for Physical Sciences and Technology (FTMC), Vilnius, Lithuania
(4) Institut d'Electronique de Microélectronique et de Nanotechnologie (IEMN), Université de Lille, Lille, France

irmantas.kasalynas@ftmc.lt

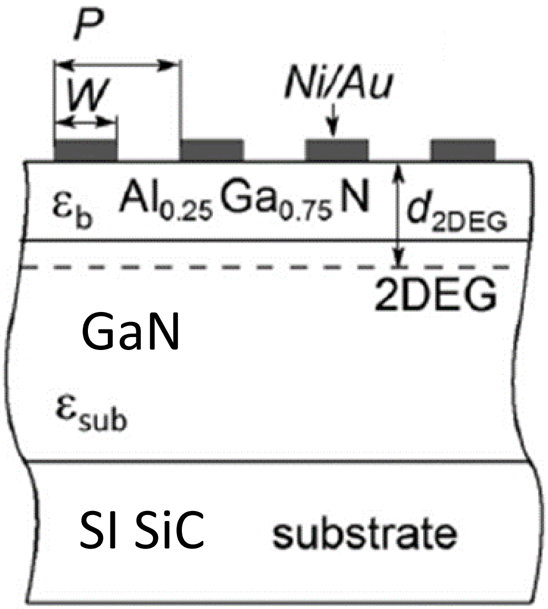
International Conference on Electromagnetics in Advanced Applications
IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications
September 2-6, 2024 | Lisboa, Portugal

Outline

- Introduction
- Samples
- Results
- Conclusions

2D plasmons in AlGaN/GaN HEMTs

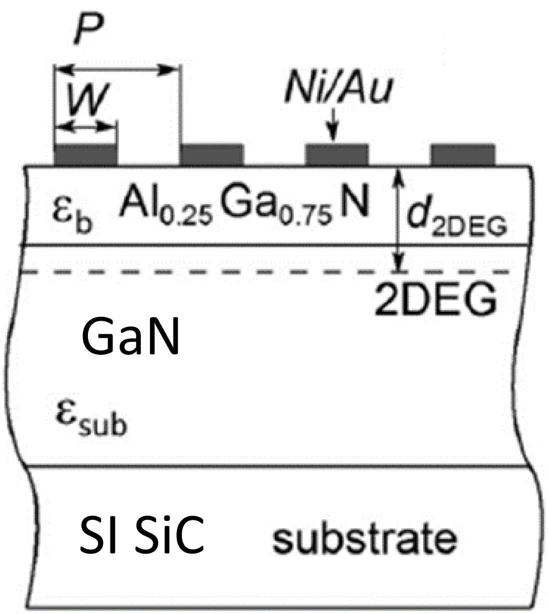
$$2\pi f_{pn} = \sqrt{\frac{e^2 N_{2DEG} k_n}{m^* \varepsilon_0 [\varepsilon_{sub} + \varepsilon_b \coth(k_n d_{2DEG})]}}$$

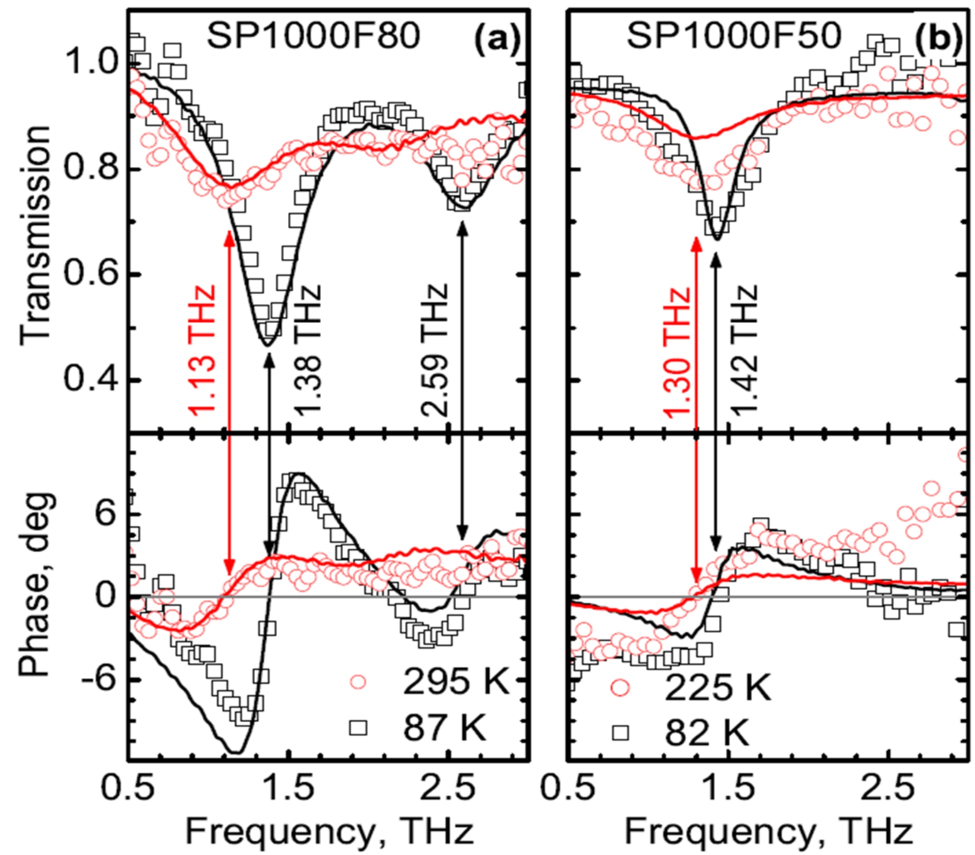


D. Pashnev et. al., APL **117**, p.51105 & p.62101 (2020)

2D plasmons in AlGaN/GaN HEMTs

$$2\pi f_{pn} = \sqrt{\frac{e^2 N_{2DEG} k_n}{m^* \varepsilon_0 [\varepsilon_{sub} + \varepsilon_b \coth(k_n d_{2DEG})]}}$$

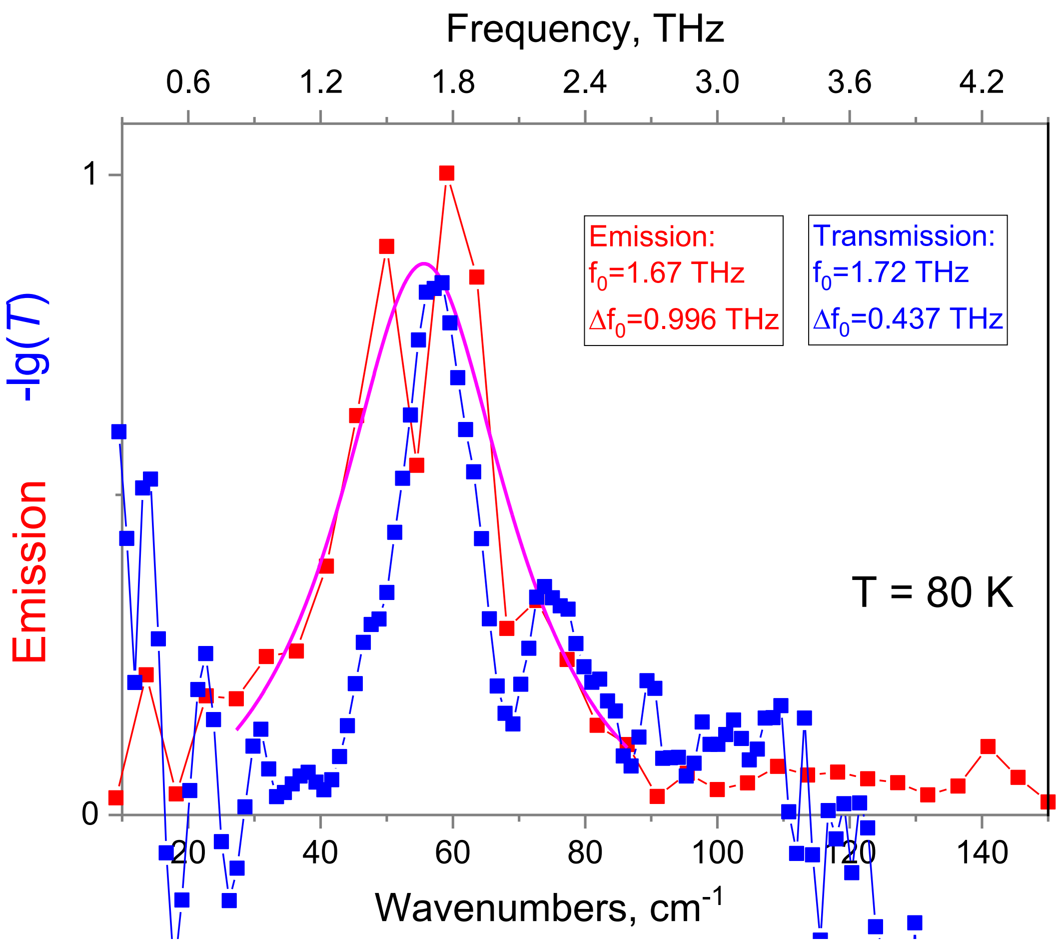




Transmission amplitude and phase spectra measured (dots) and calculated (lines) for 2D plasmonic samples with grating-gate of 50% (a) and 80% FF (b).

D. Pashnev et. al., APL **117**, p.51105 & p.62101 (2020)

Performance of plasmonic THz emitters



THz emission Power:

~10 (35..420) nW.

Wall-plug efficiency:

$\sim 10^{-9}$.

FWHM ≈ 1.0 THz, Q ≤ 3 (exp. E)

FWHM ≈ 0.4 THz, Q ≤ 6 (exp. T)

FWHM < 0.1 THz, Q ≈ 40 (exp. Hall)

$$\tau_{eff} = 1/2\pi\Delta f_p = 0.40 \text{ (ps)}$$

$$\tau_s = 2.40 \text{ (ps)}$$

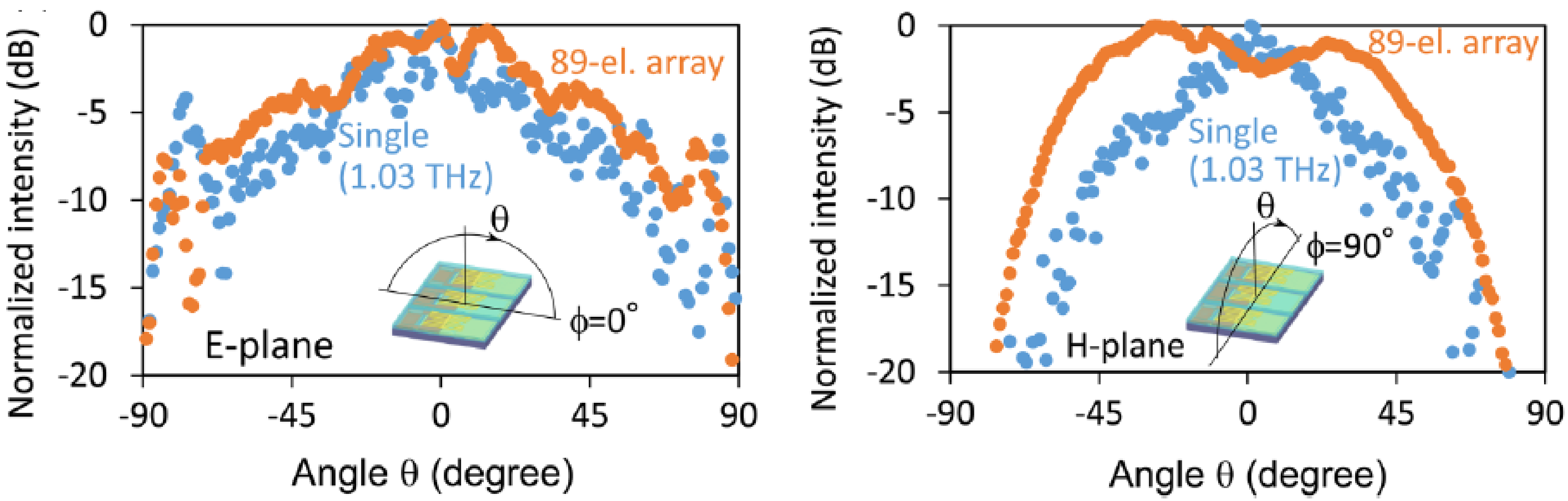
$$\mu = \frac{e}{\gamma m^*}$$ μ(80 K)=1.9 m^2/Vs

V. Janonis et al., "Electrically-pumped THz emitters based on plasma waves excitation in III-nitride structures," Proc SPIE 2020, vol. 11499, p. 8, doi: 10.1117/12.2569261

*D. Pashnev et al, (**under publication)***

Large-scale array of RTD THz oscillators

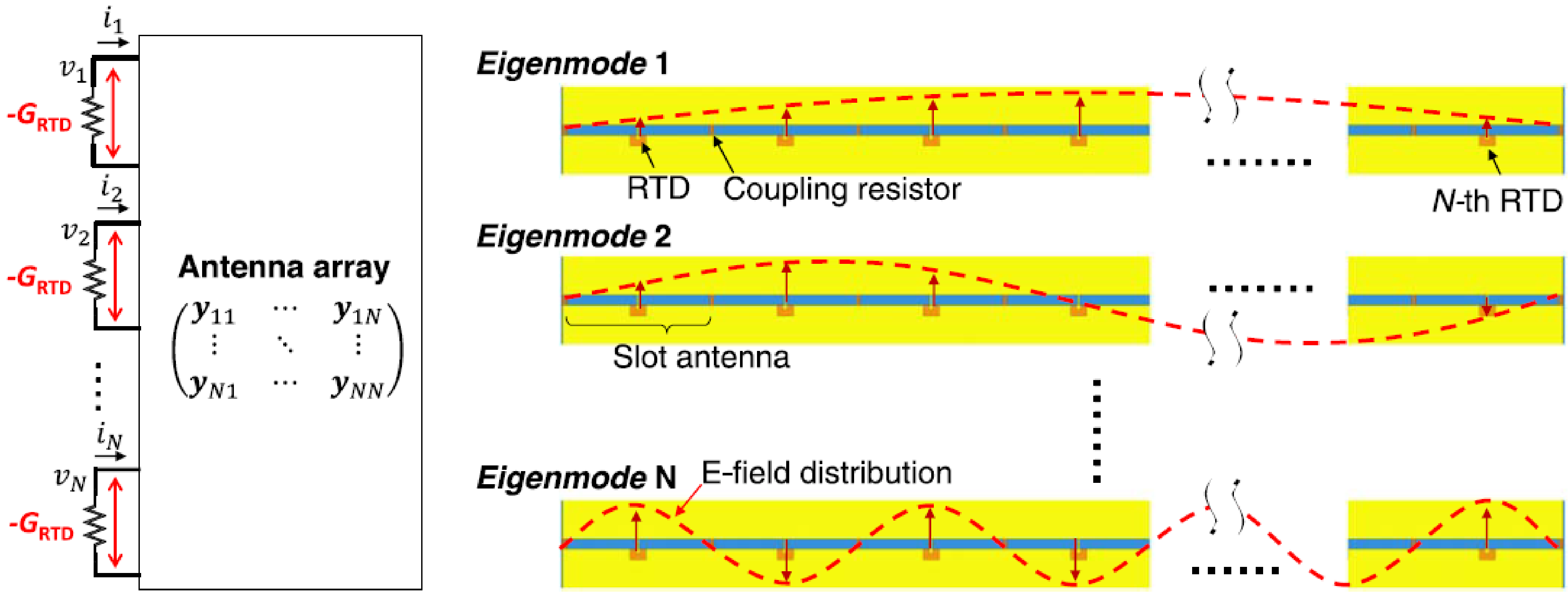
A non-coupled array, 89 elements oscillate at 0.7mW at 1 THz - the spectrum exhibits multipeak characteristics.



Measured radiation patterns for 89-element array and single oscillators for (a) E- and (b) H-planes.

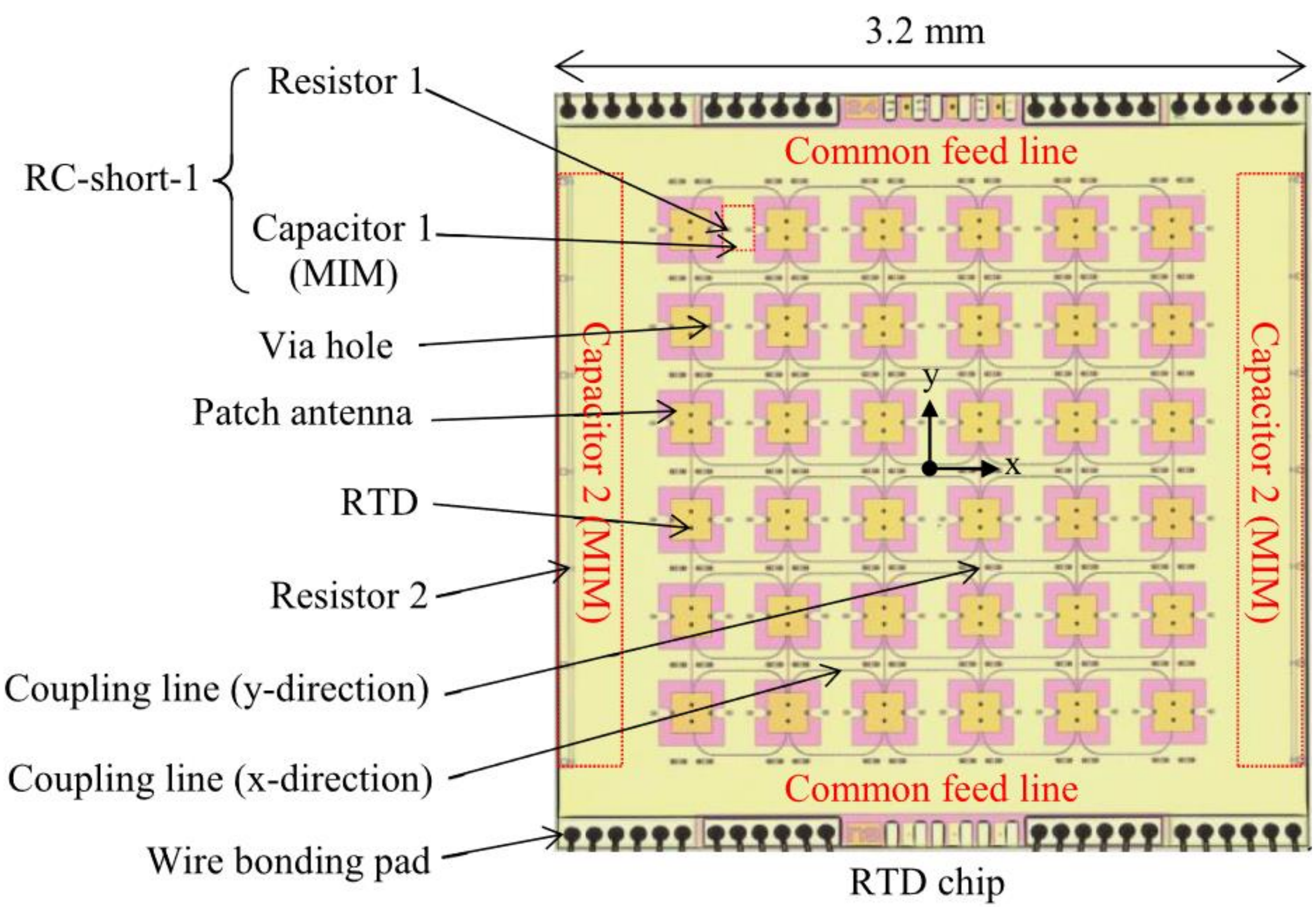
K. Kasagi, S. Suzuki, M. Asada, "Large-scale array of resonant-tunneling-diode terahertz oscillators for high output power at 1 THz ", JAP **125**, p.151601 (2019); https://doi.org/10.1063/1.5051007

Large-scale array of RTD THz oscillators



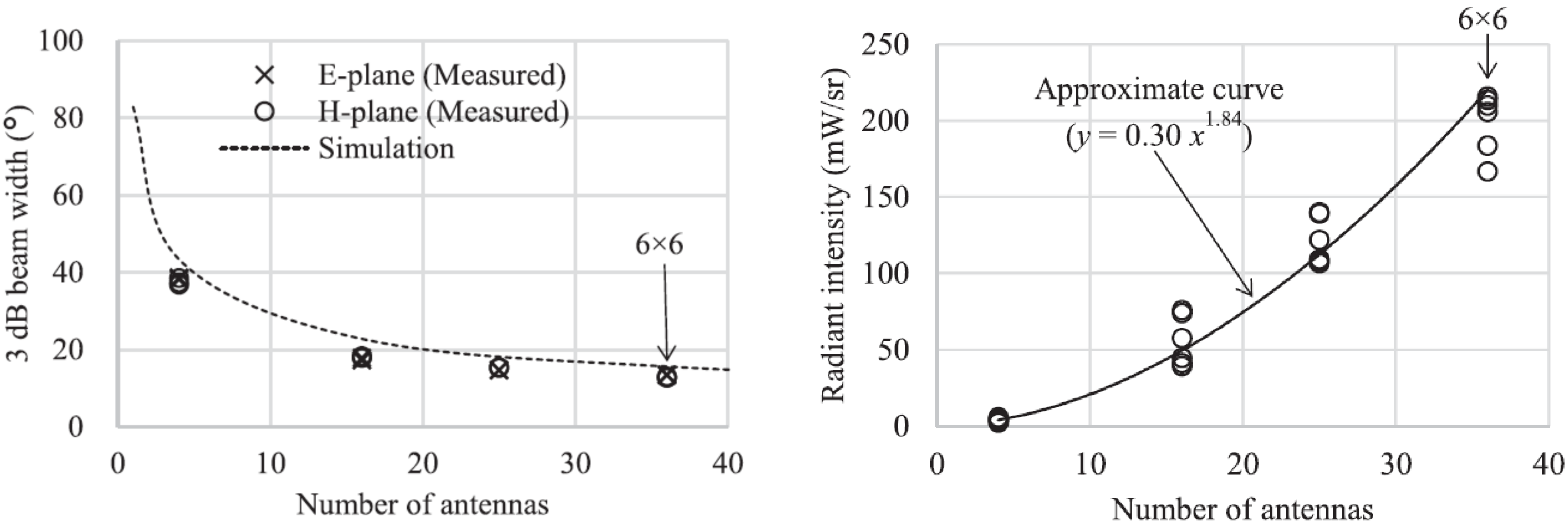
Safumi Suzuki and Masahiro Asada., "Fundamentals and recent advances of terahertz resonant tunneling diodes," Appl. Phys. Express 17, 070101 (2024), https://doi.org/10.35848/1882-0786/ad5c27

Large-scale array of RTD THz oscillators



Y. Koyama et al., "A High-Power Terahertz Source Over 10 mW at 0.45 THz Using an Active Antenna Array With Integrated Patch Antennas and Resonant-Tunneling Diodes," IEEE TTST **12**(5), pp. 510-519 (2022), doi: 10.1109/TTHZ.2022.3180492.

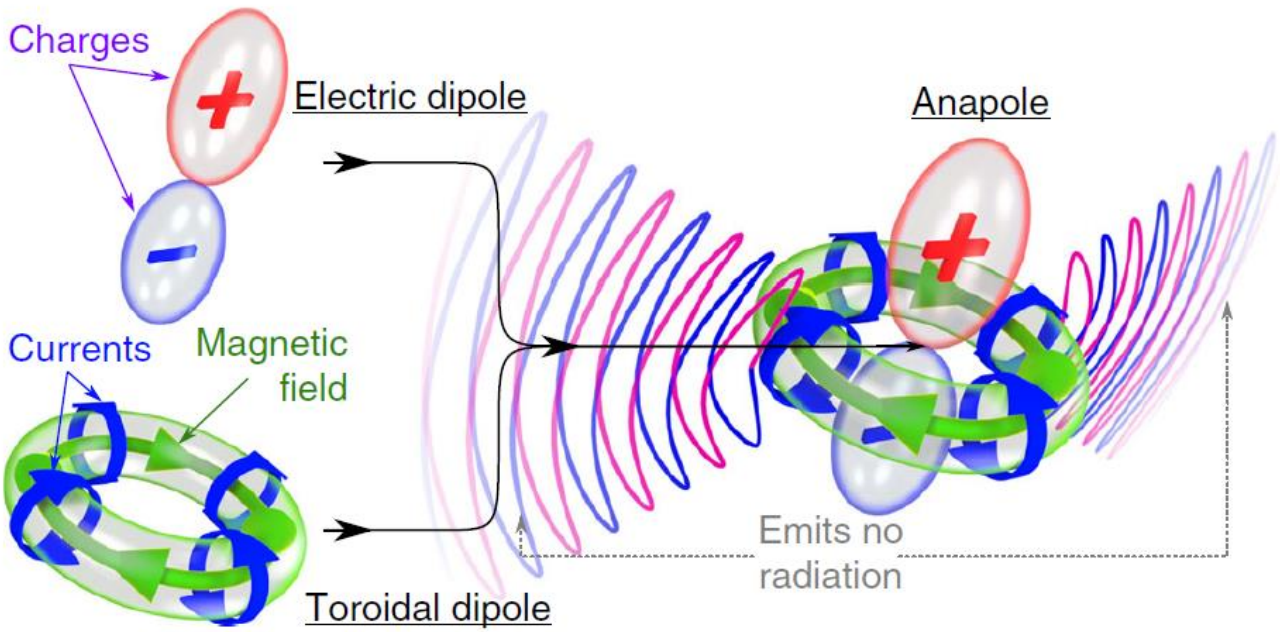
Large-scale array of RTD THz oscillators



Antenna number dependence of the measured (a) 3-dB beamwidth and (b) radiant intensity.

Y. Koyama et al., "A High-Power Terahertz Source Over 10 mW at 0.45 THz Using an Active Antenna Array With Integrated Patch Antennas and Resonant-Tunneling Diodes," IEEE TTST **12**(5), pp. 510-519 (2022), doi: 10.1109/TTHZ.2022.3180492.

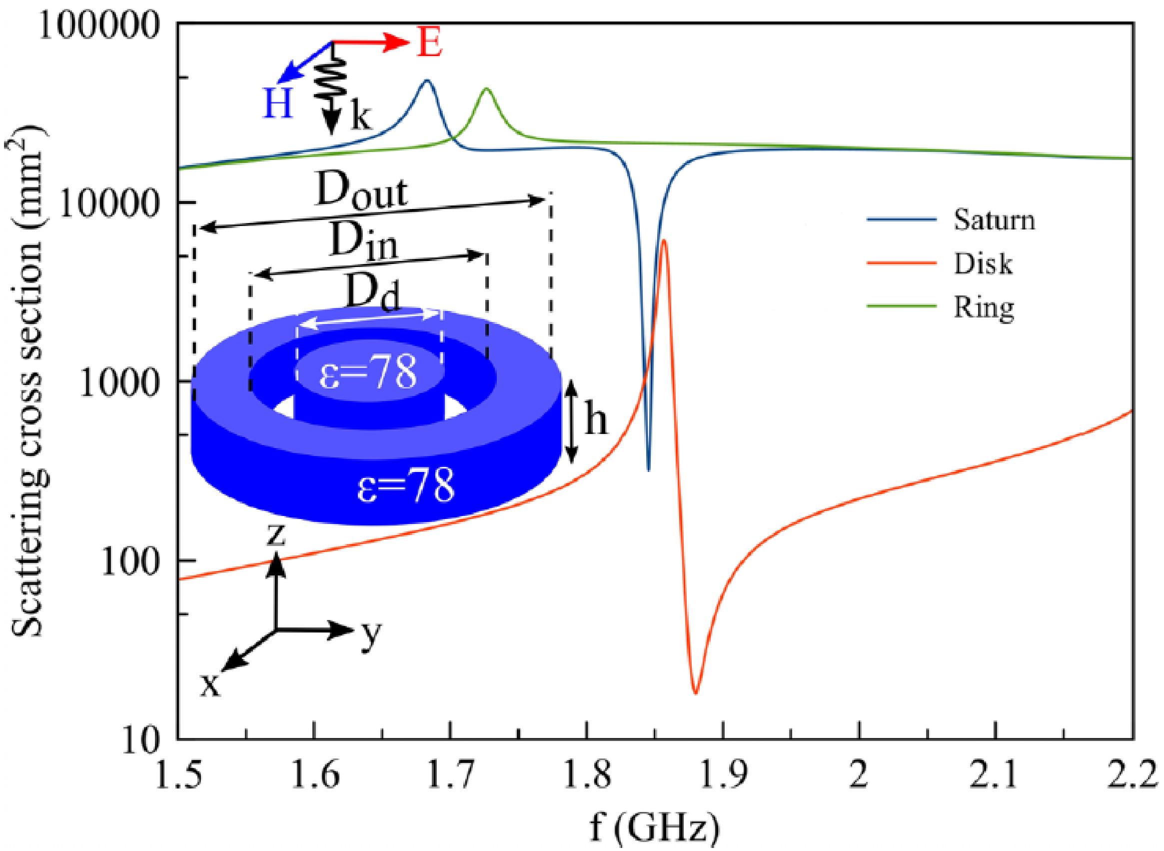
Anapoles emit no radiation



Anapole is a balanced superposition of electric and toroidal dipoles. Electric dipole corresponds to a pair of opposite charges. Toroidal dipole corresponds to a poloidal current on a torus. Anapole emerges when the fields radiated by the electric and toroidal dipoles cancel each other out

V. Savinov, N. Papasimakis, D.P. Tsai, & N.I. Zheludev, Optical anapoles. Commun Phys 2, 69 (2019).

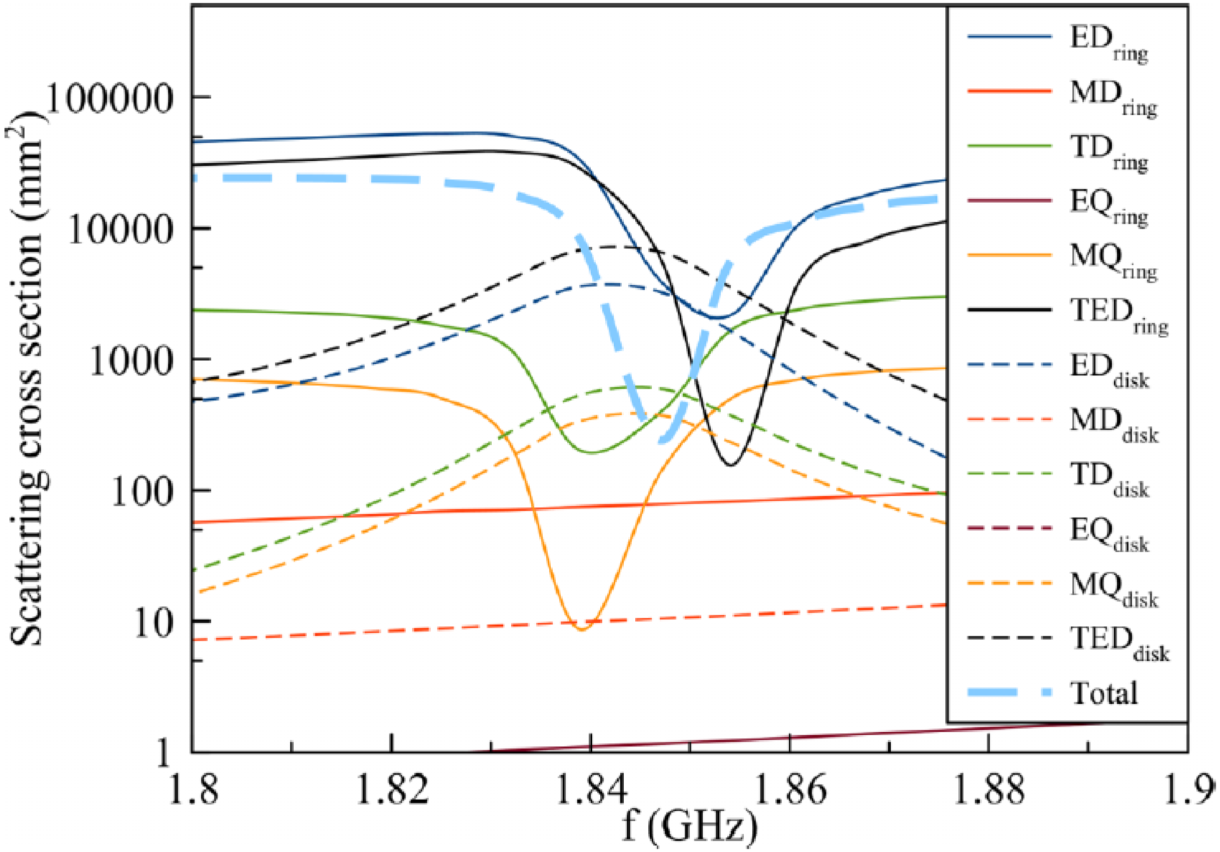
Compound Anapole



Numerically calculated SCS of the StS and separately for disk and ring irradiated by plane waves propagating along the *z*-axis with linear electric-polarization directed along the *x*-axis. Inset shows the StS with the following dimensions: *h* = 8 mm; *D*out =80 mm; *D*in = 50 mm; *D*d = 30 mm.

A.A. Basharin et al, "*Selective superinvisibility effect via compound anapole*", PRB **107**, 155104 (2023)

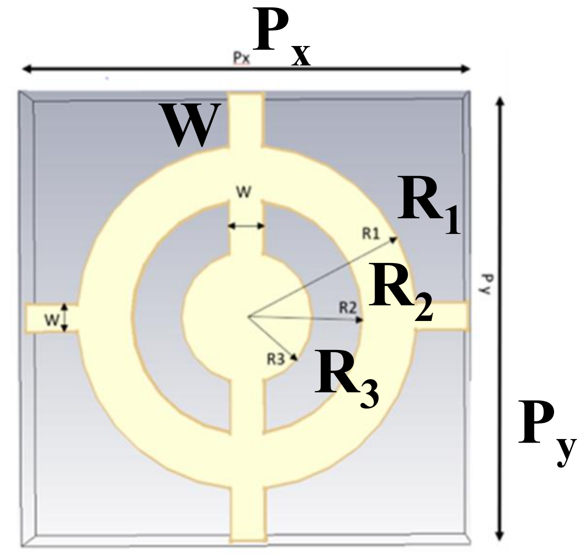
Compound Anapole



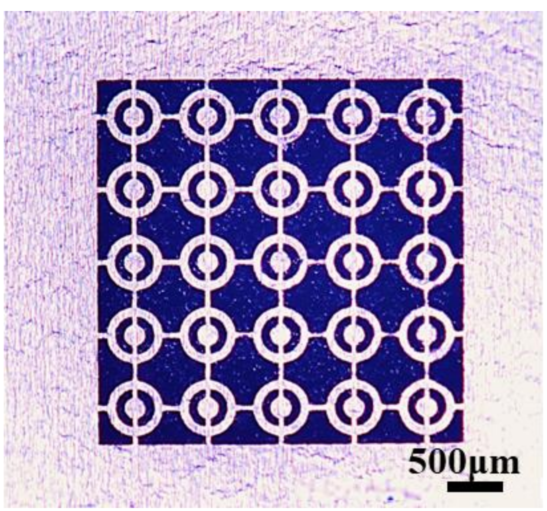
Calculated total SCS of the StS and the multipole SCSs calculated separately for the ring $(\cdot)_{ring}$ in the presence of the disk and for the disk $(\cdot)_{disk}$ in the presence of the ring.

A.A. Basharin et al, "*Selective superinvisibility effect via compound anapole*", PRB **107**, 155104 (2023)

Samples & Methods

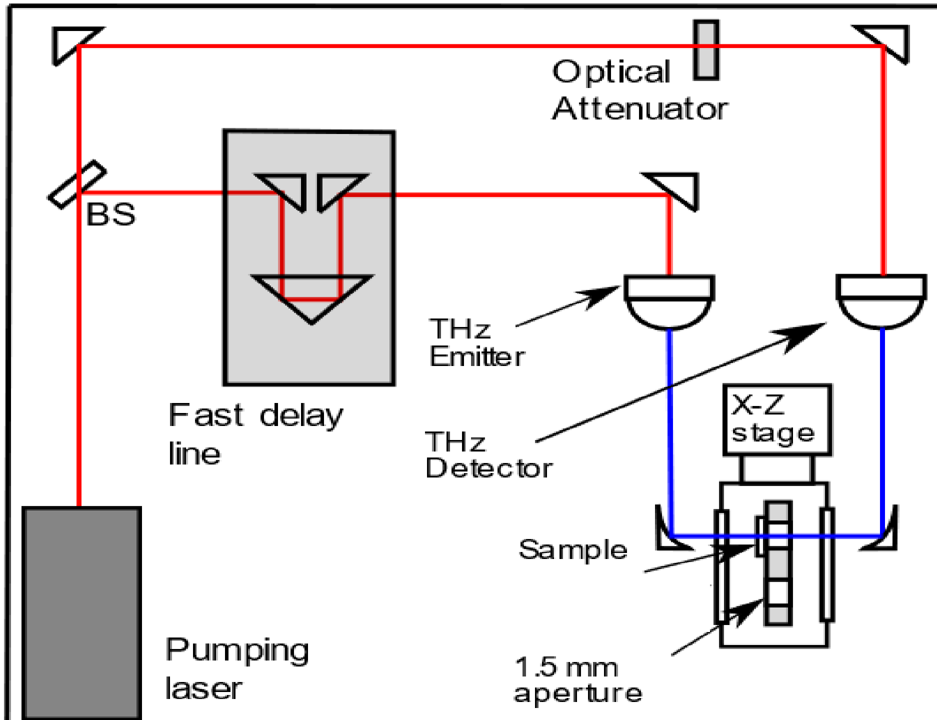


Schematic representation



DLA fabricated 5x5 sample

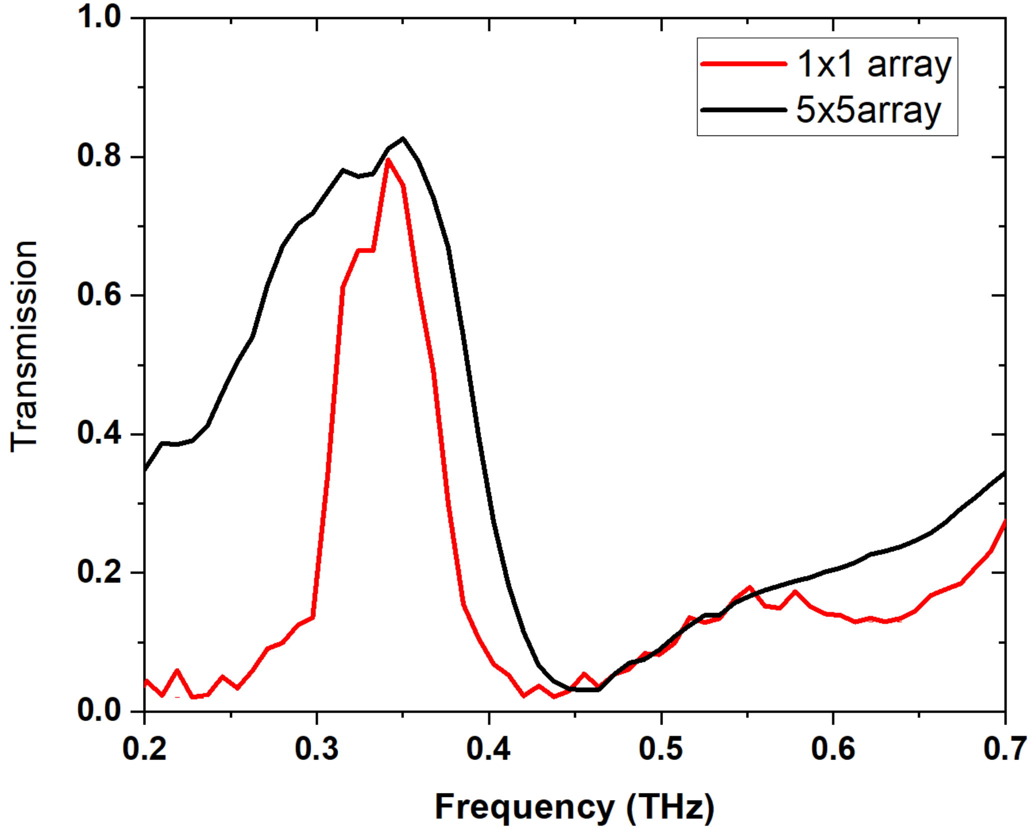
R1=250 µm, R2=170 µm, R3=96 µm, W=42 µm, P_x= P_y= 650 µm.
A stainless steel of 50 µm thickness.



Experimental setup based on THz TDS system

S.R. Ayyagari et al, Proc IRMMW-THz (2022)

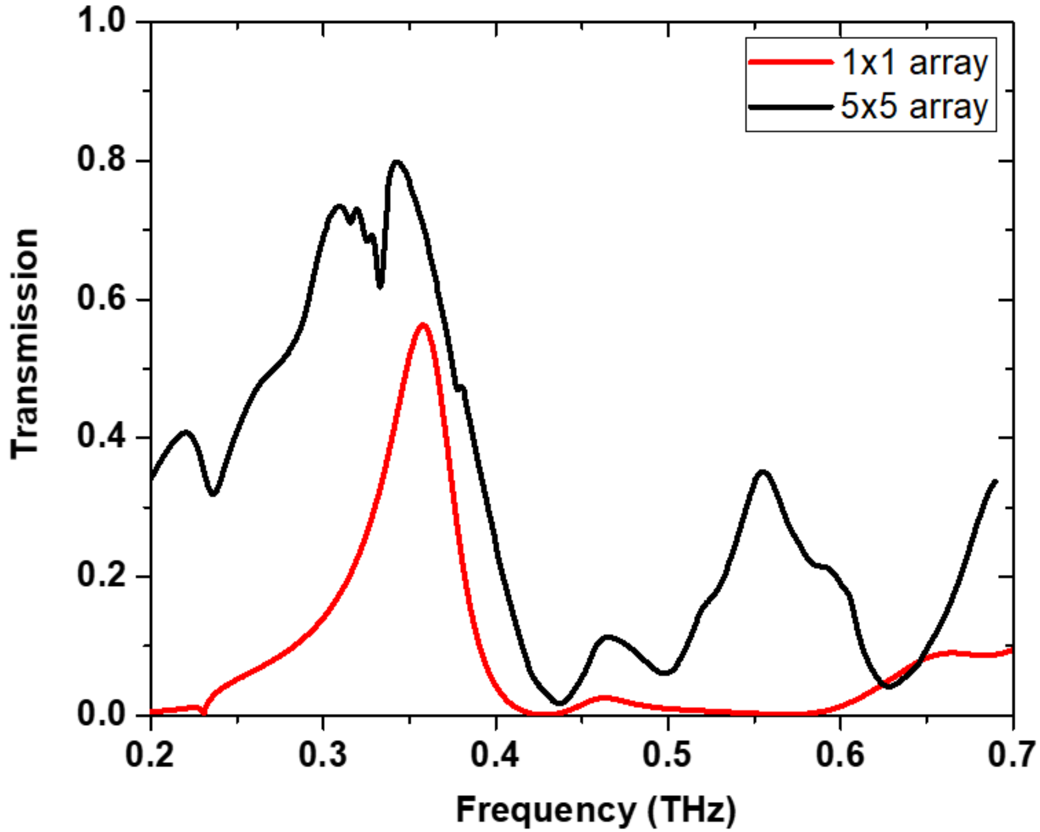
Results experiment



THz-TDS measurements. of the transmission spectra at TM polarization of the sample composed of 5x5 array (black color) and single (red color) meta-atom in a frame.

S.R. Ayyagari et al, Proc IRMMW-THz (2022)

Results modelling



FDTD simulations of the transmission spectra at TM polarization of the sample composed of 5x5 array (black color) and single (red color) meta-atom in a frame.

S.R. Ayyagari et al, Proc IRMMW-THz (2022)

Bandwidth and Q-factor

Amount of meta-atoms	Bandwidth (Δ*f*) Sim/Exp	Peak frequency (*f*) Sim/Exp	Q-factor (*f*/Δ*f*) Sim/Exp
1 (single element)	46GHz/71GHz	350GHz/340GHz	7.6/4.8
4 (2x2 array)	159GHz/148GHz	361GHz/360GHz	2.3/2.4
25 (5x5 array)	160GHz/172GHz	345GHz/350GHz	2.1/2.0
100 (10x10 array)	175GHz/184GHz	346GHz/340GHz	1.9/1.8 (4 times drop)

S.R. Ayyagari et al, Proc IRMMW-THz (2022)

S.R. Ayyagari et al, (under publication)

Conclusions

- ✓ Anapole modes in the ring-shaped subwavelength periodic structures fabricated on optically thin metal film have been investigated experimentally and numerically.
- ✓ We found the increase of the resonance FWHM with the number of meta-atoms attributing effect to the collective response of the meta-atoms (mutual coupling).
- ✓ Compound Anapole was observed at frequency of about 462 GHz, for case of the infinite number of ring-shaped subwavelength periodic structures on optically thin metal film.

Thank you for your attention!

Questions?

Acknowledgement

This work received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie ITN project TERAOPTICS (grant No. 956857).