SAND2012-4640C

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Terahertz plasmonic cavities and crystals: coherent phenomena in 2D electronic systems

Gregory C. Dyer, **Sandia National Laboratories**

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PECS-X 2012, Wednesday June 6

The City University of New York

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U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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Outline

- THz Plasmonics
- Integrated 2D plasmonic THz and sub-THz detectors
  - Grating gated & plasmonic cavity detectors
  - Figures of merit: NEP < 50 $pW/Hz^{1/2}$, Responsivity > 100 kV/W
- Generalized 2D Plasmonic Transmission Line Model
  - Hydrodynamic and Finite Element approaches
  - Connecting screened and unscreened limits via TL model
- Tunable THz plasmonic cavities and crystals
  - On-chip 2D plasmonic engineering
  - Finite plasmonic crystal
- Conclusions

Plasmonics in the Terahertz Band

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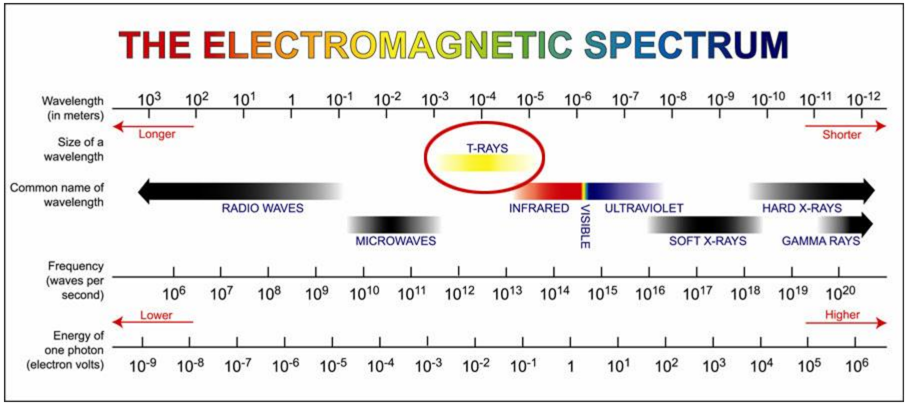


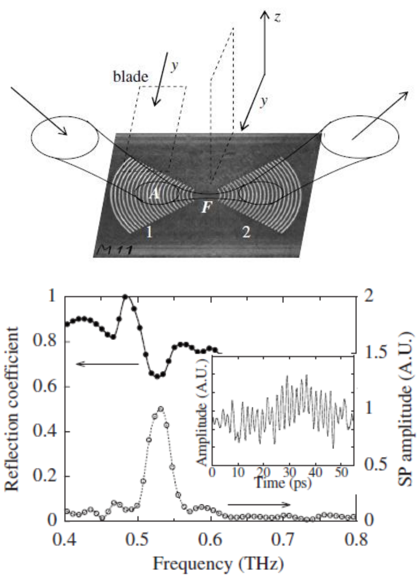
<u>Electronics</u>: *RC* limited bandwidth

<u>Photonics</u>: *kT* limited below 1 THz

<u>Plasmonics</u>: $\omega\tau$ cutoff

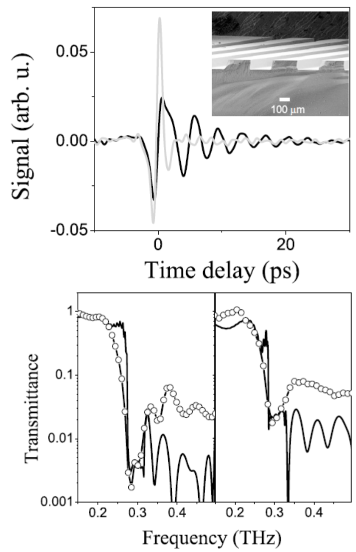
from *http://web.njit.edu/~barat/RBB_research.html*

Metal Gratings



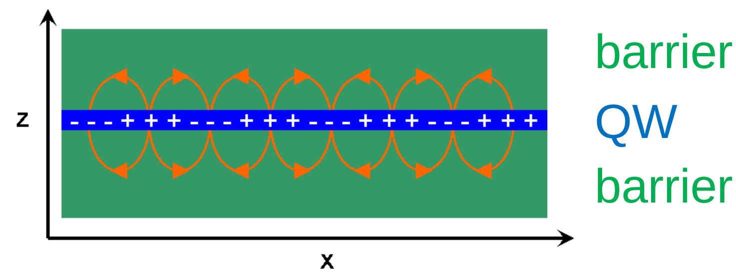
G. Gaborit et. al., *APL* **94**, 231108 (2009)

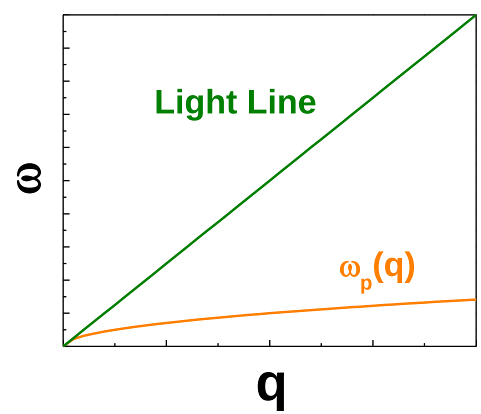
Semiconductor Gratings



J. G. Rivas et. al., *PRL* **93**, 256804 (2004)

Semiconductor 2DEGs





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

THz 2D Plasmonic Systems

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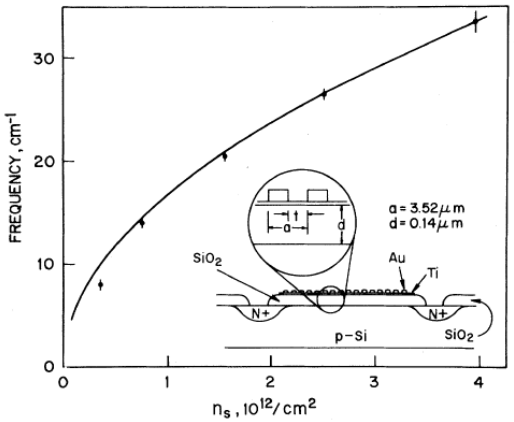
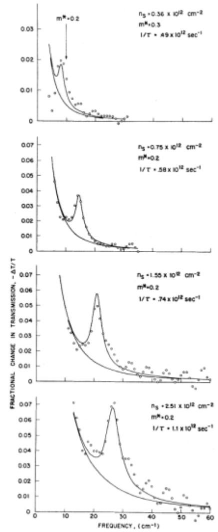
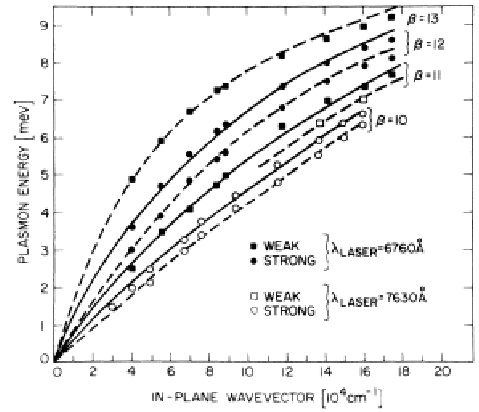
Grating Gated Si MOSFETs

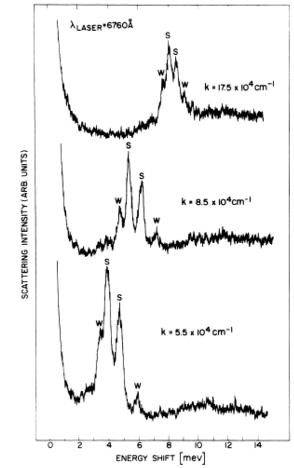




S. J. Allen et. al., *PRL* **38**, 980 (1977)

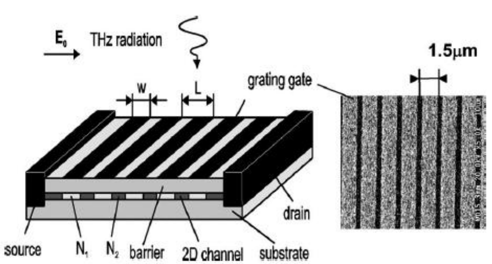
GaAs/AlGaAs Heterostructures

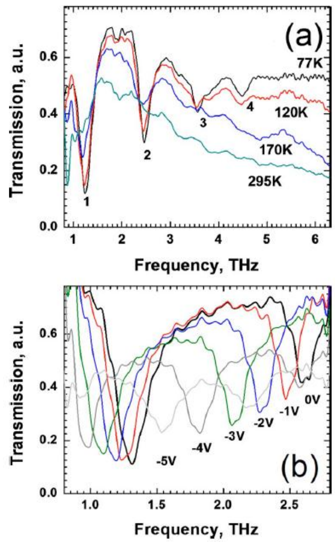




A. Pinczuk et. al., *PRL* **56**, 2092 (1986)

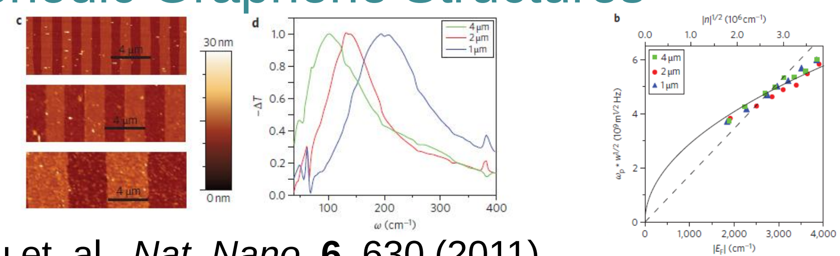
Grating Gated GaN/AlGaN HEMTs



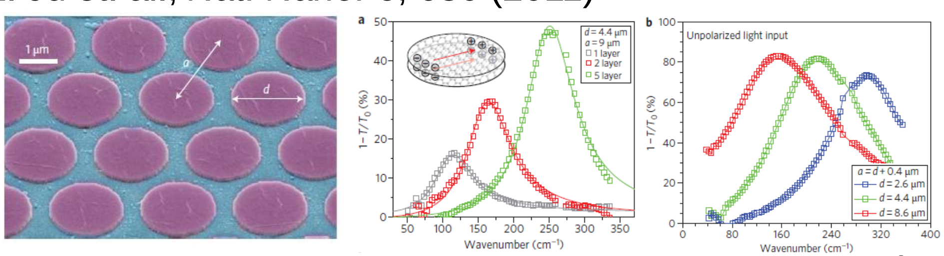


A. V. Muravjov, et. al., *APL* **96**, 042105 (2010)

Periodic Graphene Structures



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



H. Yan et. al., *Nat. Nano.* **adv. online pub.** (2012)

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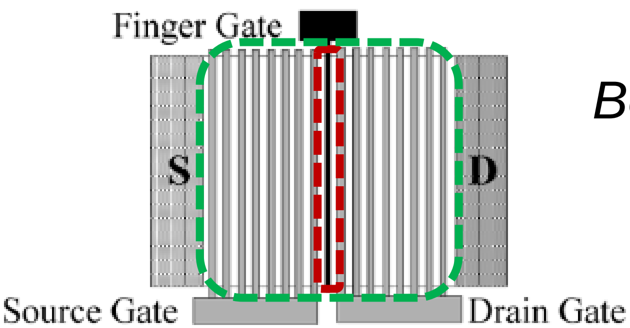
Integrated 2D Plasmonic Detectors

Grating Gated HEMT Detector

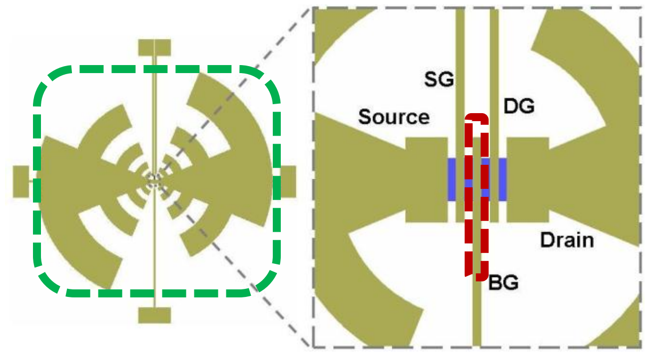
Antenna Coupled HEMT Detector

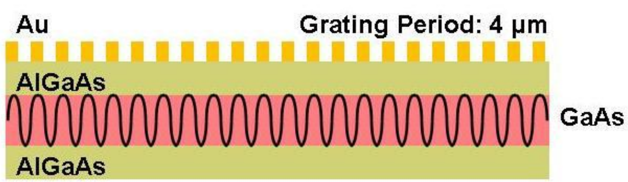


Bolometric Sensor

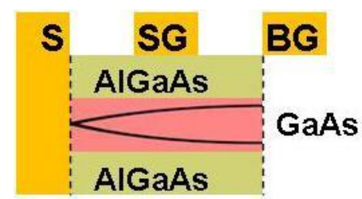
THz Coupling

2D Plasmons





$$\omega_p \propto \sqrt{n_{2D} q}$$



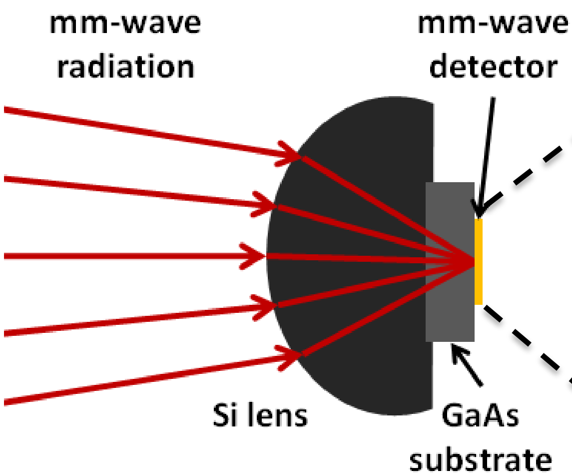
- 1 mm square channel
- 4 μm grating period, 50% duty cycle
- Detection: bolometric sensor
- THz coupling: grating gate
- Resonant absorption: 2D plasmon defined by grating period

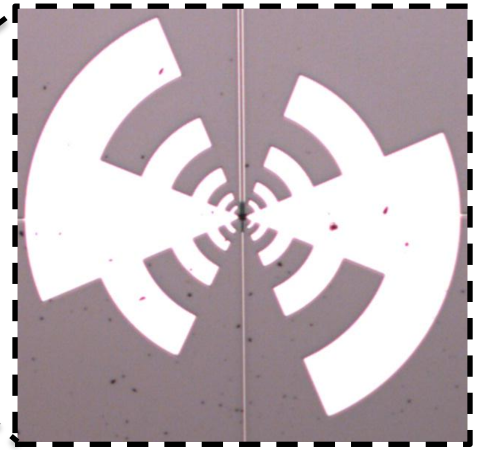
- 1.5 mm diameter antenna
- 10 x 14 μm channel, 2 μm gates
- Detection: bolometric sensor
- THz coupling: log-periodic antenna
- Resonant absorption: 2D plasmon cavity at antenna vertex

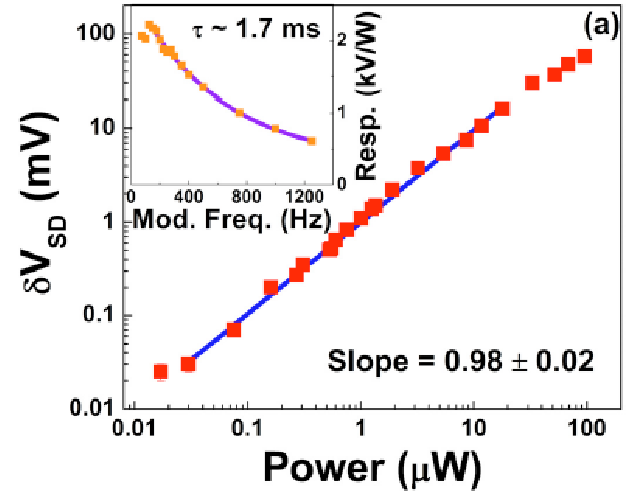
E. A. Shaner et. al., *IEEE Phot. Tech. Lett.* **18**, 1925 (2006)

G. C. Dyer et. al., *APL* **97**, 193507 (2010)

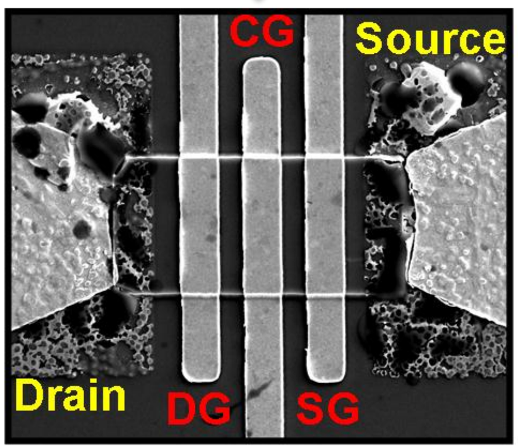
Log Periodic Antenna & Si Lens

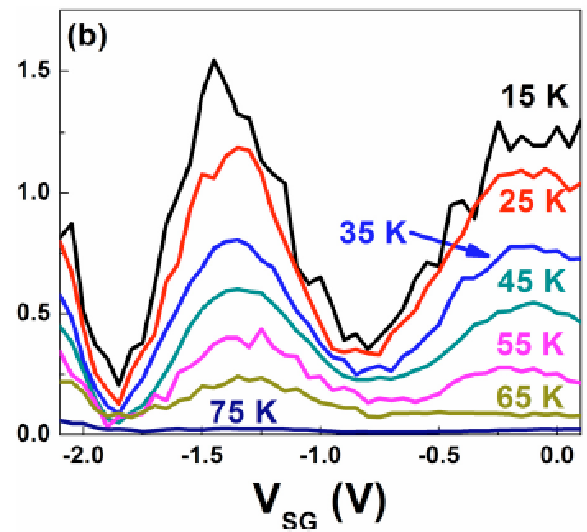






Five terminal HEMT at antenna vertex: S, D and gates (SG, CG and DG)

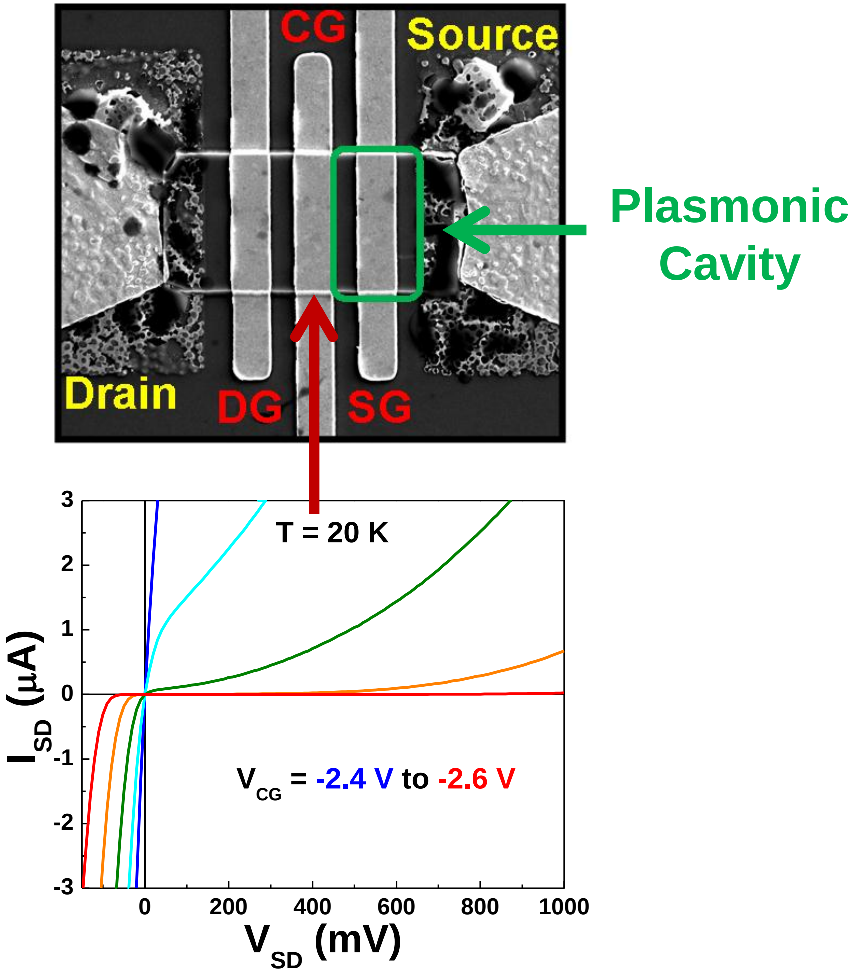


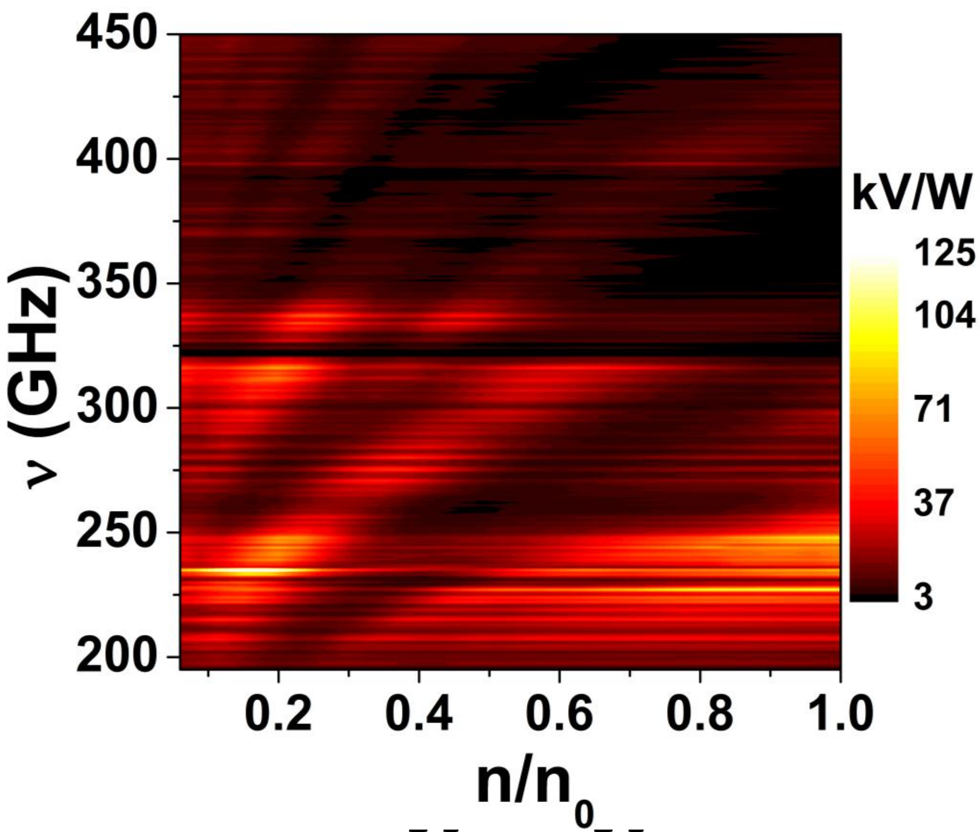


Self complementary antenna: impedance of ~72 Ω on substrate

G. C. Dyer et. al., *APL* **97**, 193507 (2010) & *APL* **100**, 083506 (2012)

Gate Controlled Plasma Cavity



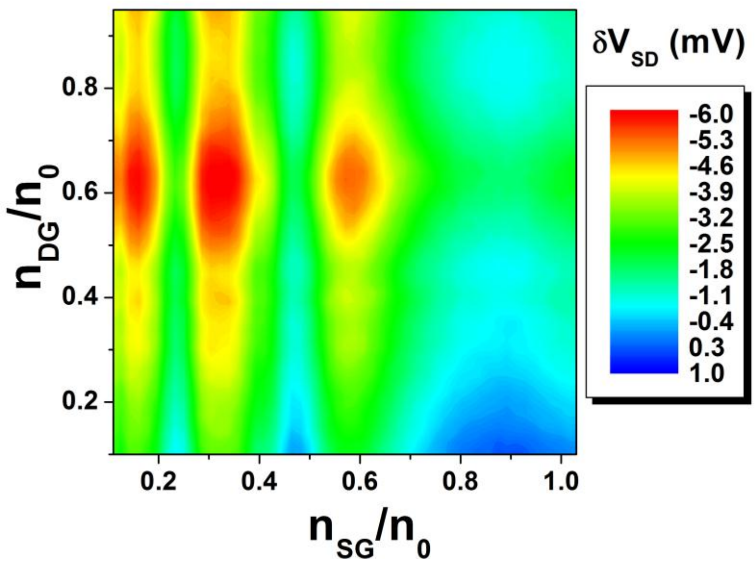


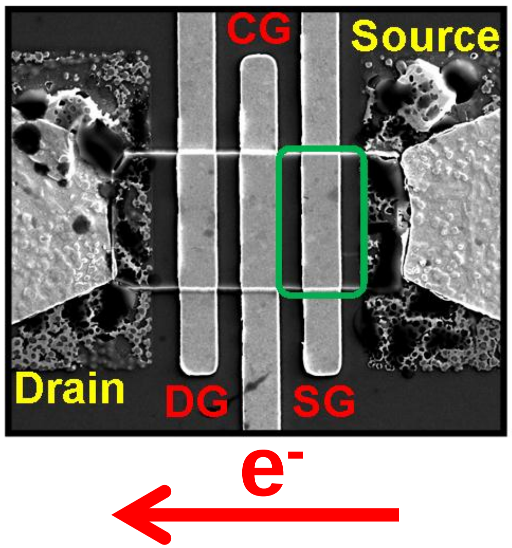
$$\frac{n}{n_0} = \frac{V_{TH} - V_{SG}}{V_{TH}}$$

- Source gate (SG) tunes plasma resonance with center gate (CG) beyond threshold

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

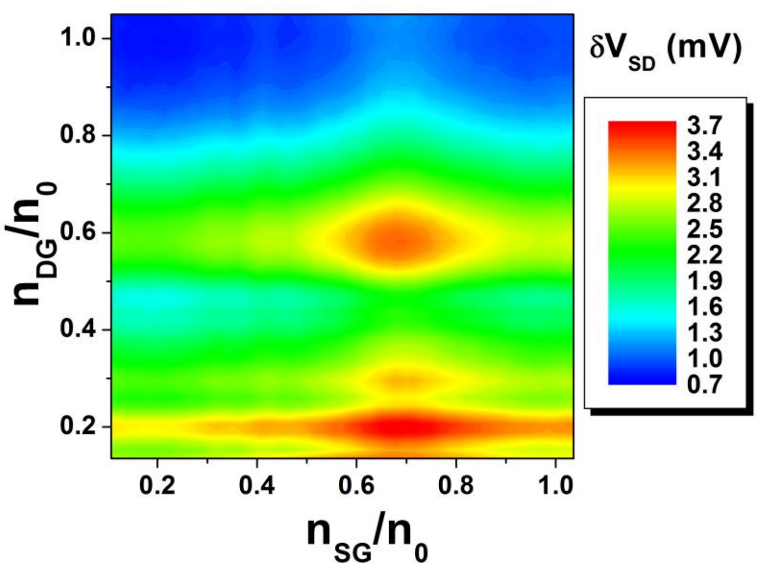
S-D Bias Cavity Tuning

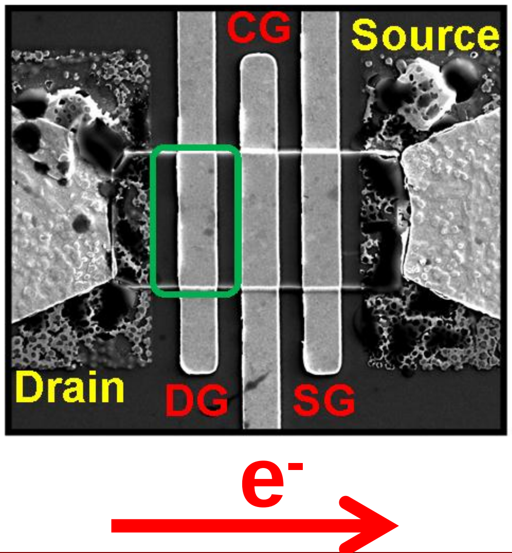




370 GHz

I = +500 nA

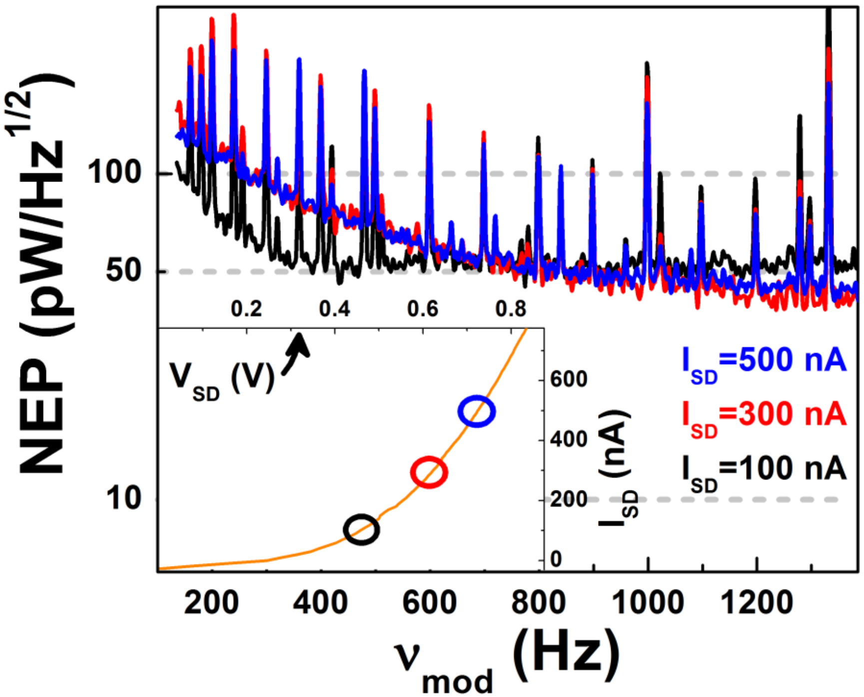


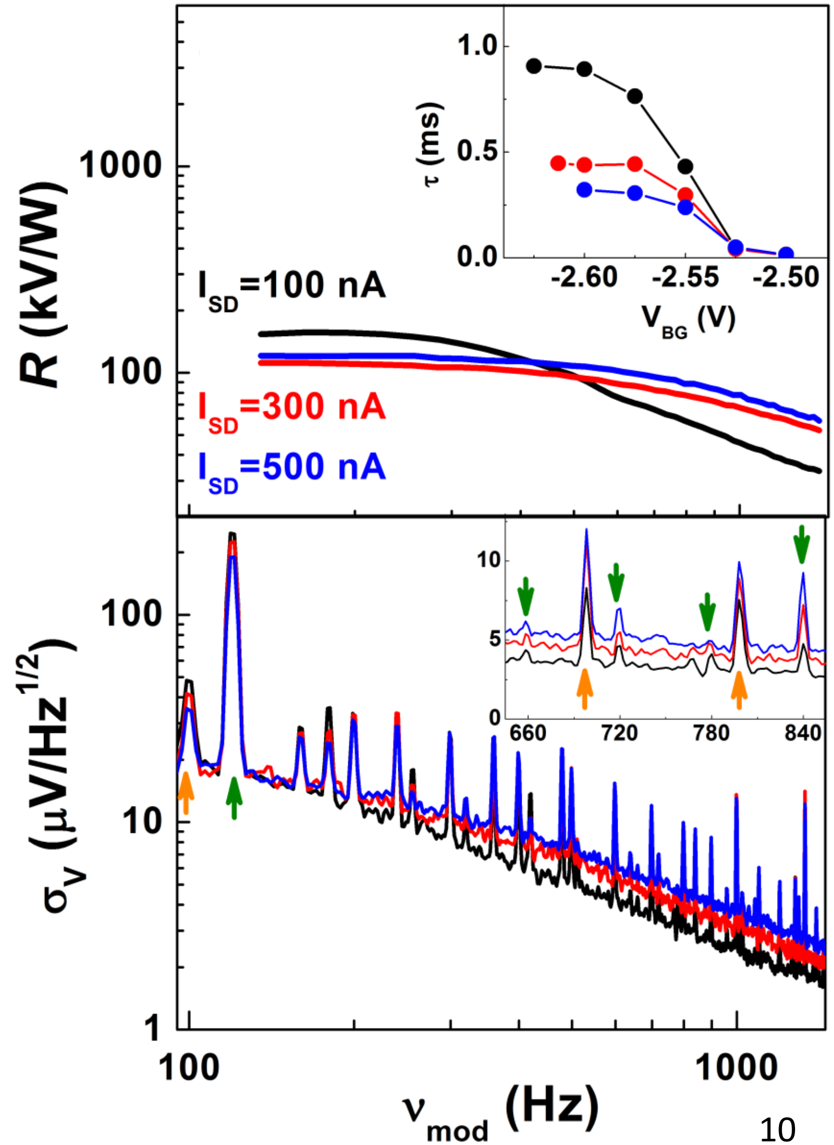


I = -500 nA

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

Figures of Merit





<u>11K Operation, 243 GHz</u>

***R* > 100 kV/W**

***NEP* < 50 pW/Hz$^{1/2}$**

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

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Hydrodynamic Model

$$\frac{\partial \delta v}{\partial t} + \delta v \frac{\partial \delta v}{\partial x} = \frac{e}{m}\frac{\partial \phi}{\partial x} \quad \& \quad \frac{\partial n}{\partial t} + \frac{\partial (n \delta v)}{\partial x} = 0$$

Self-consistent soln. of Euler's hydrodynamic eqn. of motion with continuity eqn.

- **Pros**:
  - little computational overhead
  - accurately predicts both linear and non-linear phenomena (absorption, mixing, emission)
- **Cons**:
  - non-trivial to phrase in Maxwell or circuit formalism
  - must choose boundary conditions
  - assumptions about screening
  - simple geometry

Detection, Mixing, and Frequency Multiplication of Terahertz Radiation by Two-Dimensional Electronic Fluid

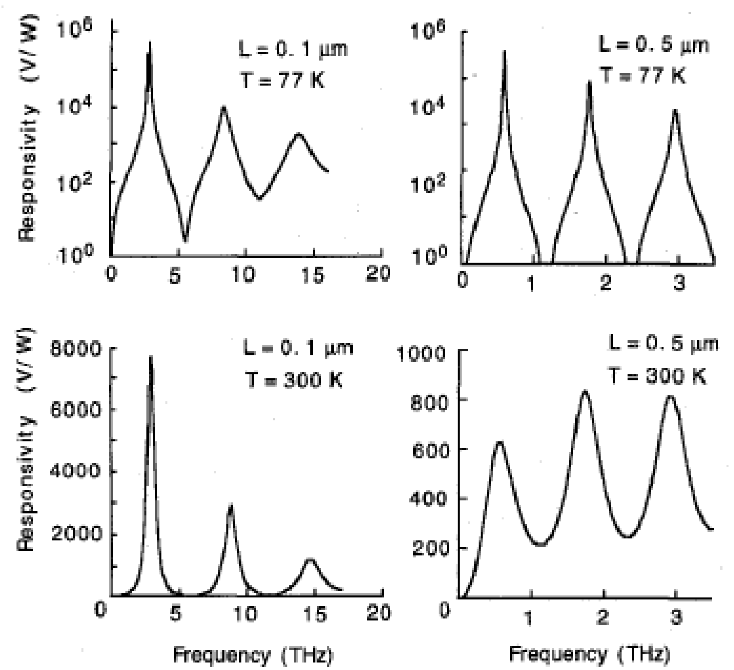

Fig. 5. Calculated responsivity as a function of frequency for 0.1 μm and 0.5 μm gate HEMT's at 77 K and 300 K. Parameters used in the calculation: $U_o = 0.5$ V, G = 1.5, $\nu = 15$ cm ^{2}s, m = $0.063 m_o$, $\mu = 300{,}000$ cm^2/Vs at 77 K, $\mu = 8{,}000$ cm^2/Vs at 300 K.

M. I. Dyakonov and M. S. Shur, *PRL* **71**, 2465 (1993) & *IEEE Trans. on Electron Devices* **43**, 380 (1996)

Finite Element Analysis (Full EM)

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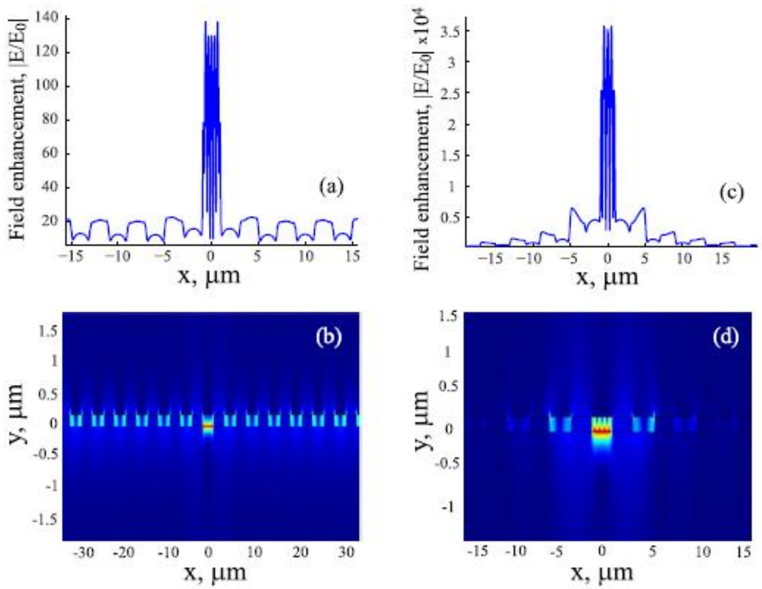
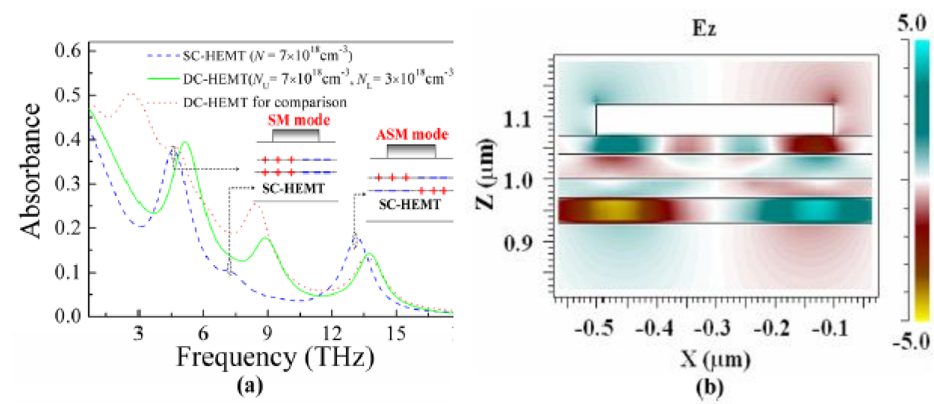
Tailoring Terahertz Near-Field Enhancement via Two-Dimensional Plasmons



A. R. Davoyan et. al., *PRL* **108**, 127401 (2012)

The plasmonic resonant absorption in GaN double-channel high electron mobility transistors



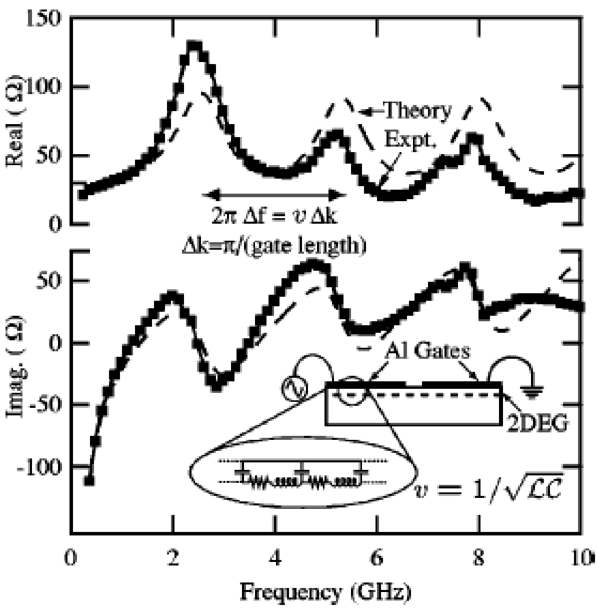
L. Wang et. al., *APL* **99**, 063502 (2011)

- **Pros**:
  - direct solution of EM parameters (fields, absorption, transmission, etc.)
  - can embed 2DEG in complex geometry including material parameters
  - Maxwell imposes boundary conditions
- **Cons**:
  - large computational overhead
  - expensive
  - “intuition before computation”

Plasmon Transmission Line Model

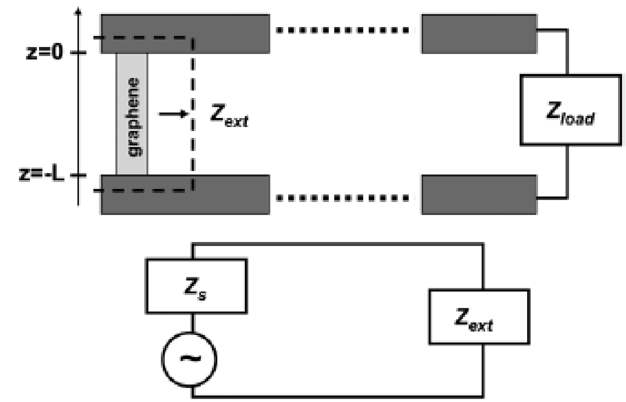
High frequency conductivity of the high-mobility two-dimensional electron gas

Graphene Terahertz Plasmon Oscillators



$$Z_0 = \sqrt{\frac{Z_{2DEG}}{i\omega C(\omega)}}$$

$$iq = \sqrt{i\omega C(\omega) Z_{2DEG}}$$



$$Z_{2DEG} = R_{2DEG} + i\omega L_{2DEG}$$

→ *from Drude model*

L is <u>kinetic inductance</u>

$$\lim_{qd\to 0} C(\omega) = \frac{W\epsilon}{d}$$

(fully screened limit)

$$\lim_{qd\to\infty} C(\omega) = 2W\epsilon q$$

(unscreened limit)

P. J. Burke et. al., *APL* **76**, 745 (2000)

F. Rana, *IEEE Trans. on Nanotechnology* **7**, 91 (2008)

Generalized Plasmonic TL Model

$$\Phi(x,z) = \left[\Phi_+ e^{-iqx} + \Phi_- e^{+iqx}\right]\begin{cases} sinh[q(d-z)]\, e^{-qd}, z \geq 0 \\ sinh[qd]\, e^{q(z-d)}, z < 0 \end{cases}$$

$$\frac{I(x)}{W} = \mathrm{j}(x,z) = \frac{1}{Z_0}\left[\Phi_+ \mathrm{e}^{-iqx} - \Phi_- \mathrm{e}^{+iqx}\right]\delta(z)$$

$$C(\omega) = \frac{\Phi(x, z=0)}{\rho(x)} = W\epsilon q(1 + \coth[qd])$$

The 2D plasmon is in general a TM wave: P = ½ VI* is correct only for TEM wave in fully screened limit

$$\mathrm{P}(x) = \tfrac{1}{2}\iint S_x dydz = -\tfrac{W}{2}\iint E_z H_y dydz$$
$$= \tfrac{1}{2}\Phi(x,0)\mathrm{I}^*(x)\, \xi^*(\omega, d)$$

$$\mathrm{P}(x) \rightarrow \begin{cases} \lim_{qd\rightarrow 0} \mathrm{P}(x) = \tfrac{1}{2}\Phi(x,0)\mathrm{I}^*(x) \\ \lim_{\tau, qd\rightarrow \infty} \mathrm{P}(x) = \tfrac{1}{4}\Phi(x,0)\mathrm{I}^*(x) \end{cases}$$

$$\xi(\omega, d) = 1 - \frac{q\left(1 - e^{-2q'd}\cos[2q''d]\right)}{2q'(1 - e^{-2q^*d})} + \frac{q\, e^{-2q'd}\sin[2q''d]}{2q''(1 - e^{-2q^*d})}$$

Effective *V*, *I* & *Z*

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$$\frac{1}{2}\tilde{V}(x)\tilde{I}^*(x) = \frac{1}{2}\Phi(x,0)I^*(x)\,\xi^*(\omega,d)$$

$$\tilde{V}(x) \equiv \Phi(x,0)$$

$$\tilde{I}(x) \equiv I(x)\xi(\omega,d)$$

$$\tilde{Z}_0 \equiv \frac{Z_0}{\xi(\omega,d)}$$

Characteristic Impedance of Microstrip Lines

JOHN R. BREWS, MEMBER, IEEE

FOR non-TEM structures such as microstrip lines it generally is agreed that the characteristic impedance is not unique. It also is agreed that the root of this uncertainty is the longitudinal field components of non-TEM modes. Because of these components, current and voltage are not uniquely defined in terms of the usual TEM path integrals of the fields. Faced with an ambiguity in the meaning of current I and voltage V a variety of results for the characteristic impedance Z_0 is obtained.

J. R. Brews, *IEEE Trans. on Microwave Theory and Techniques* **35**, 30 (1987)

Above definitions are not unique, but accurately address physics:

1. *Effective potential $\tilde{V}(x)$ is continuous*
2. *Power $\tilde{V}(x)\tilde{I}^*(x)$ is continuous*
3. *Discontinuity in <u>real</u> carrier density $\rho(x)$ and <u>real</u> current $I(x)$ is consistent with edge charge accumulation at step-like boundary*

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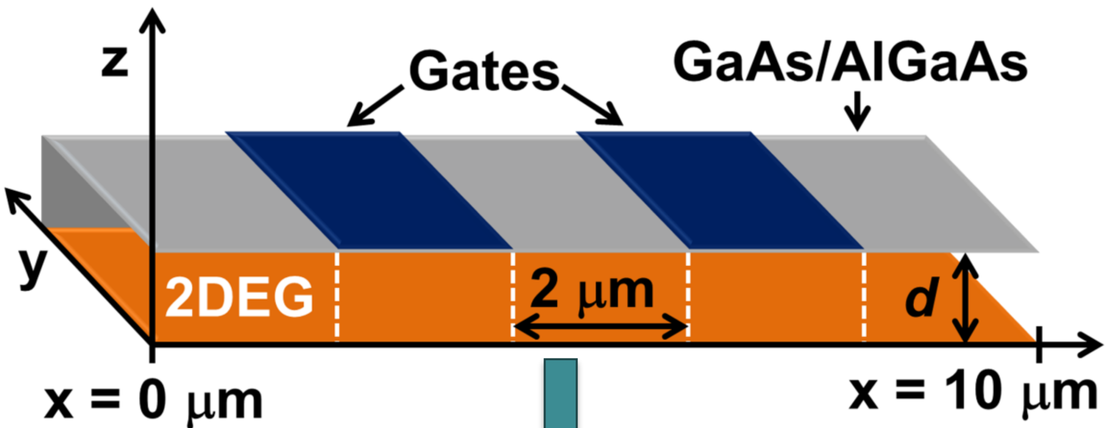
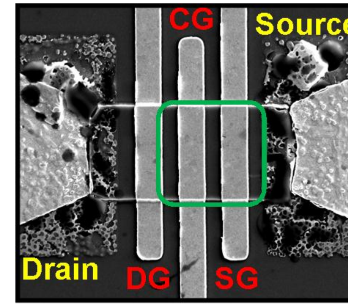
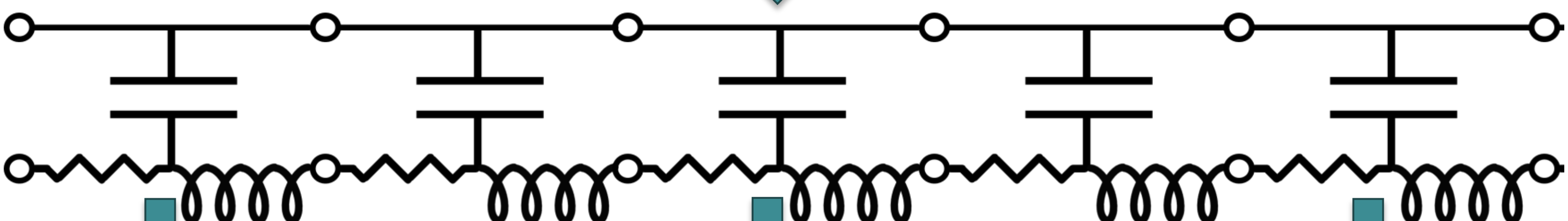
Stepped Plasmonic TL







$$\begin{pmatrix} \cos[q_1 a_1] & i\tilde{Z}_1 \sin[q_1 a_1] \\ i\sin[q_1 a_1]\,/\tilde{Z}_1 & \cos[q_1 a_1] \end{pmatrix}$$

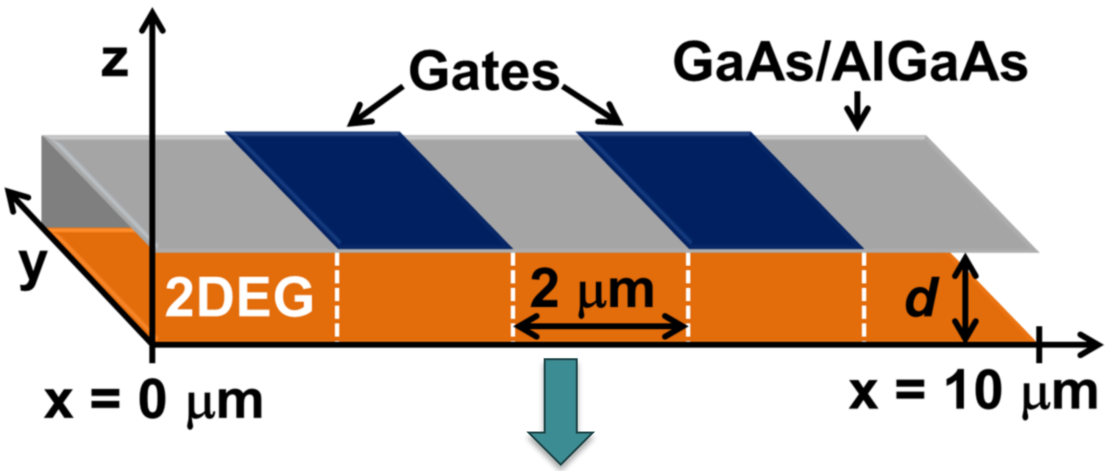
$$\begin{pmatrix} \cos[q_3 a_3] & i\tilde{Z}_3 \sin[q_3 a_3] \\ i\sin[q_3 a_3]\,/\tilde{Z}_3 & \cos[q_3 a_3] \end{pmatrix}$$

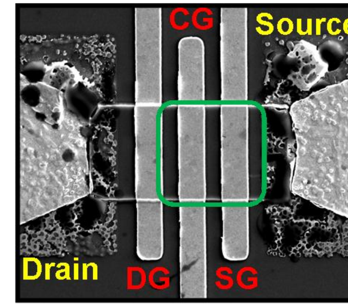
$$\begin{pmatrix} \cos[q_5 a_5] & i\tilde{Z}_5 \sin[q_5 a_5] \\ i\sin[q_5 a_5]\,/\tilde{Z}_5 & \cos[q_5 a_5] \end{pmatrix}$$

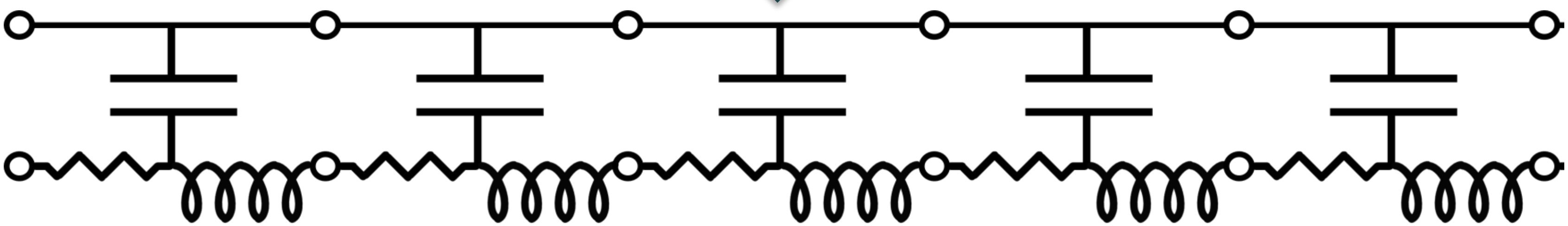
$$\begin{pmatrix} \cos[q_2 a_2] & i\tilde{Z}_2 \sin[q_2 a_2] \\ i\sin[q_2 a_2]\,/\tilde{Z}_2 & \cos[q_2 a_2] \end{pmatrix}$$

$$\begin{pmatrix} \cos[q_4 a_4] & i\tilde{Z}_4 \sin[q_4 a_4] \\ i\sin[q_4 a_4]\,/\tilde{Z}_4 & \cos[q_4 a_4] \end{pmatrix}$$

Stepped Plasmonic TL



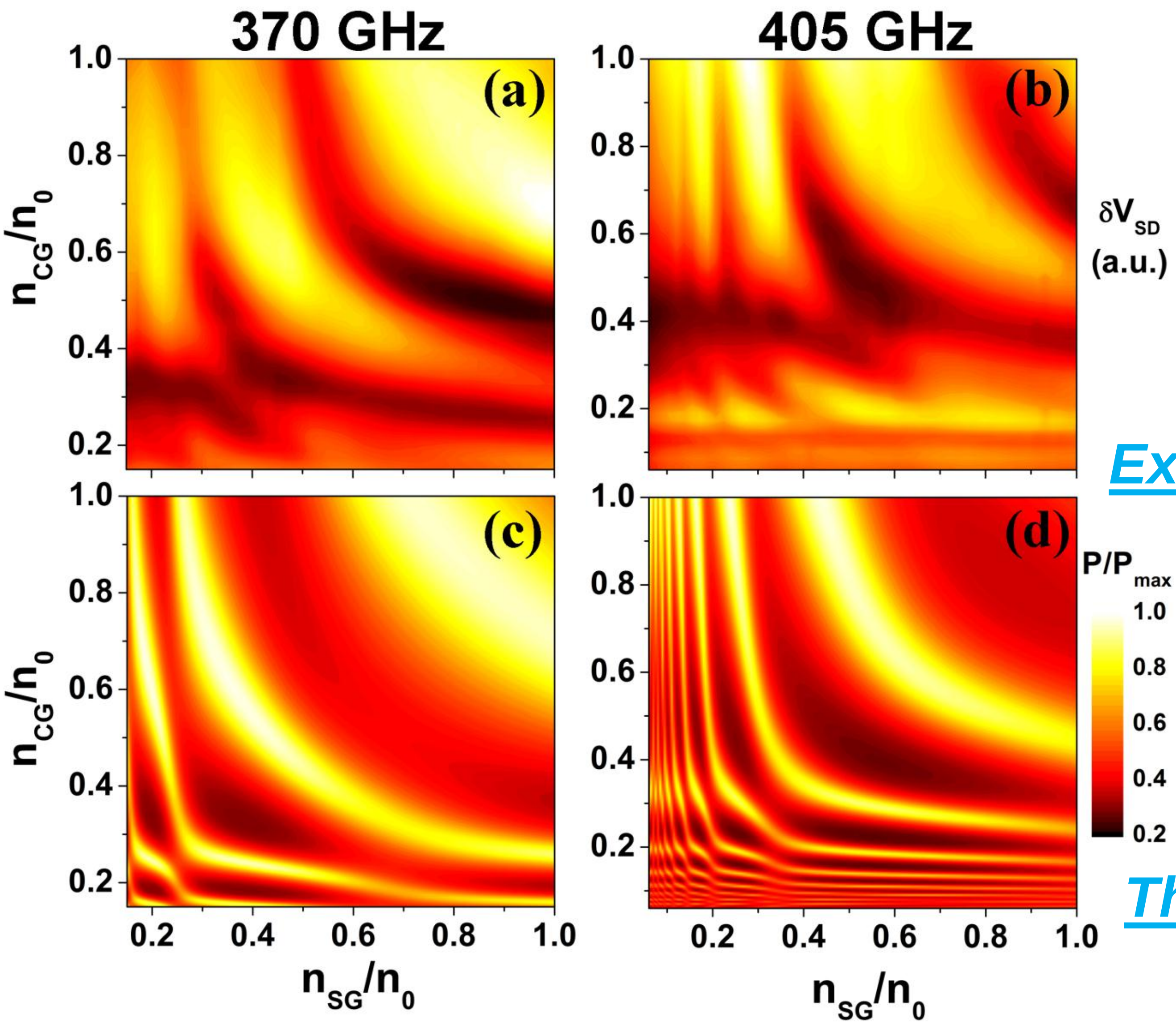


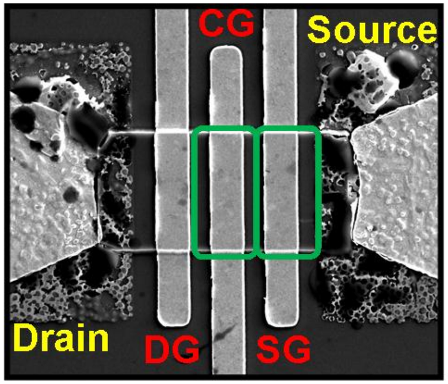


Solution for an inhomogeneous cavity with step-like boundaries between TL elements is reduced to matrix multiplication:

$$\begin{pmatrix} \tilde{V}_m \\ \tilde{I}_m \end{pmatrix} = \left[\prod_m^n \begin{pmatrix} \cos[q_m a_m] & i\tilde{Z}_m \sin[q_m a_m] \\ i\sin[q_m a_m] / \tilde{Z}_m & \cos[q_m a_m] \end{pmatrix} \right] \begin{pmatrix} \tilde{V}_{n+1} \\ \tilde{I}_{n+1} \end{pmatrix}$$

Coherent Sub-Cavity Interaction





Expt.

Thy.

Coupled plasmonic crystal lattice unit cells:

band-stop/band-pass filter

Gate Bias Cavity Tuning

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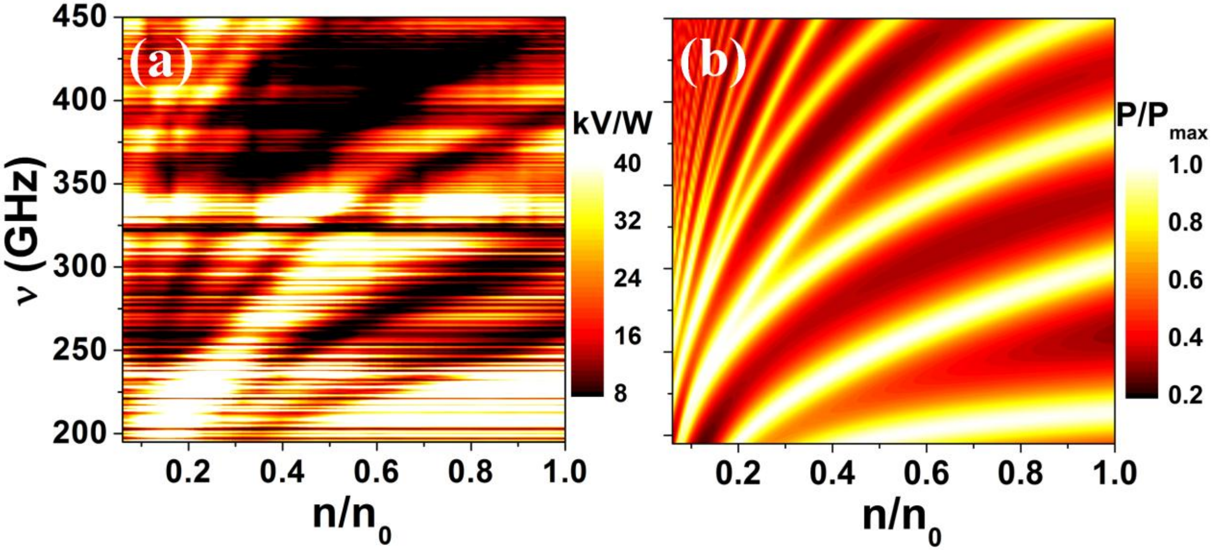
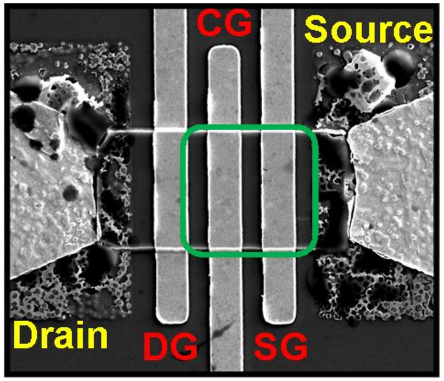
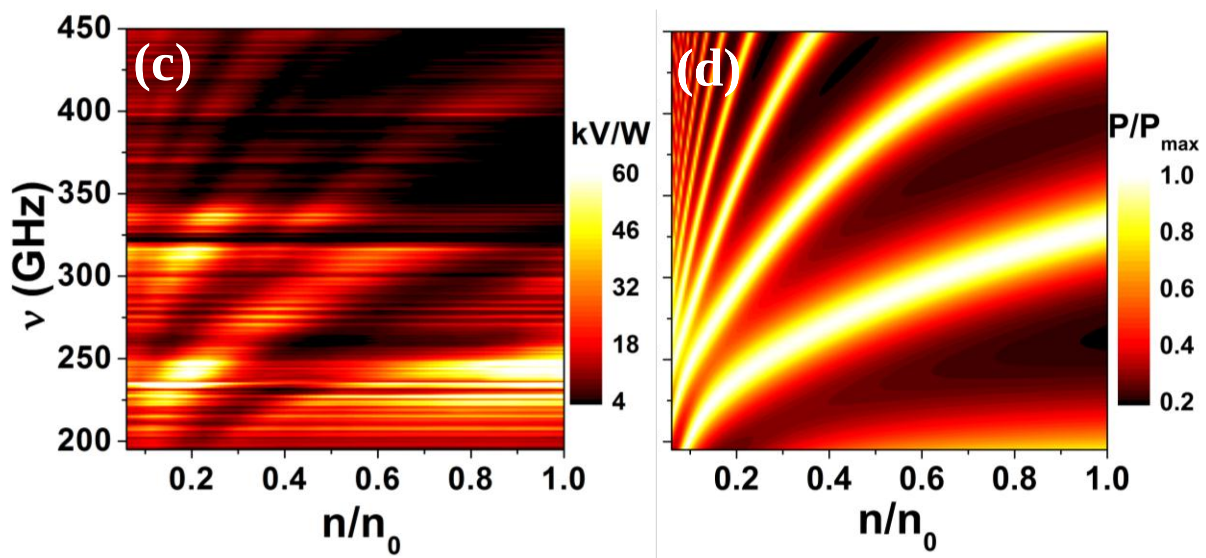
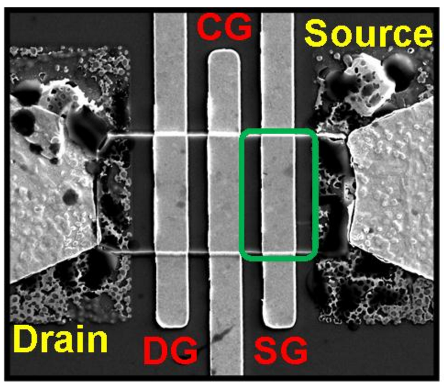




$L_0 = 10\ \mu m$

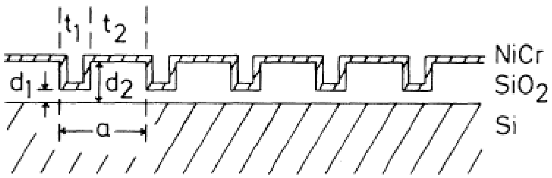


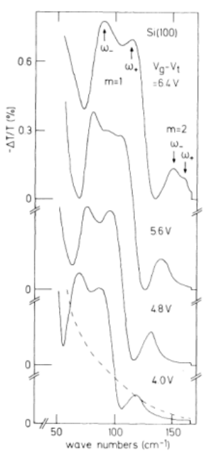


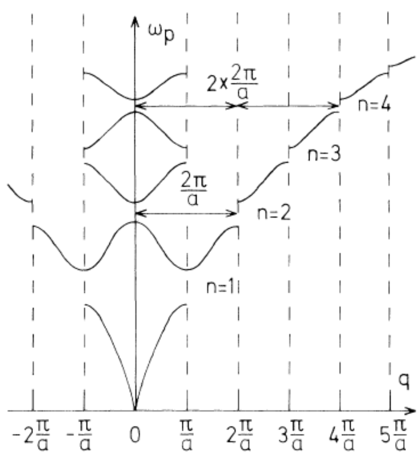
$L_0 = 6\ \mu m$

Finite Plasmonic Crystal

Quasi-Infinite Plasmonic Crystal in Si MOSFET

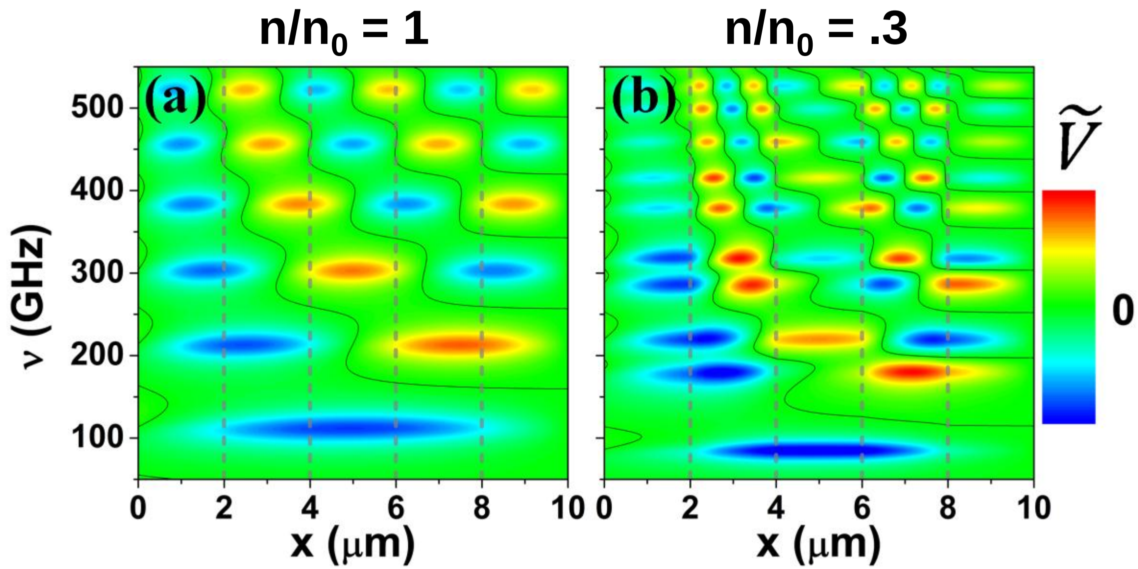


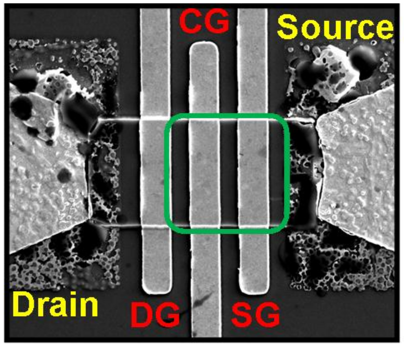




U. Mackens et. al., *PRL* **53**, 1485 (1984)

TL Model Cavity Voltage Distribution





Two-period 1D plasmonic crystal embedded in 10 μm source cavity

TL Model: 2, 4 & 8 Period Crystals

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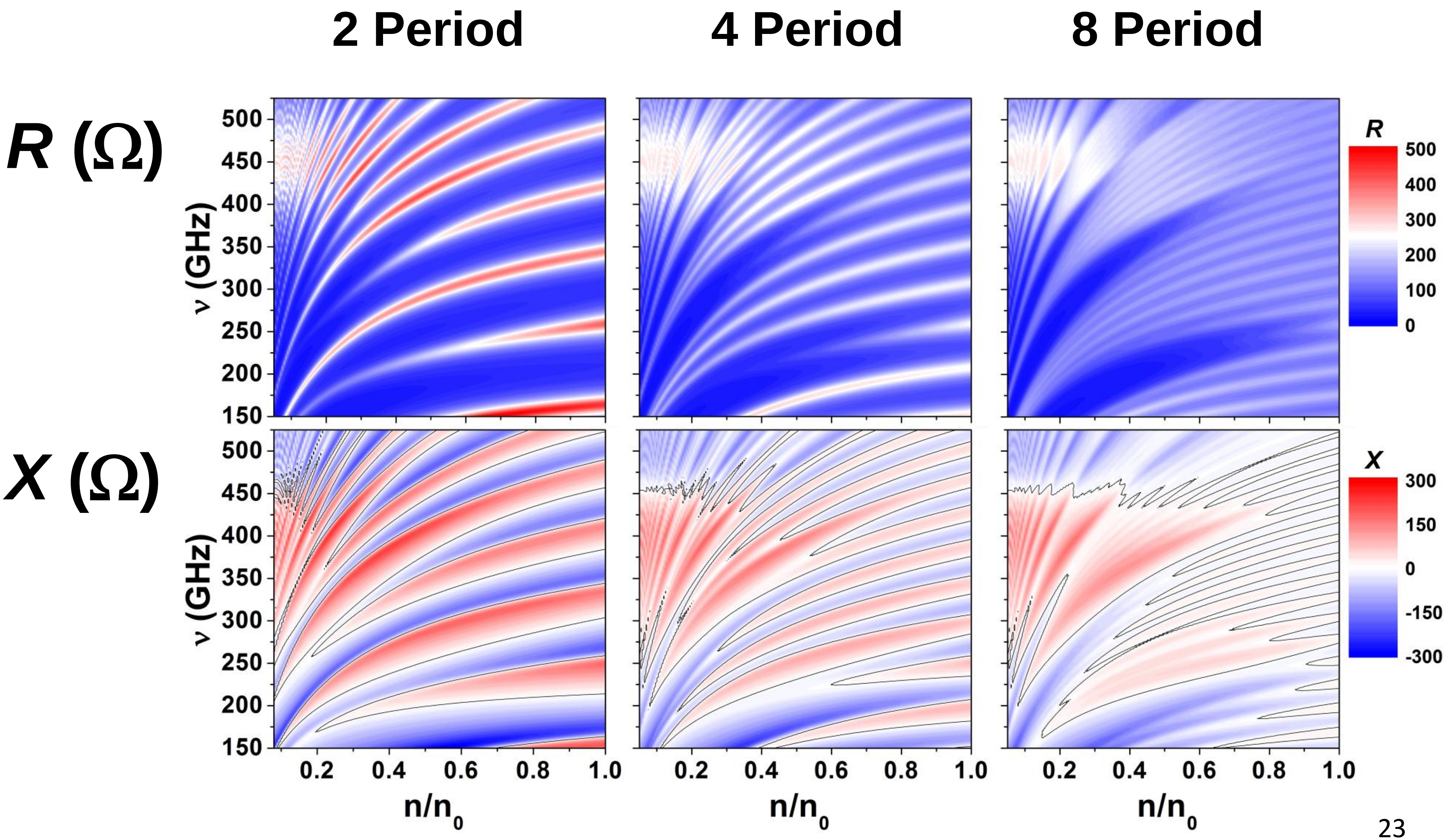
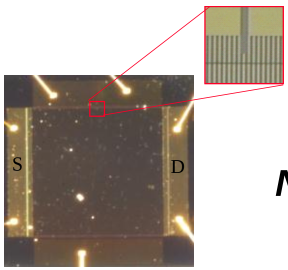
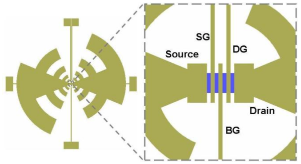


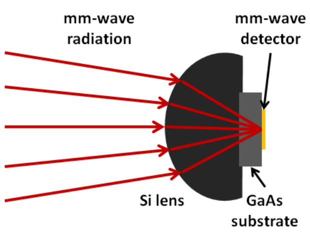
Evolution, Conclusions & Future



R ~ 50 V/W
NEP ~ 100 nW/Hz$^{1/2}$
T = 20 K

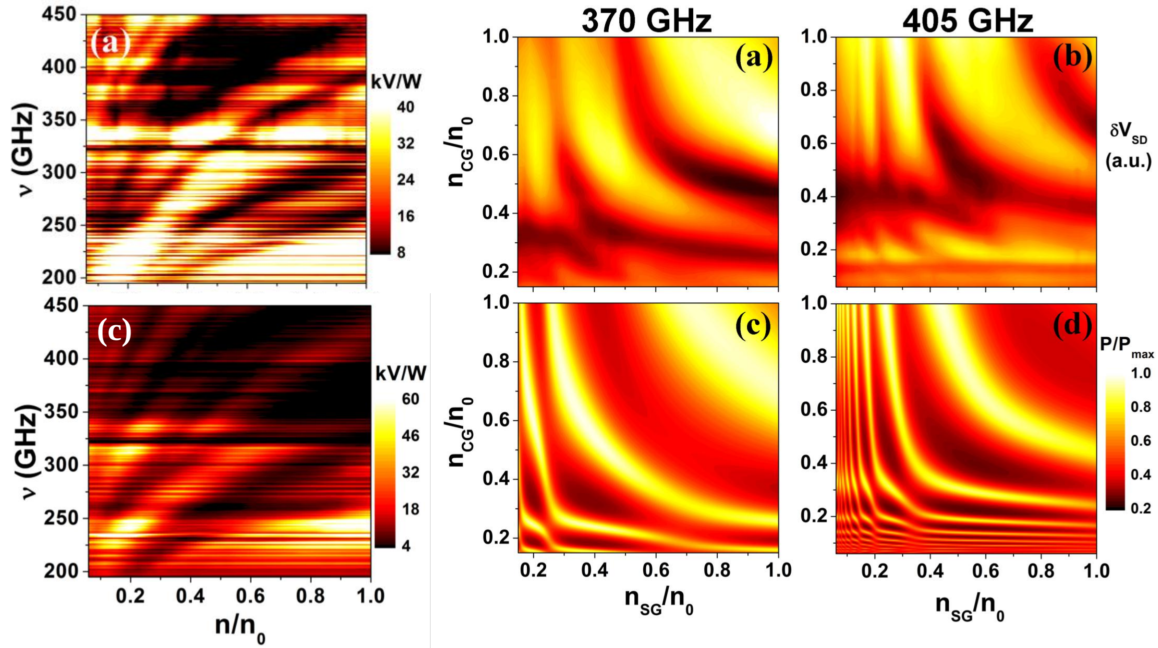


R ~ 5 kV/W
NEP ~ 500 pW/Hz$^{1/2}$
T = 20 K

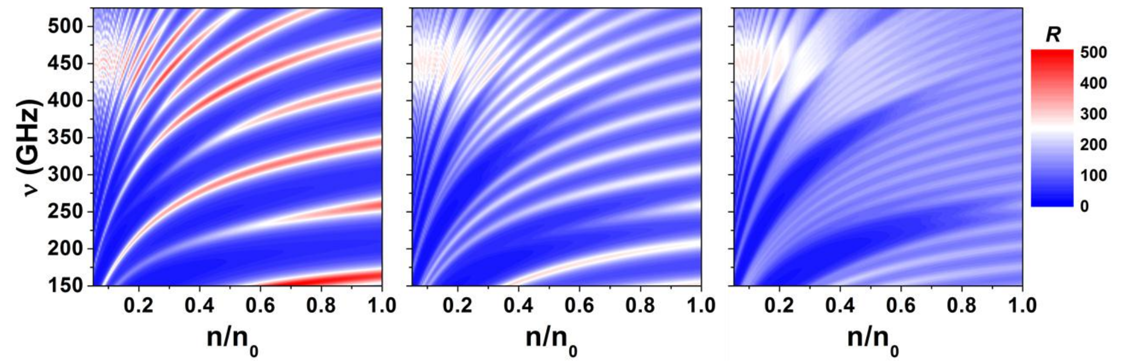


R > 100 kV/W
NEP < 50 pW/Hz$^{1/2}$
T = 11 K

On-chip THz spectroscopy



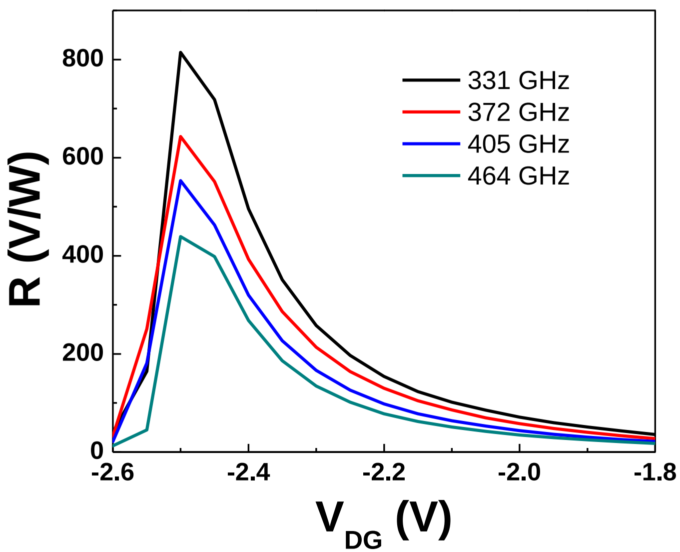
***in-situ* 2D plasmonic engineering**

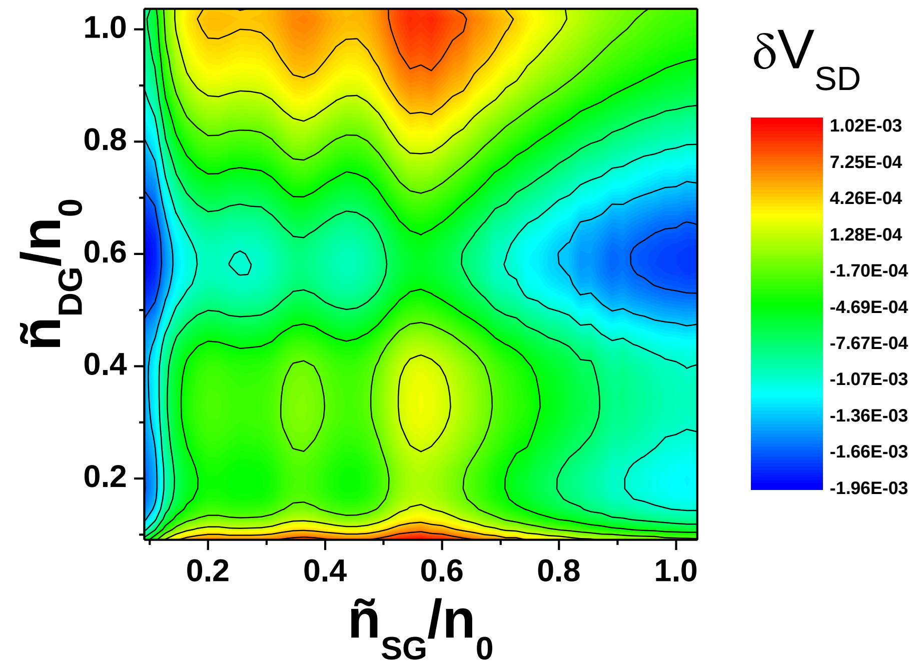


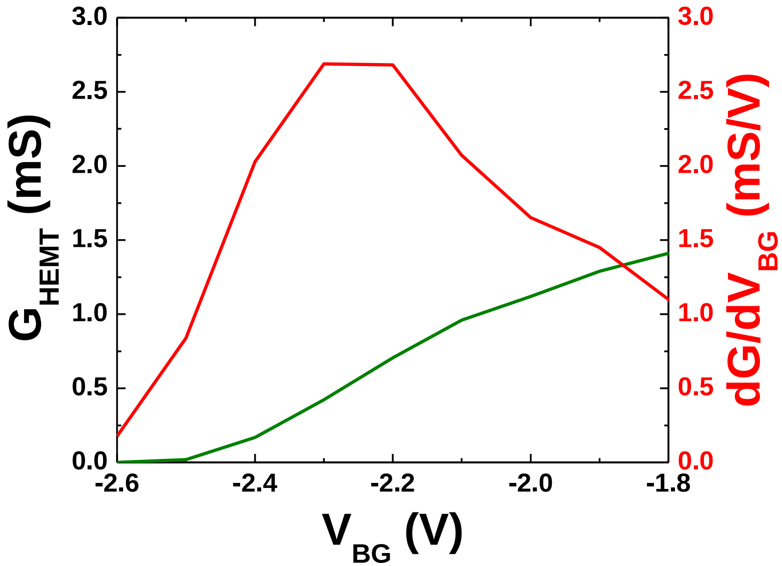
Finite plasmonic crystal

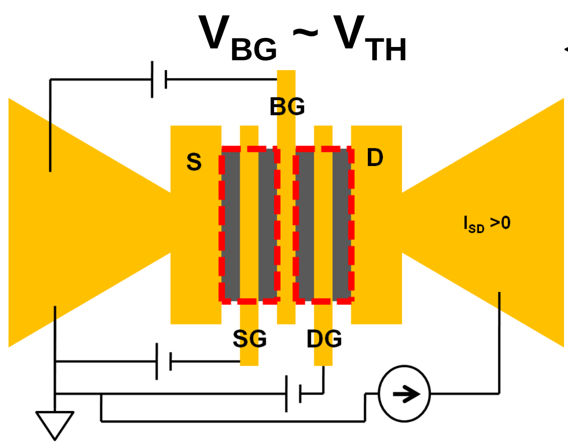
ADDITIONAL MATERIAL

Resonant Self-mixing Response









$$< \delta I_{SD} >$$

$$= \frac{\partial G}{\partial V_G} < \delta V_{SD} \delta V_G >$$

$$= \frac{1}{2} \delta V_{THz} \delta V'_{THz} \frac{\partial G}{\partial V_G} \cos(\phi)$$

Resonant Terahertz Response

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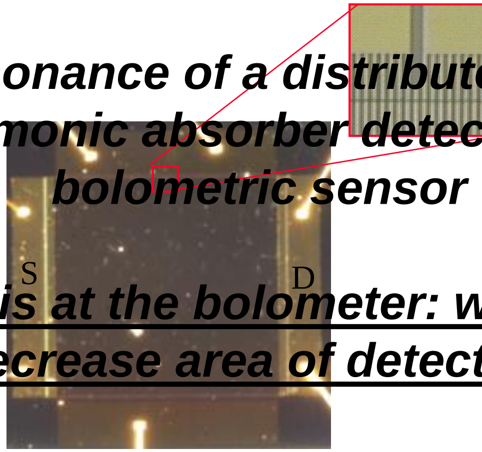
Resonance of a distributed 2D plasmonic absorber detected by bolometric sensor



<u>Action is at the bolometer: what if we decrease area of detector?</u>