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Low dimensional plasmonic spectroscopy through inversion of the far infrared detection problem

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[1]Sandia Nat'l Labs, [2]Kingsborough College (CUNY), [3]The Univ. of Texas at Dallas

SPIE D+CS 2016: Terahertz Physics, Devices, and Systems X
THz: Advanced Concepts I, Paper 9856-6, 4/17/16

CUNY The City University of New York

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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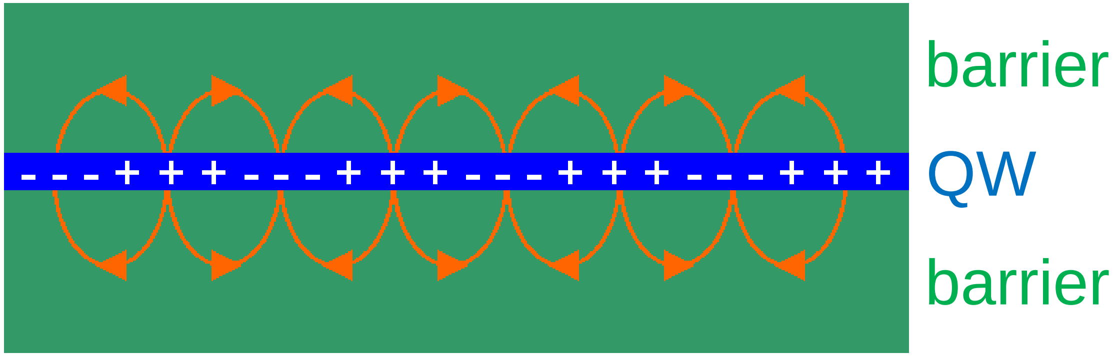
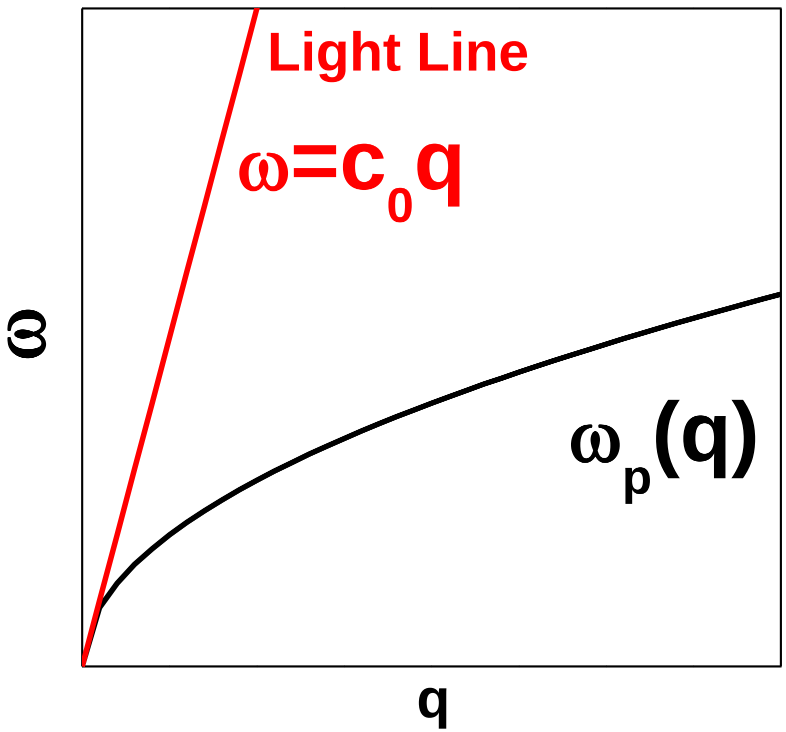
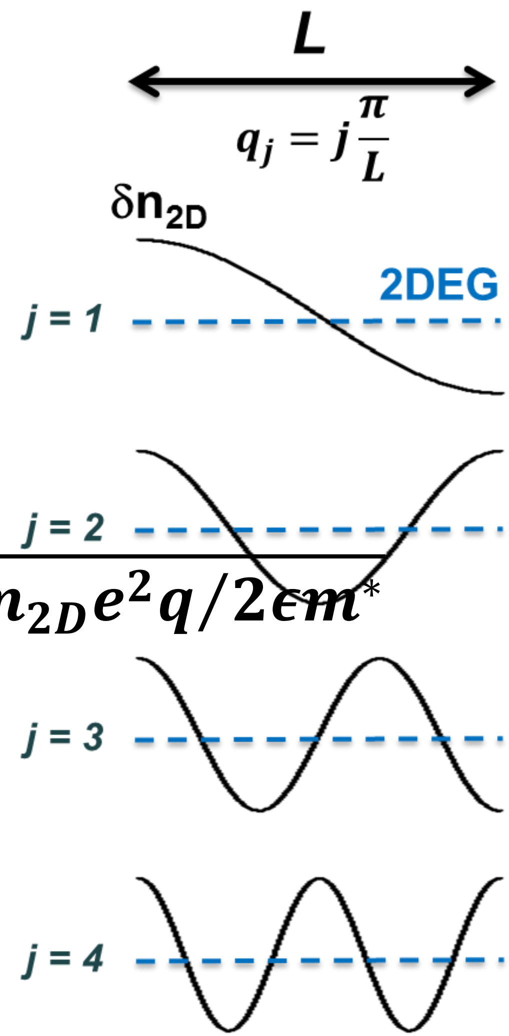
Outline

- Low dimensional far infrared plasmonics
- GaAs/AlGaAs 2D plasmonic resonators
  - Strong coupling of 2D plasmonic resonators
  - Coupled oscillator & transmission line models
  - Active control of plasmonic crystal band structure
- Edge photoresponse in inverted InAs/GaSb double quantum wells

Low Dimensional Plasmonics







$$\omega_p = \sqrt{n_{2D}e^2q/2\epsilon m^*}$$

FIR 2D Plasmonic Systems

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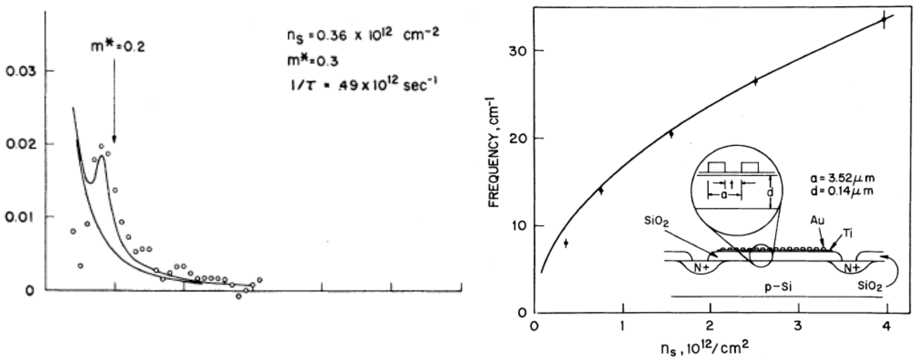
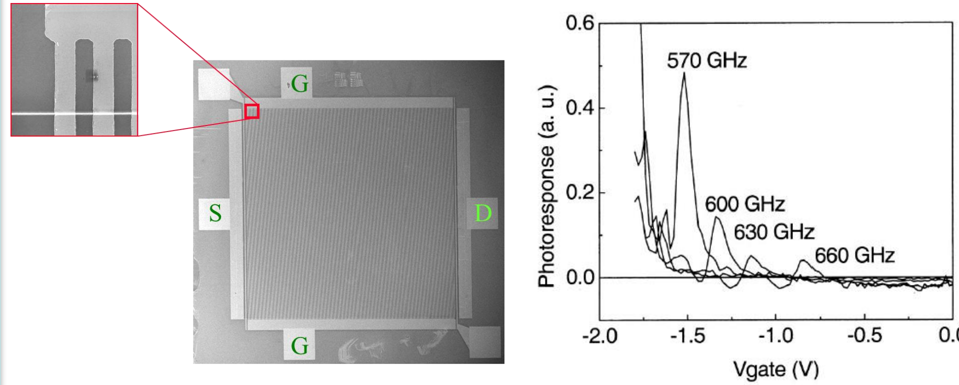
Grating Gated Si MOSFETs



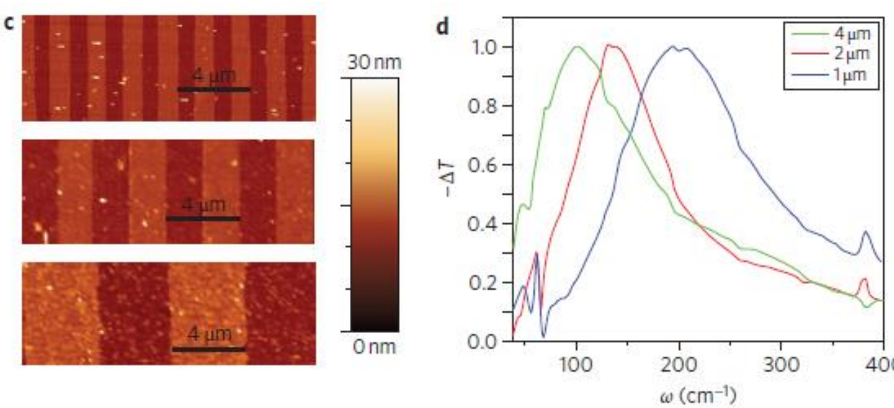
S.J. Allen *et al.*, *PRL* **38**, 980 (1977)

Grating Gated GaAs/AlGaAs HEMTs



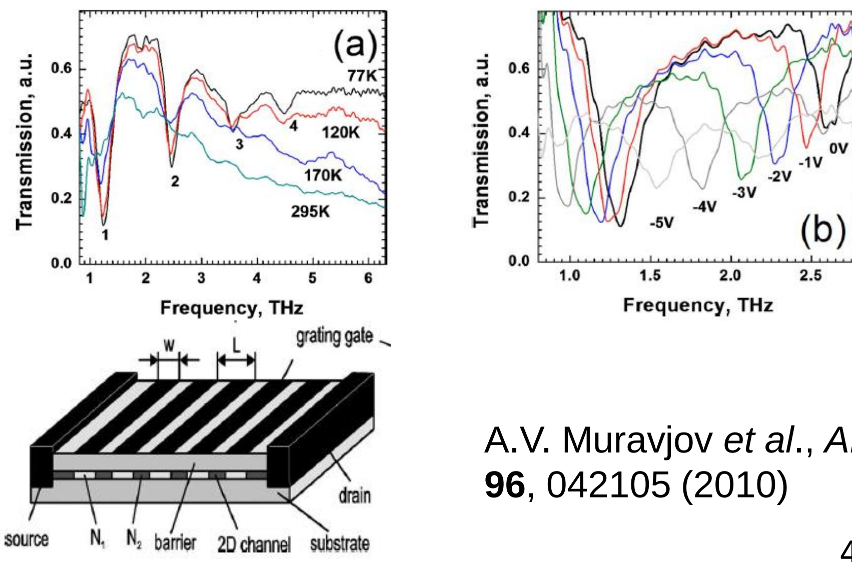
X.G. Peralta *et al., APL* **81**, 1627 (2002)

Graphene Gratings



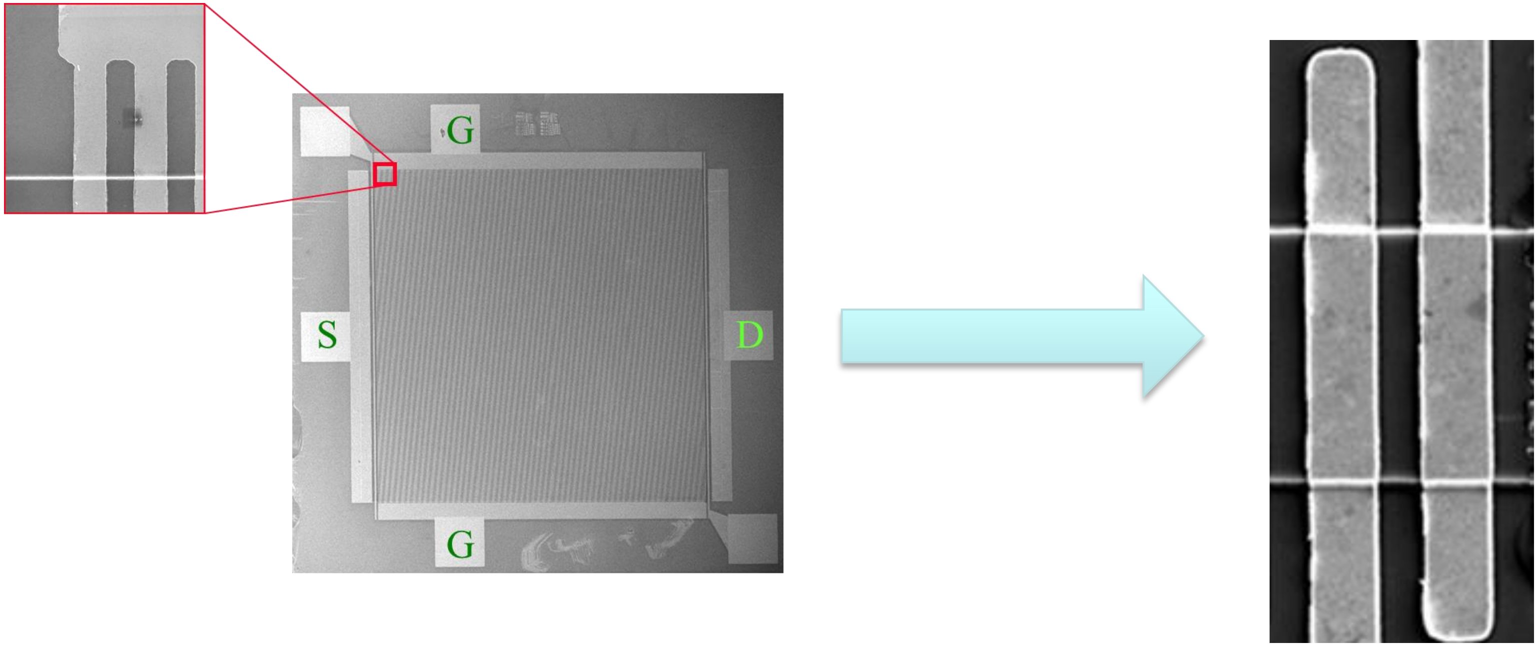
L. Ju *et al.*, *Nat. Nano.* **6**, 630 (2011)

Grating Gated GaN/AlGaN HEMTs



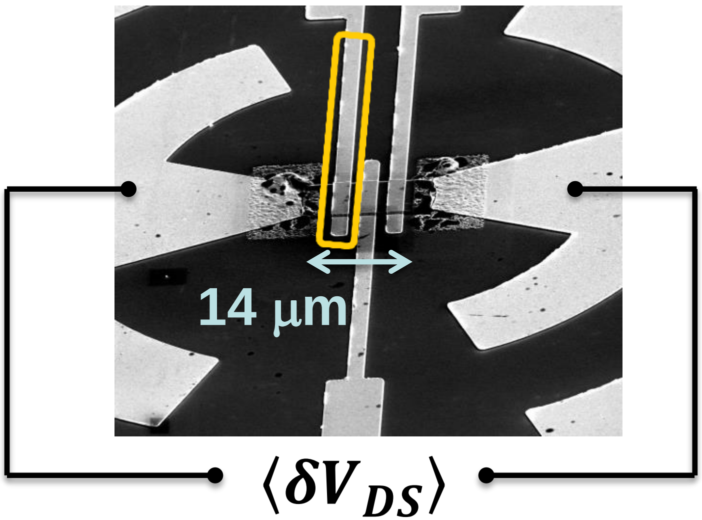
A.V. Muravjov *et al.*, *APL* **96**, 042105 (2010)

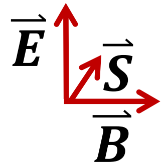
From Plasmonic Arrays to Elements



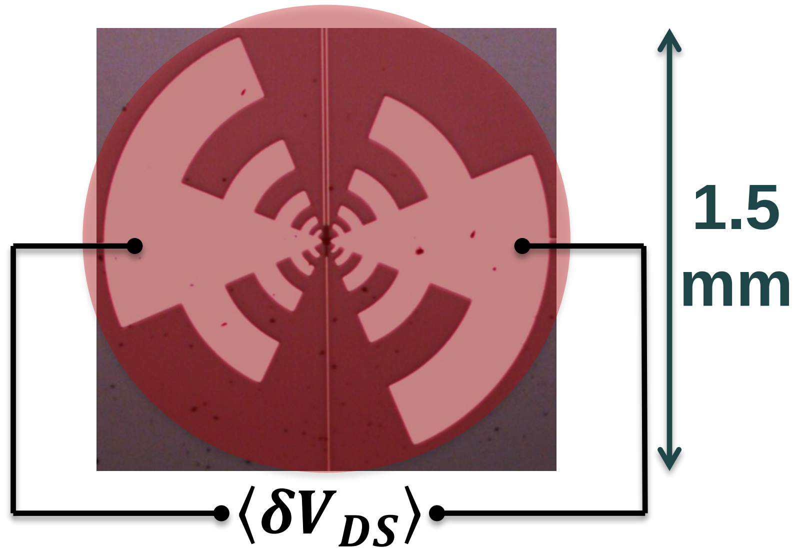
- Plasmon-plasmon coupling
- Plasmonic dispersion in coupled structures
- Plasmon damping & coherence length

Integrated 2D Plasmonic Devices

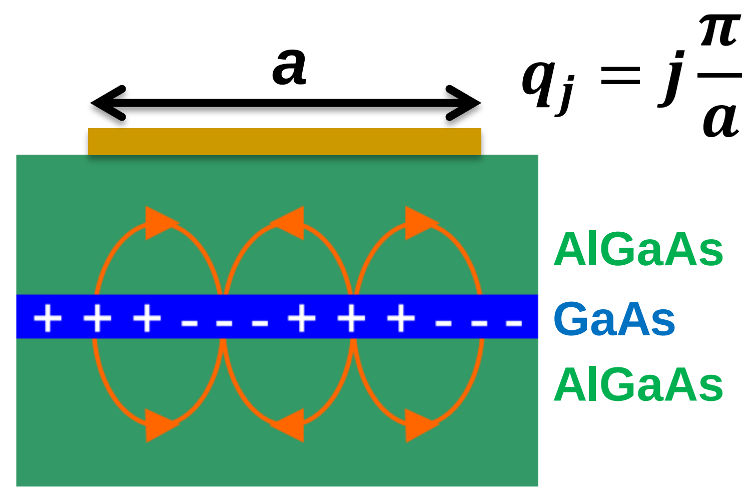




0.1 - 0.5 THz

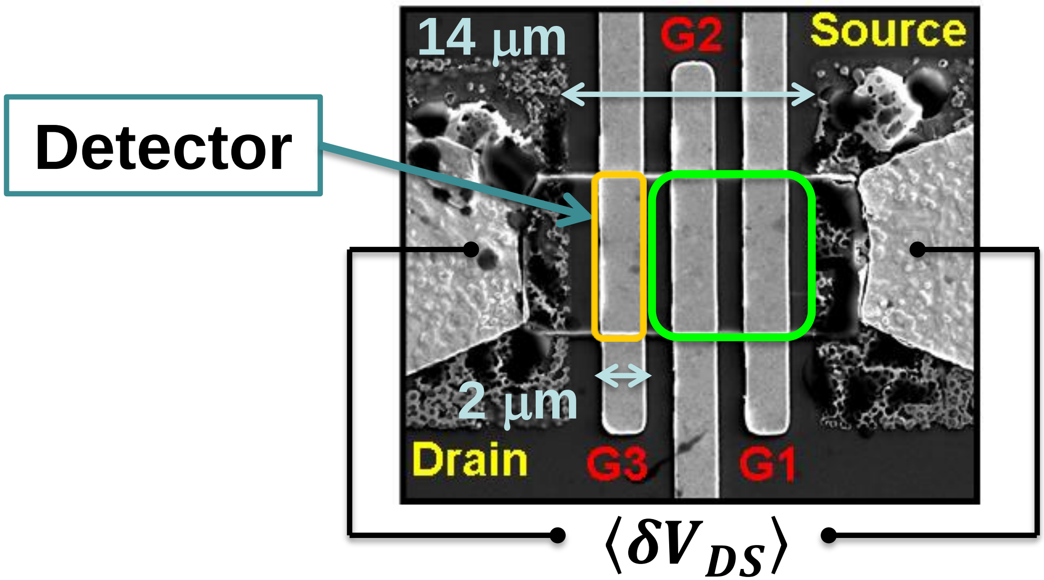


- **Detection**: depleted 2DEG
- **Coupling**: log-periodic antenna
- **Resonance**: 2D plasmon wavelength set by device geometry



G.C. Dyer *et al.*, *Phys. Rev. Lett.* **109**, 126803 (2012) & G.C. Dyer *et al.*, *Appl. Phys. Lett.* **100**, 083506 (2012)

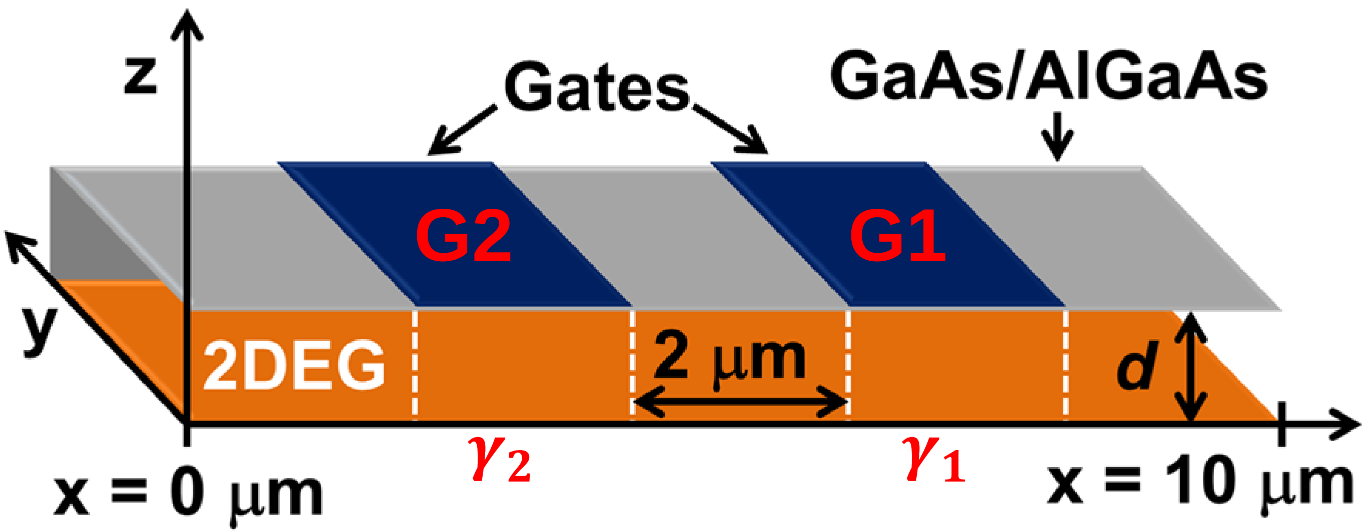
Inhomogeneous 2DEG Structures



Normalized 2DEG Density

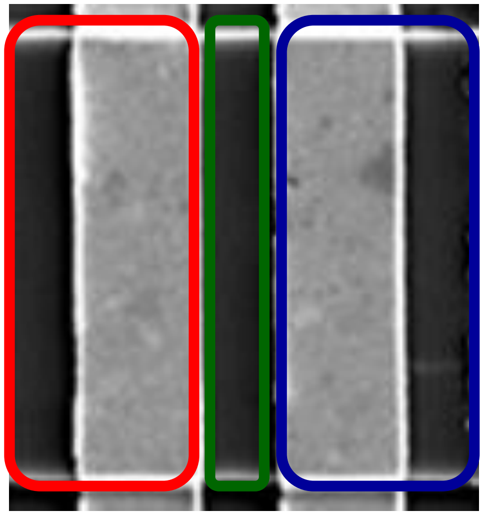
$$\gamma_1 = \frac{V_{th} - V_{G1}}{V_{th}}$$

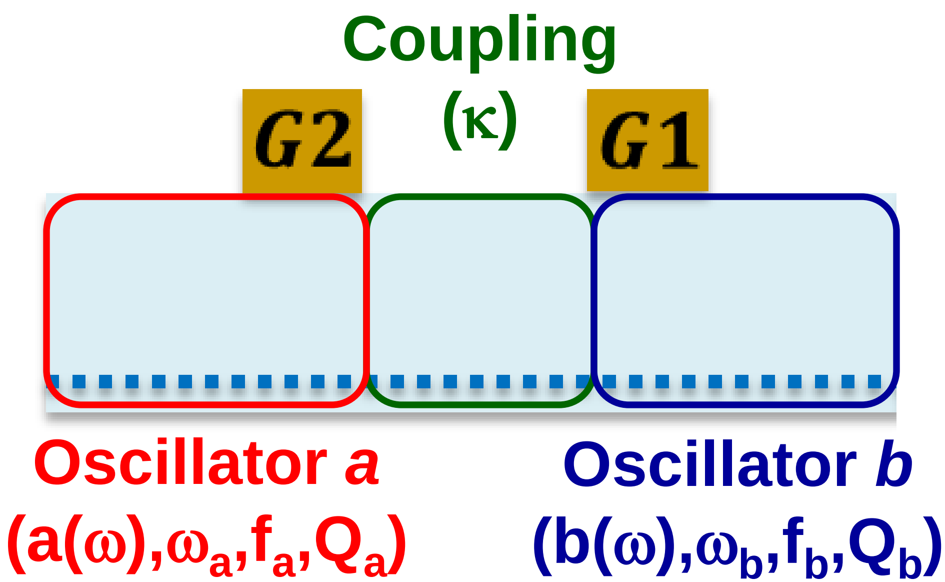
$$\gamma_2 = \frac{V_{th} - V_{G2}}{V_{th}}$$

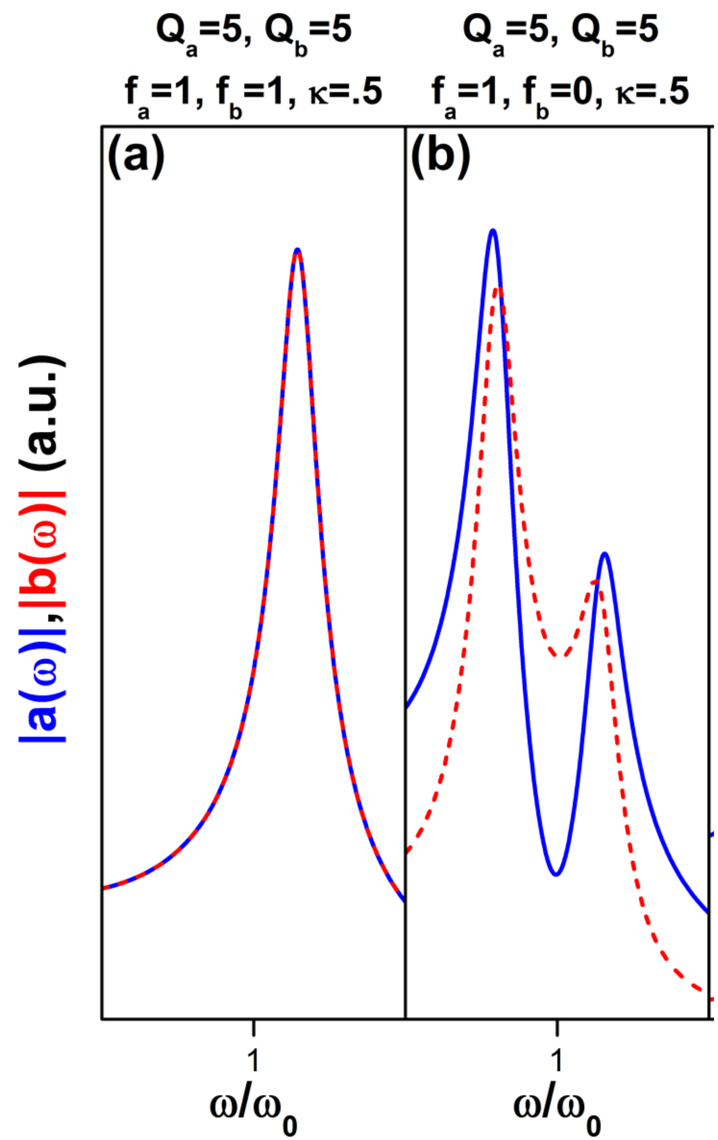


G.C. Dyer *et al.*, *Phys. Rev. Lett.* **109**, 126803 (2012) & G.C. Dyer *et al.*, *Appl. Phys. Lett.* **100**, 083506 (2012)

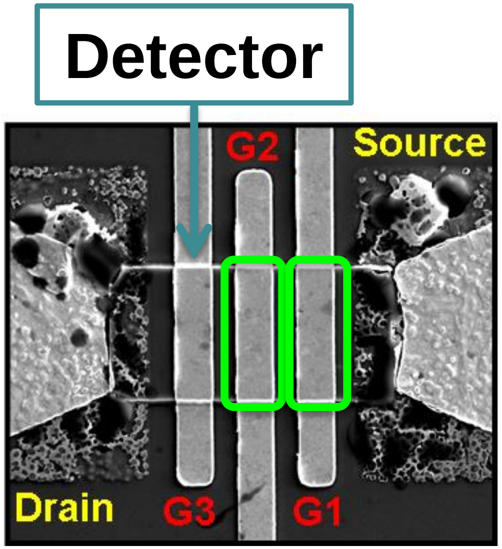
Coupled Resonator Description





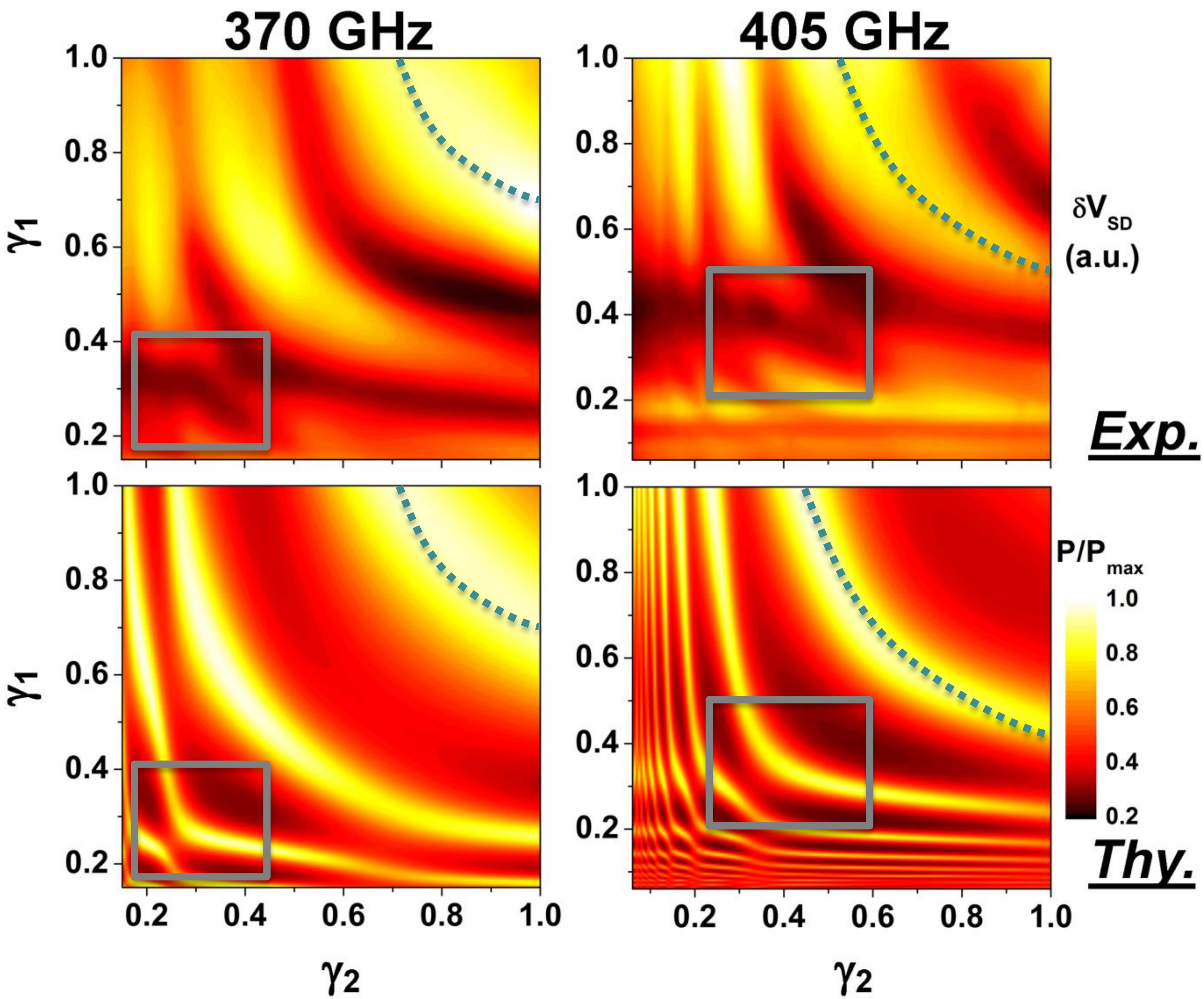


Coherent Plasmonic Coupling



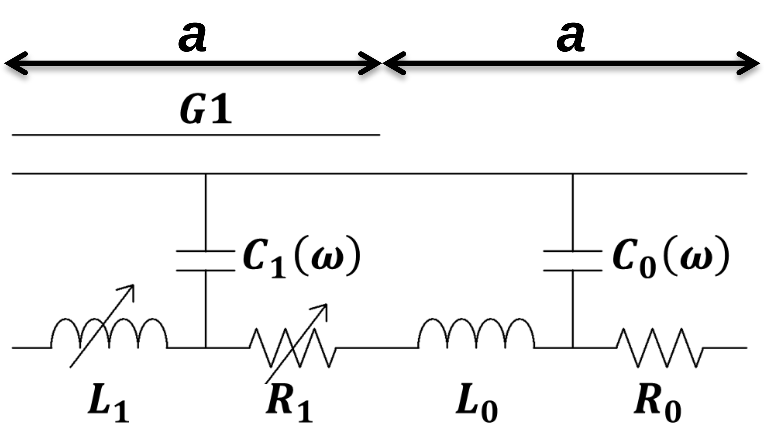
$$\gamma_{1,2} = \frac{V_{th} - V_{G1,G2}}{V_{th}}$$

Strongly coupled 2D plasmonic resonators



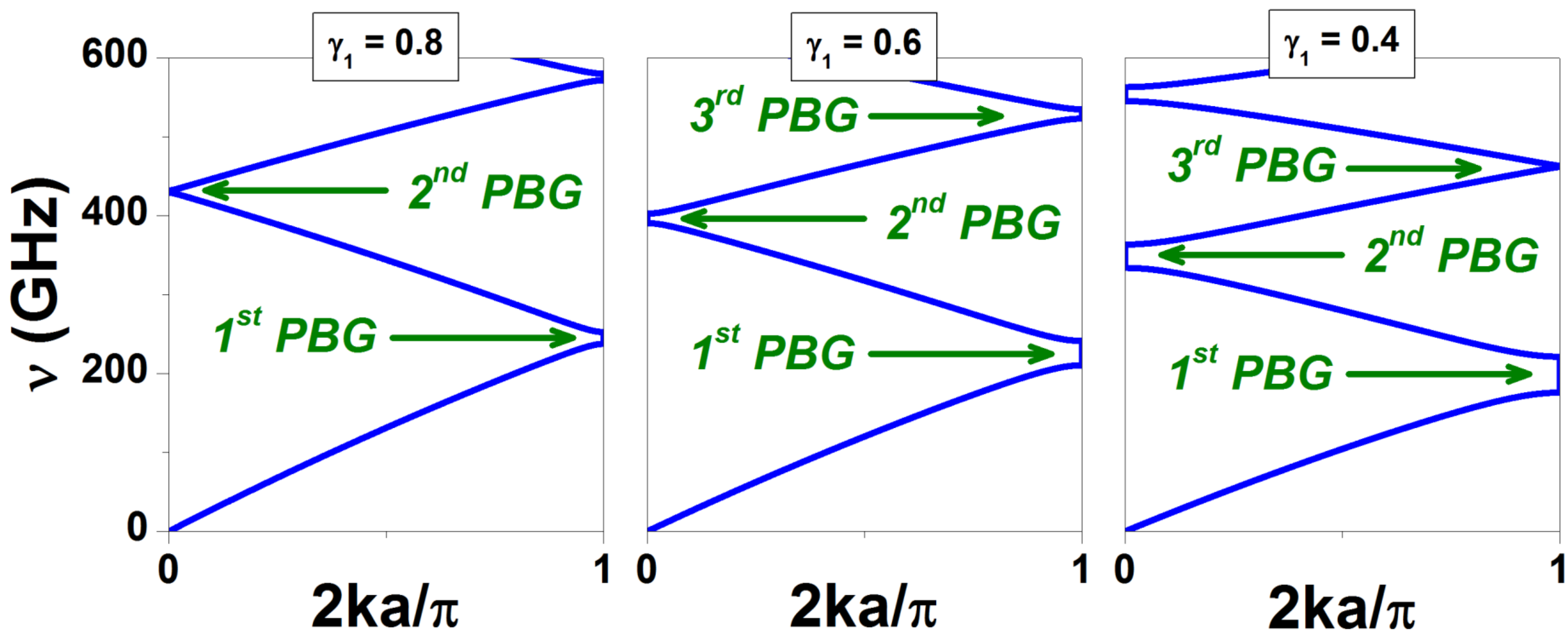
G.C. Dyer *et al.*, *Phys. Rev. Lett.* **109**, 126803 (2012)

Plasmonic Crystal Band Structure

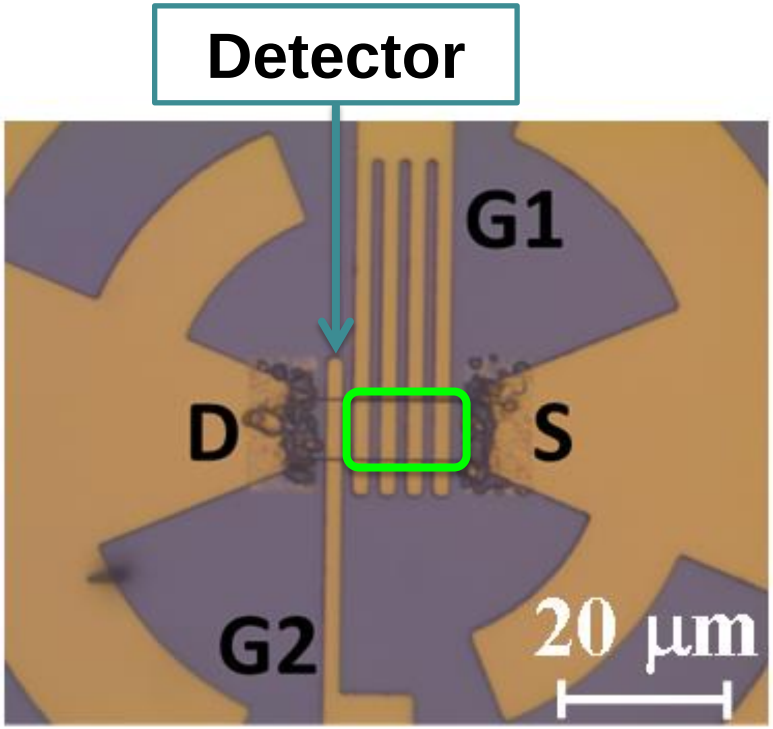


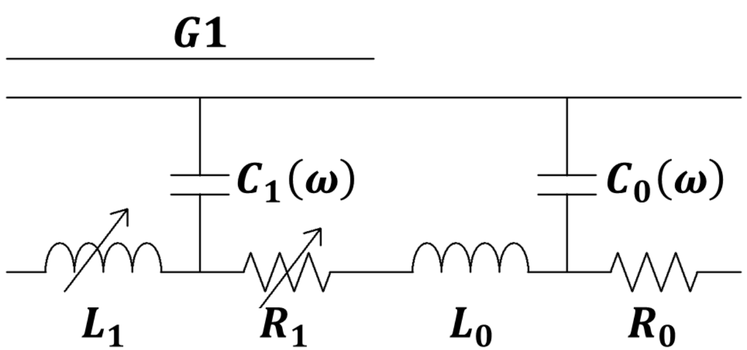
1D Kronig-Penney:

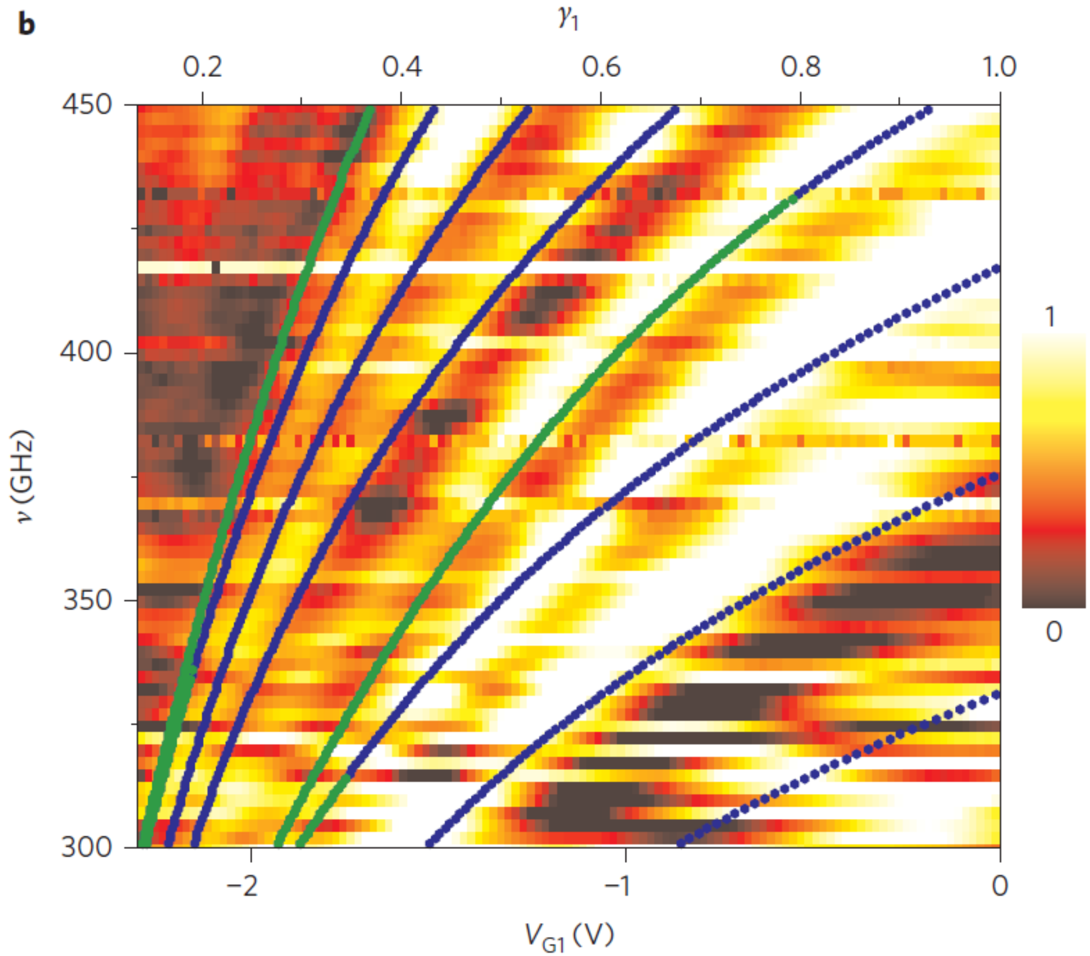
$$\cos 2k_B a = \cos q_0 a \cos q_1 a - \frac{1}{2}\left(\frac{Z_0}{Z_1}+\frac{Z_1}{Z_0}\right)\sin q_0 a \sin q_1 a$$



Four Period Plasmonic Crystal



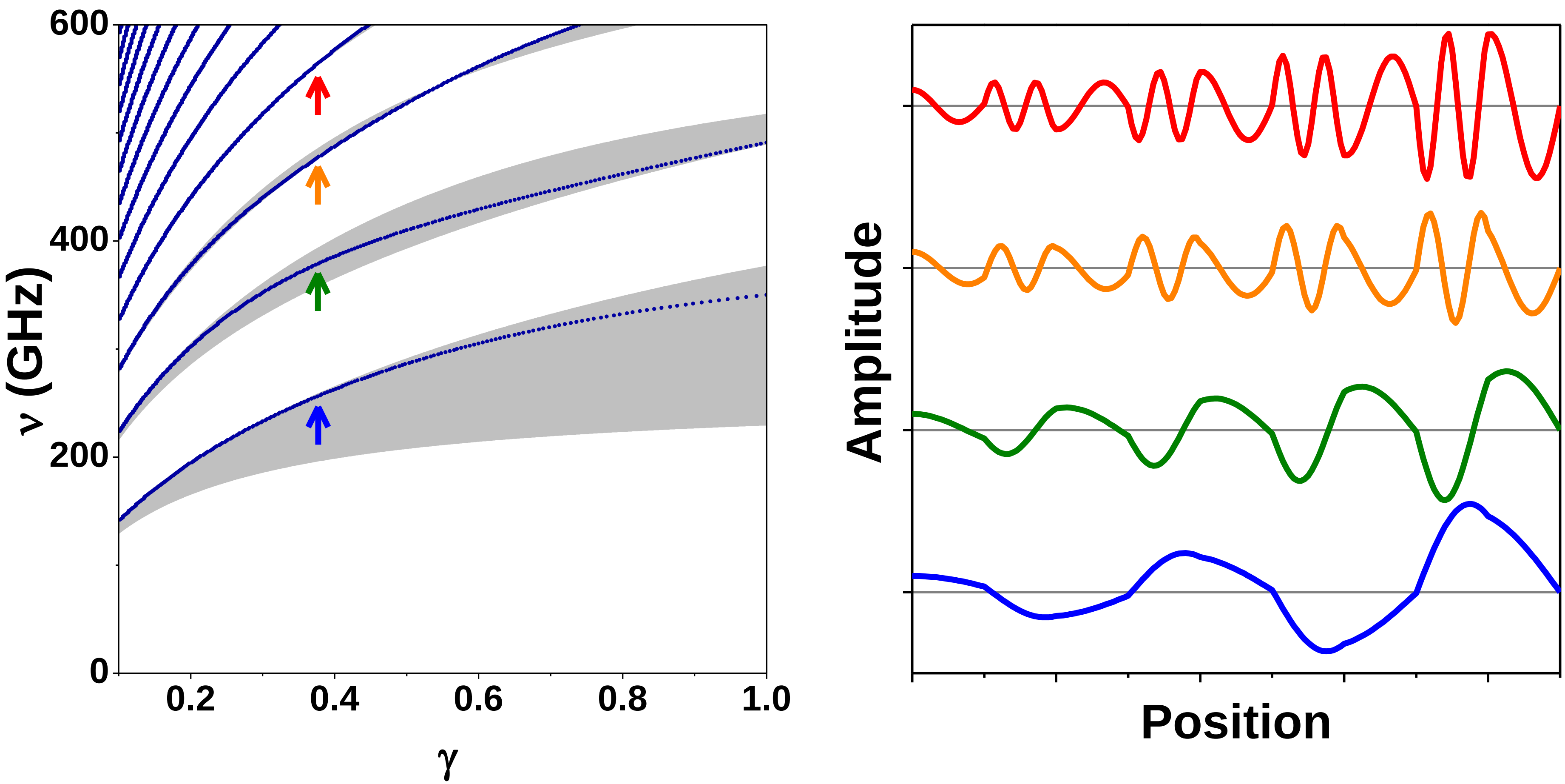




$$V_{G1} \to 0, L_1 \to \infty$$

G.C. Dyer *et al.*, *Nature Photonics*, **7**, 925 (2013)

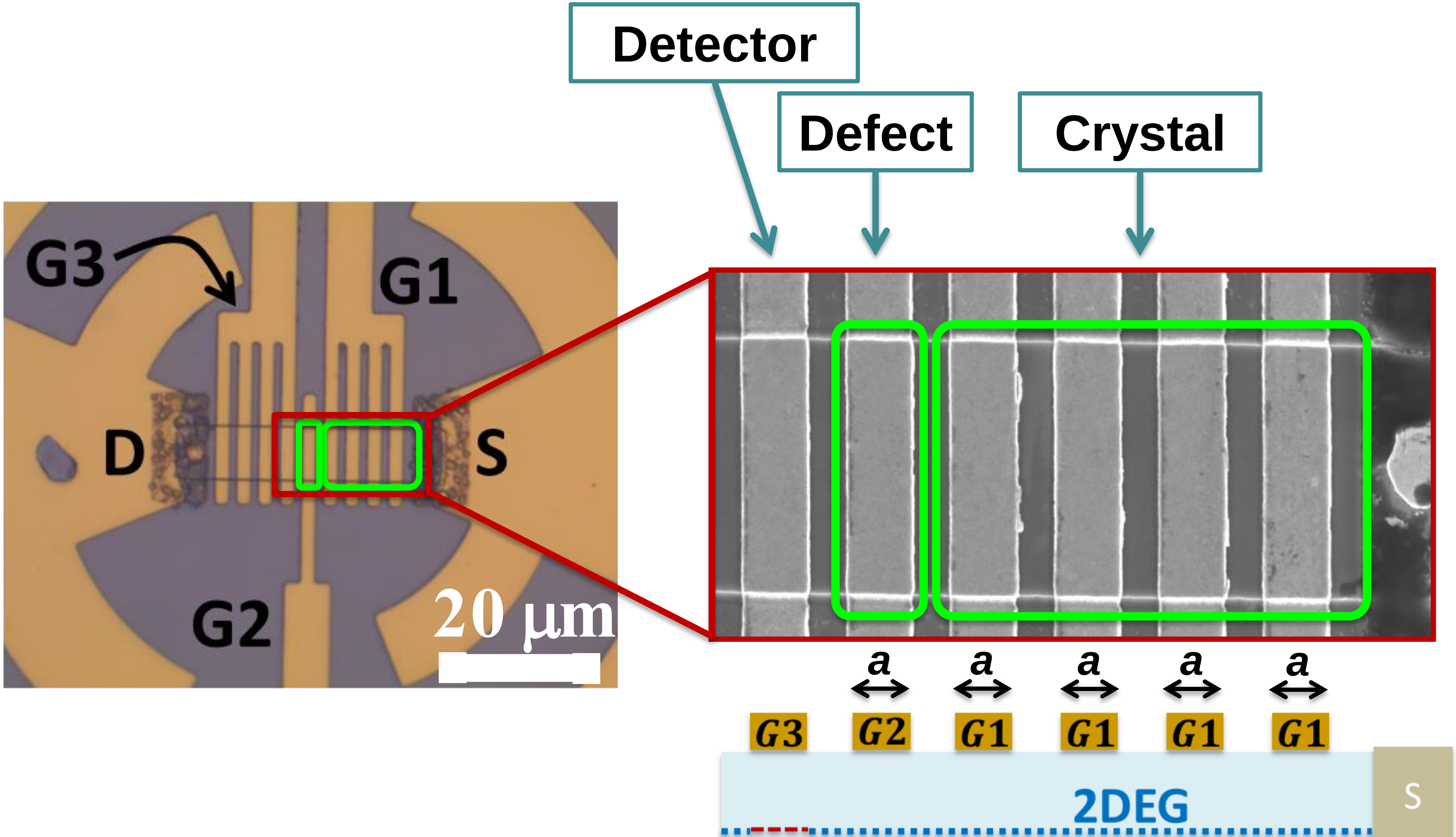
Plasmonic Tamm States



Crystal surface states typically found in crystal band gap that have complex Bloch wavevector $(Im[k_B] \neq 0)$

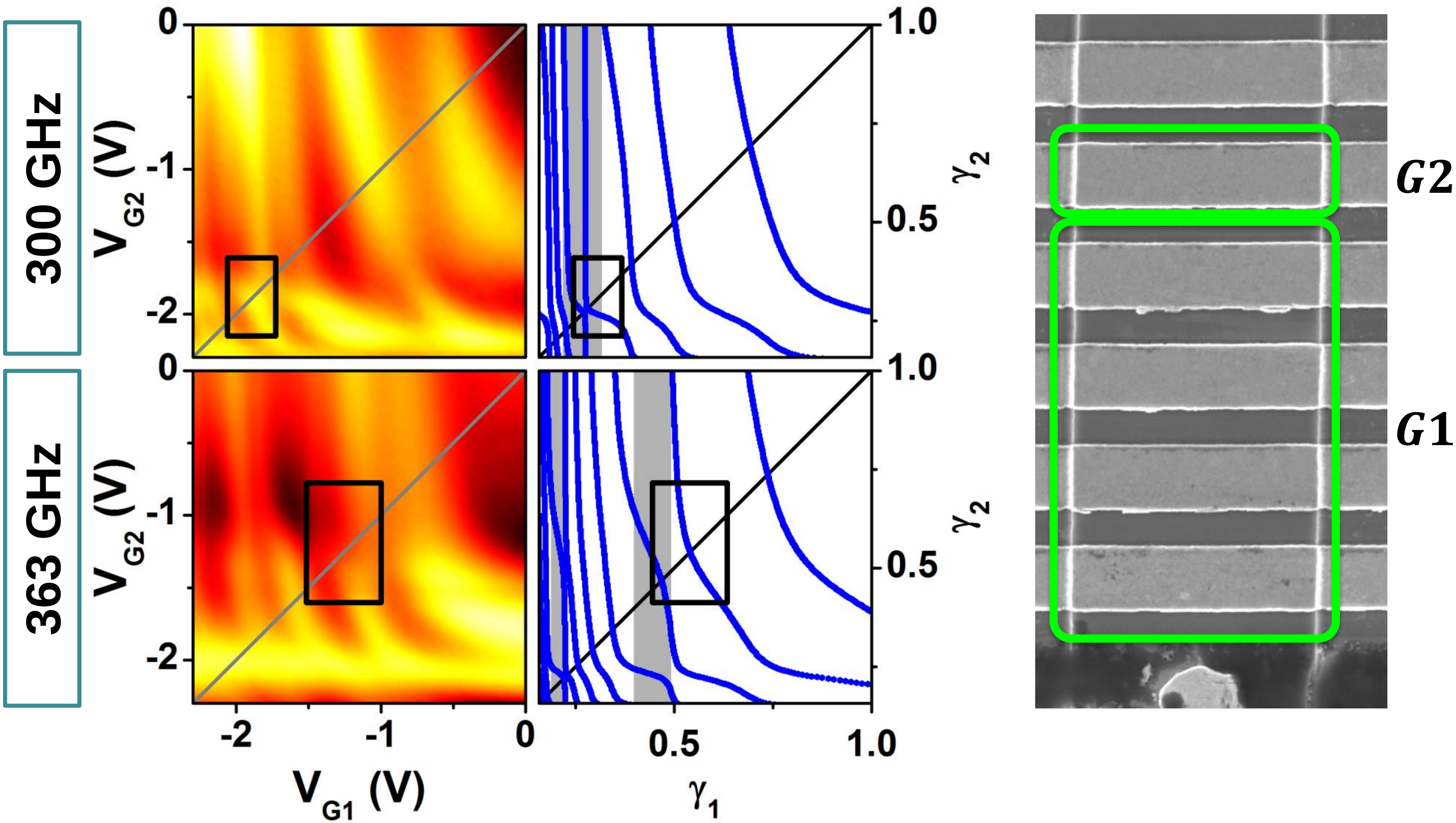
G.R. Aizin and G.C. Dyer, *Phys. Rev. B* **86**, 235316 (2012)

Defect Probing of Tamm States



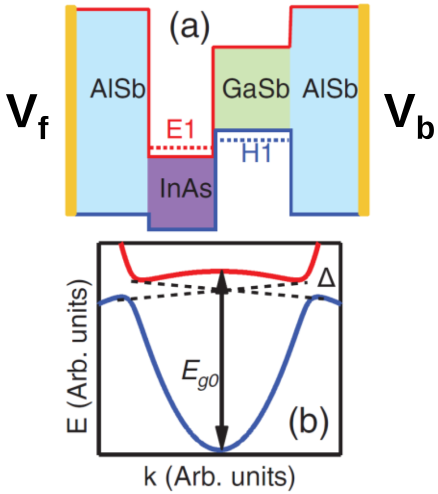
G.C. Dyer *et al.*, *Nature Photonics*, **7**, 925 (2013)

Coupled Tamm & Defect States

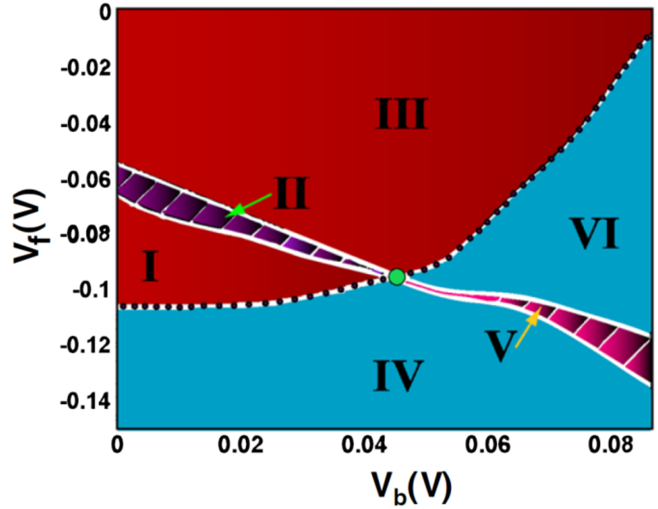


G.C. Dyer *et al.*, *Nature Photonics*, **7**, 925 (2013)

Quantum Spin Hall Insulators



Knez *et al.*, *Phys. Rev. Lett.*, **107**, 136603 (2011)



C. Liu *et al.*, *Phys. Rev. Lett.*, **100**, 236601 (2008)

Inverted Band Structure
I: p > n
II: QSH phase
III: n > p

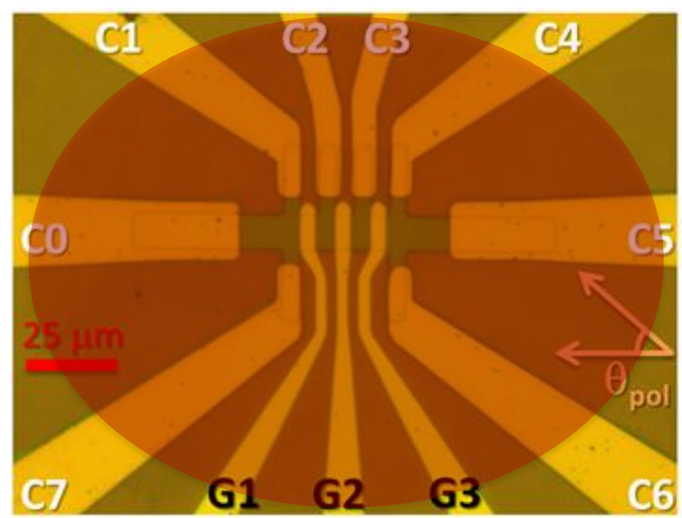
Normal Band Structure
IV-VI: p-type, insulating, n-type

<u>Direct Current Phenomenology</u>

- Spin Polarized Helical Edge Transport
- Quantized Conductance

<u>Terahertz Response</u>

- Lateral p-n rectifiers ?
- 2D plasmons ?
- Edge modes ?



G.C. Dyer *et al.*, *App. Phys. Lett.*, **108**, 013106 (2016)

InAs/GaSb DQW Device

Longitudinal

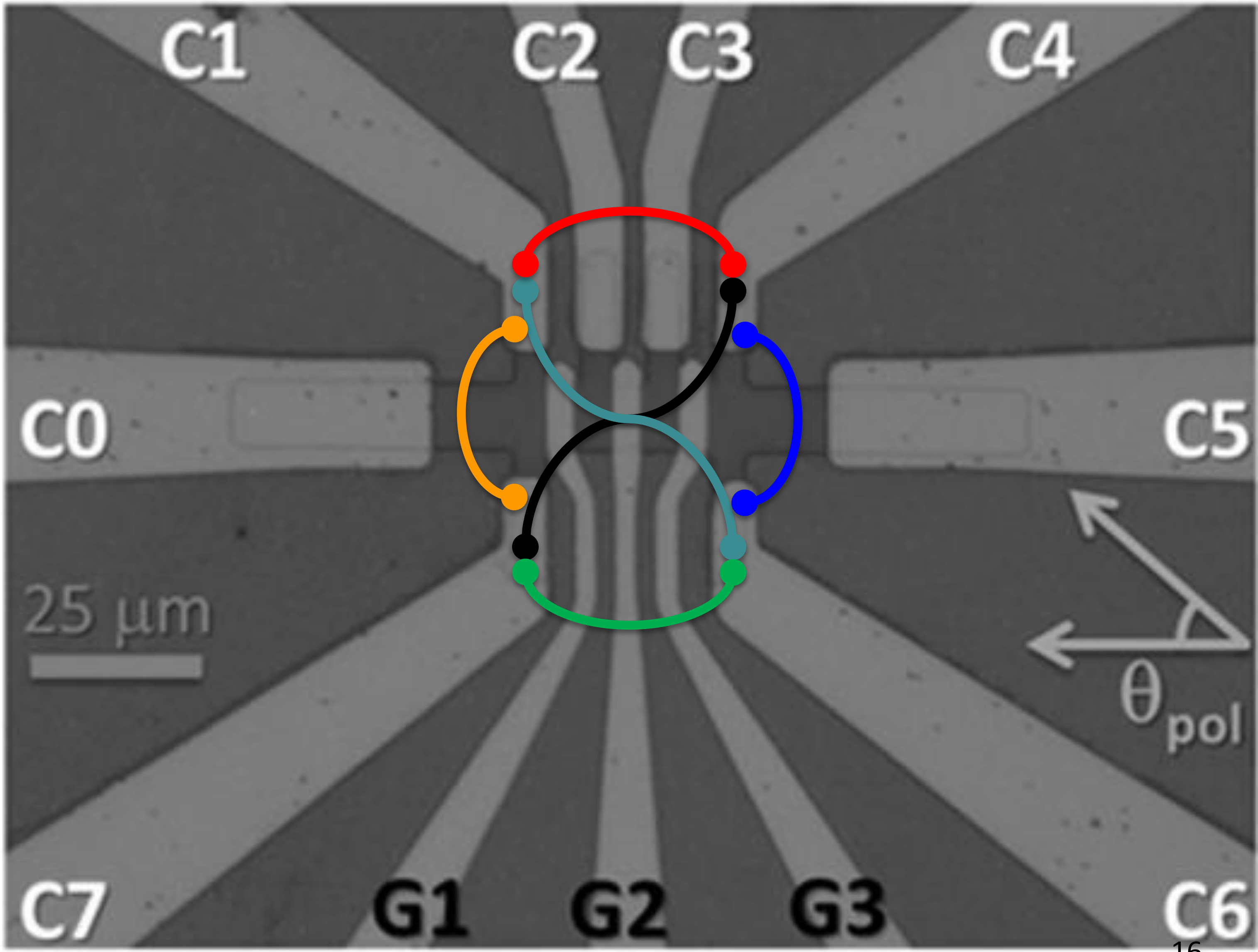
V_{67}
V_{41}

Transverse

V_{46}
V_{17}

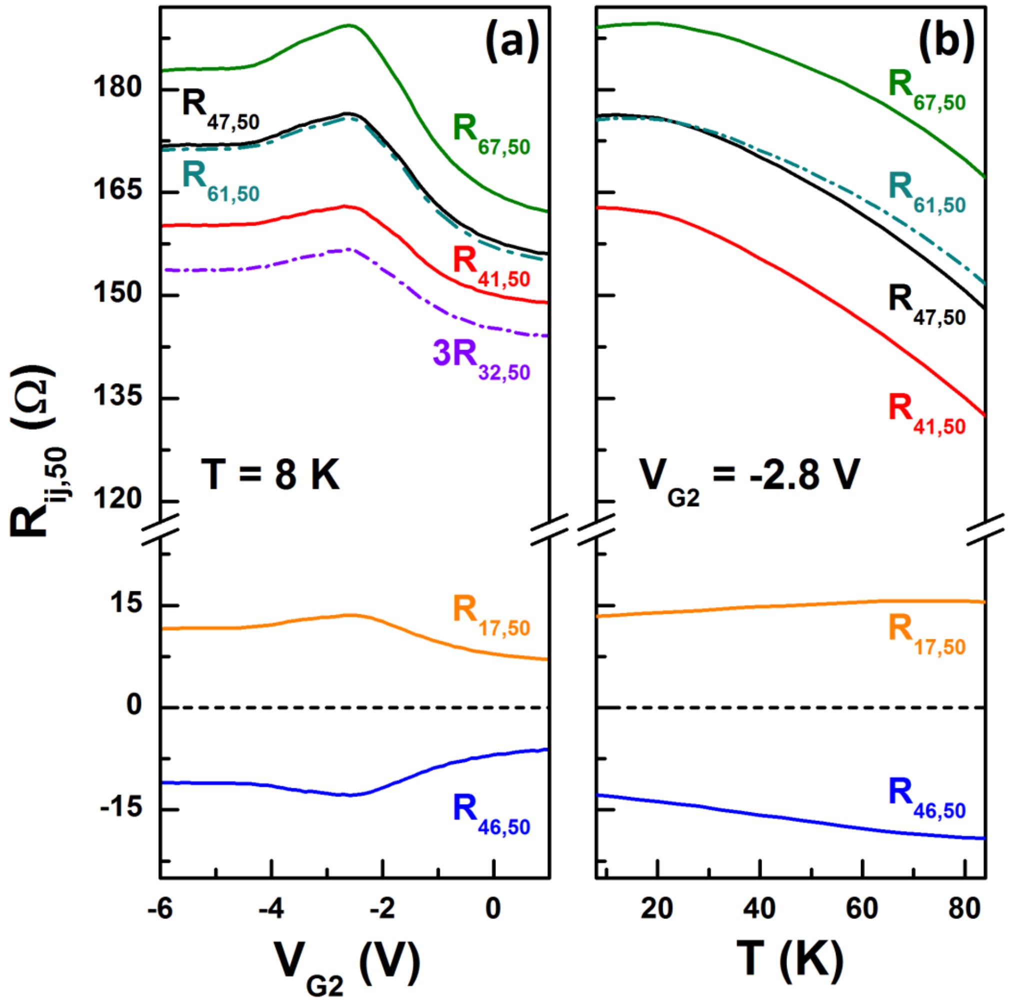
Diagonal

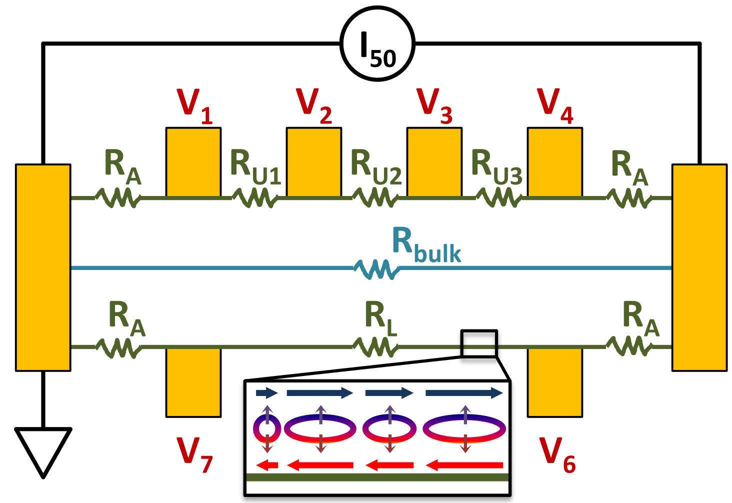
V_{47}
V_{61}



G.C. Dyer *et al.*, *App. Phys. Lett.*, **108**, 013106 (2016)

DC Transport

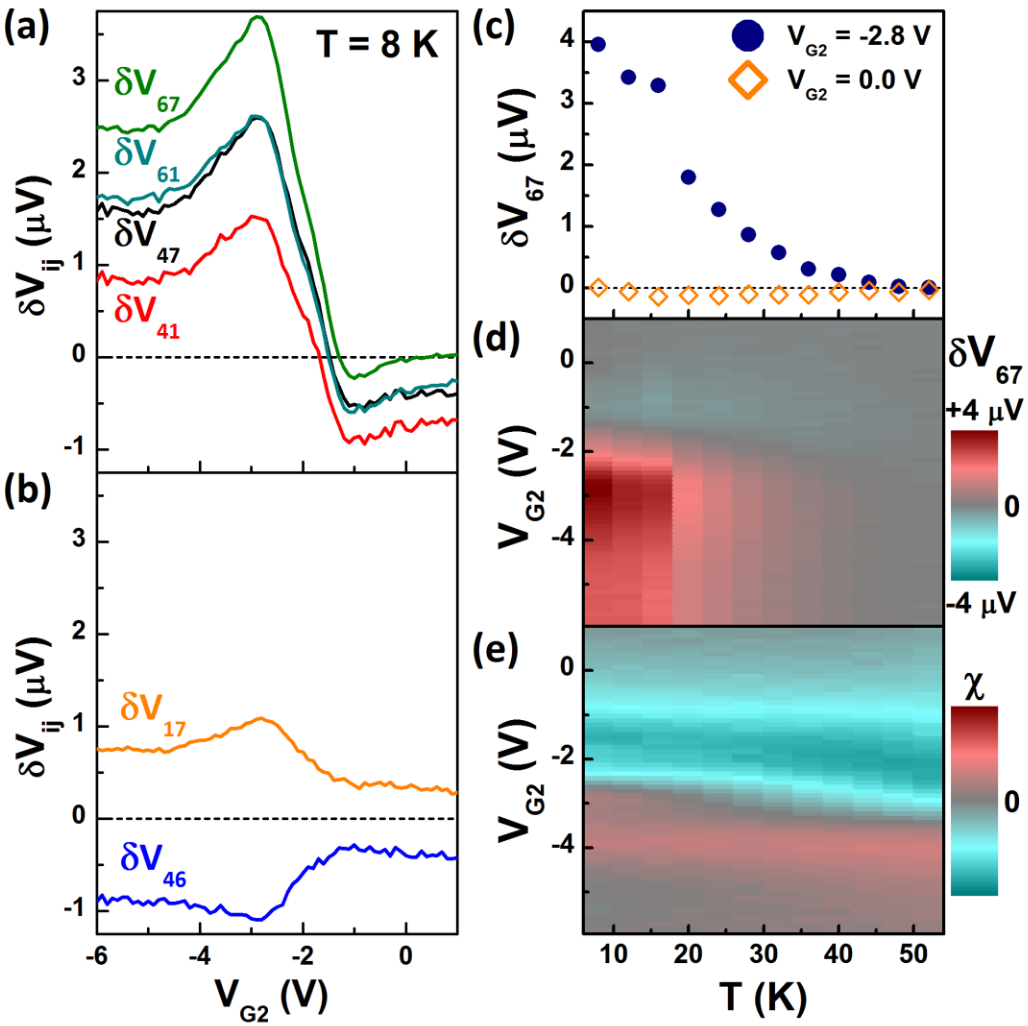


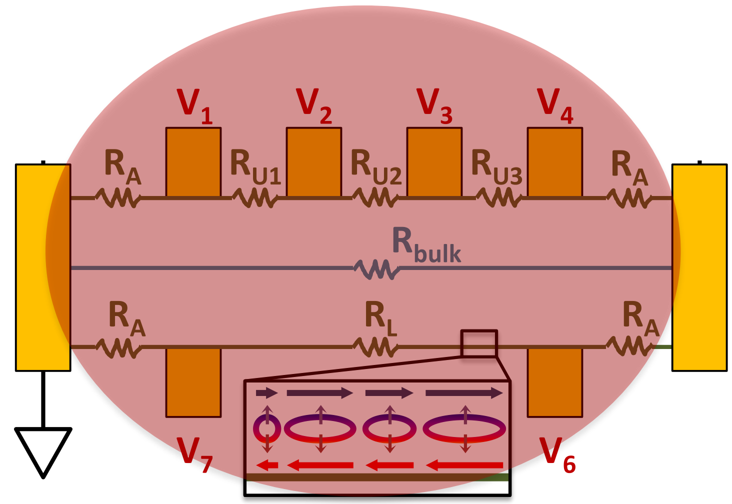


- Bulk dominant (R_{ij} << 25.8 kΩ)
- Longitudinal resistances (**green**, **red**) non-identical
- Mirrored transverse resistances (**blue**, **orange**) imply edge conduction
- $R_{67} > R_{41}$ indicates non-ballistic edge transport

G.C. Dyer *et al.*, *App. Phys. Lett.*, **108**, 013106 (2016)

180 GHz mm-Wave Response





- Mirrored transverse signals(**blue**, **orange**) imply edge response
- Longitudinal (**green**, **red**) and diagonal (**black**, **teal**) signals similarly track DC behavior
- Not a bulk self-mixing response:

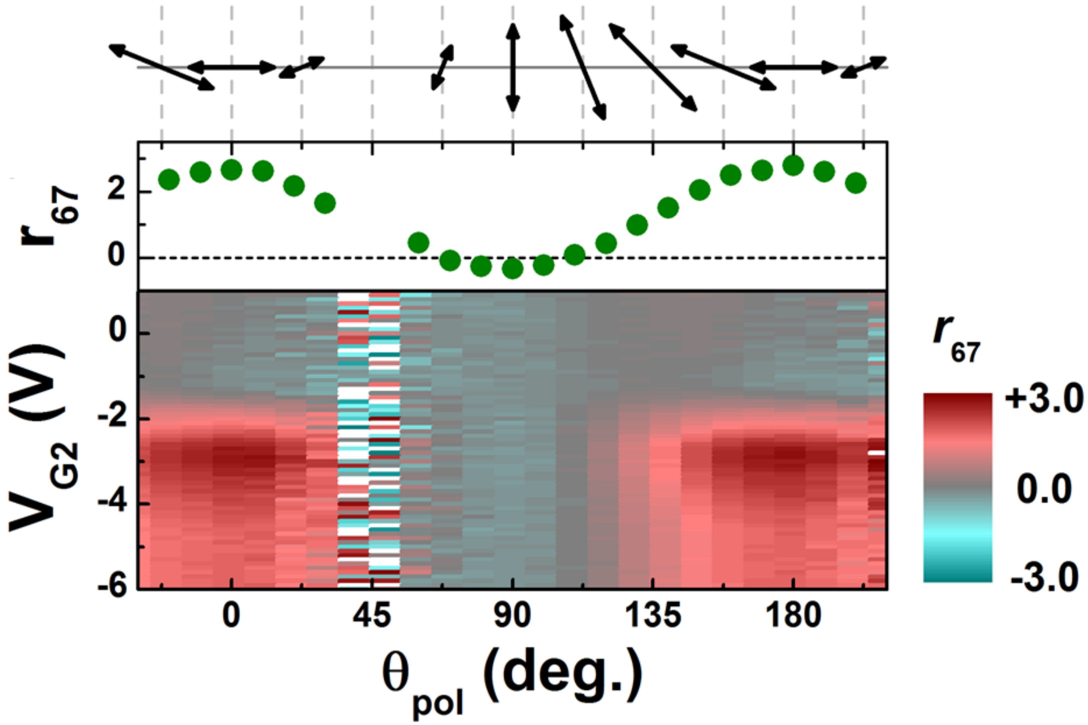
$$\chi \equiv R_{50,67} \frac{\partial(1/R_{50,67})}{\partial V_{G2}}$$

G.C. Dyer *et al.*, *App. Phys. Lett.*, **108**, 013106 (2016)

Polarization Sensitivity

- Signals peak with longitudinal THz field, $V_{G2} \sim V_{CNP}$
- Possibilities: DC photocurrent from AC excitation [1], rectification of 1D edge plasmons [2,3]

[1] B. Dora, *et al*., *PRL* **108**, 056602 (2012).
[2] O. Roslyak, *et al*., *PRB* **87**, 045121 (2013).
[3] I. Appelbaum, *et al.*, *APL* **98**, 023103 (2011).



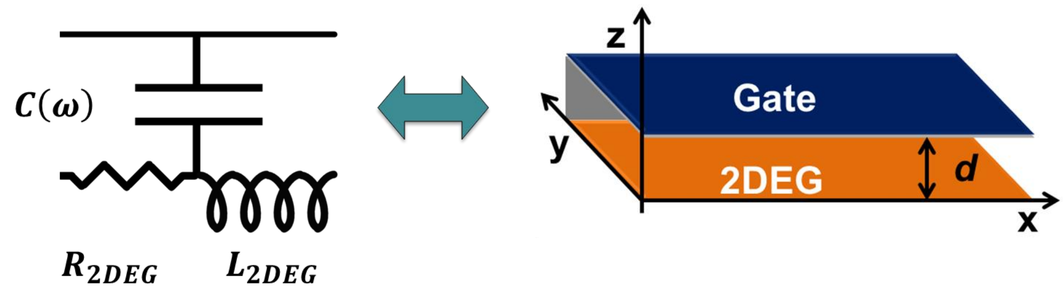
Conclusion: <u>AC driving of edge currents in a material that supports QSH effect and a TI phase</u>

G.C. Dyer *et al.*, *App. Phys. Lett.*, **108**, 013106 (2016)

Conclusions

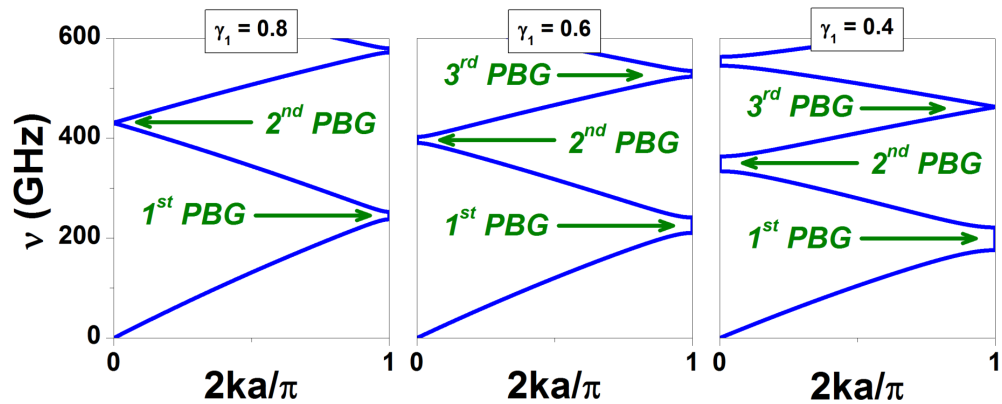
Plasmonic cavity/waveguide

G.C. Dyer *et al.*, *APL* **100**, 083506 (2012)
G.C. Dyer *et al.*, *PRL* **109**, 126803 (2012)



Active control of plasmonic dispersion

G.R. Aizin and G.C. Dyer, *PRB* **86**, 235316 (2012)
G.C. Dyer *et al.*, *Nature Photonics* **7**, 925 (2013)
G.C. Dyer *et al.*, *Opt. Expr.* **22**, 16254-16266 (2014)



Edge photoresponse in inverted DQWs

G.C. Dyer *et al.*, *APL* **108**, 013106 (2016)