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Multi-Cavity Far Infrared 2D Plasmonic Phenomena with Inhomogeneous Screening

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Abstract

We have observed coherent interaction of far infrared 2D plasma cavities in a GaAs/AlGaAs HEMT. A generalized transmission line formalism that unifies the screened and unscreened limits into a self-consistent theory describes an evolution of the plasmonic spectrum with increasing electron density modulation from homogeneous to the crystal limit.

Antenna Coupled Plasmonic HEMT

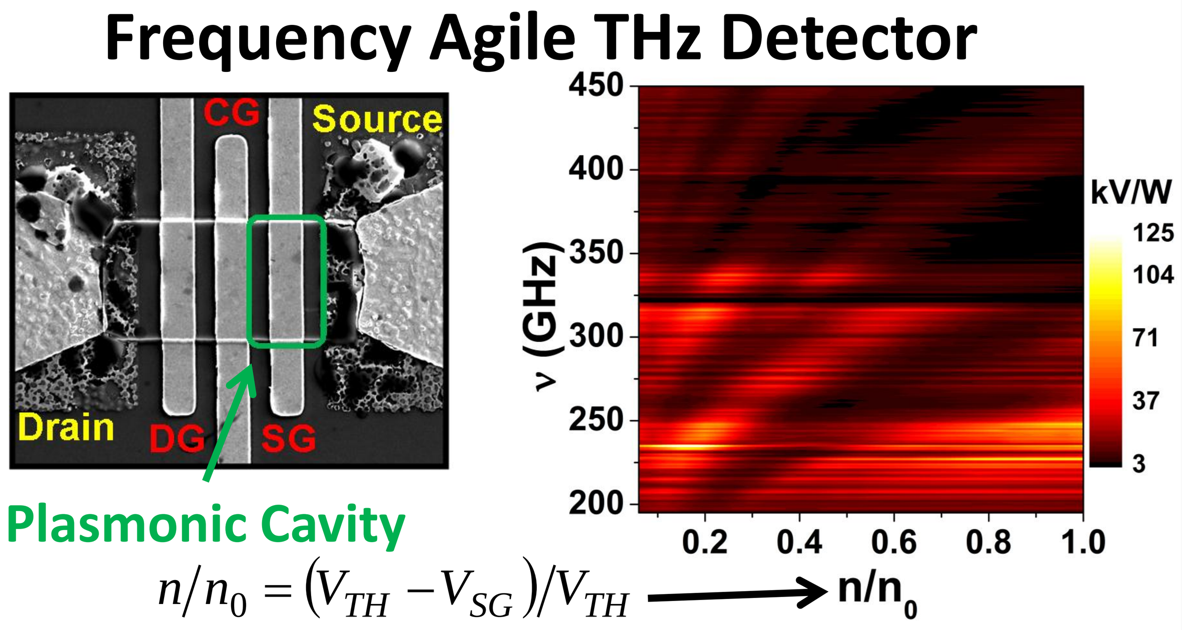
A GaAs/AlGaAs high electron mobility transistor (HEMT) is fabricated at the vertex of a broadband log-periodic antenna:

-HEMT channel is 14 μm long by 10 μm wide

-Gates are ~2 μm wide, spaced by ~2 μm

-***HEMT is reconfigurable 2D plasmonic device consisting of multiple plasmonic cavities***

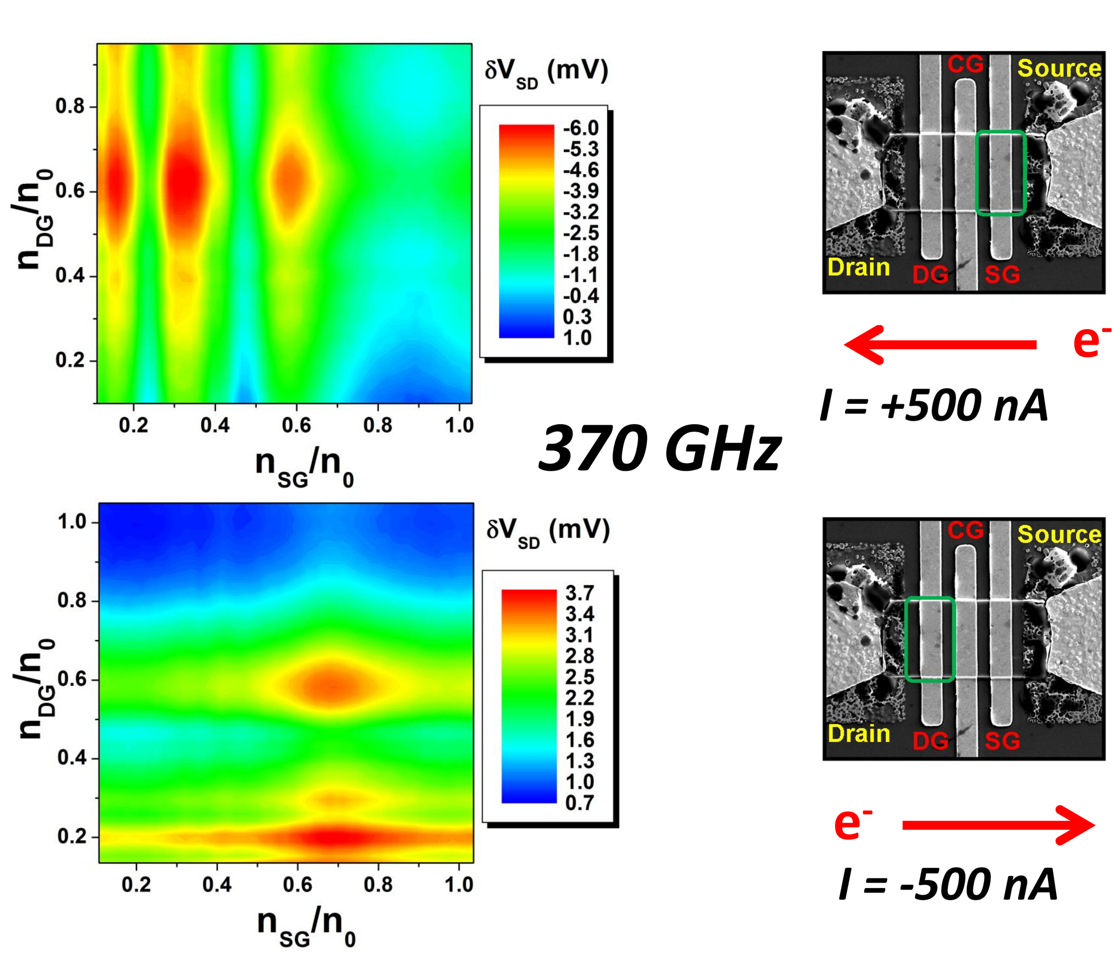
Frequency Agile THz Detector



-Center gate (CG) pinched-off to induce bolometric sensor and define plasmonic cavity and +500 nA drain current applied

-Source gate (SG) voltage-tuned & bolometric sensor preferentially detects plasmonic resonances scaling as $\omega_p \propto \sqrt{n}$ tuned by SG

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

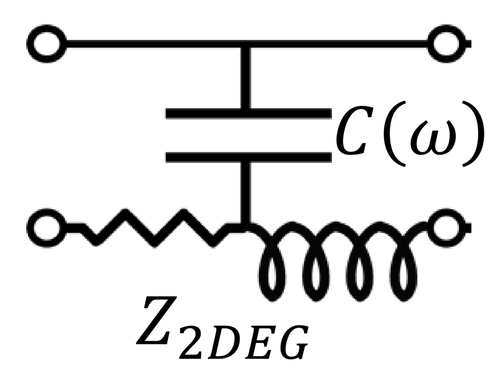


-Reverse of bias polarity changes cavity detected

-Evidence of incoherent inter-cavity coupling

Plasmonic Transmission Line Model

Plasmons excited in a 2DEG can be treated with a transmission line (TL) model though care must be taken to address the fact that a plasmon is a TM mode:



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

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

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

from Drude model L is kinetic inductance

$$\lim_{qd\to 0} C(\omega) = \frac{W\epsilon}{d} \qquad \lim_{qd\to\infty} C(\omega) = 2W\epsilon q$$

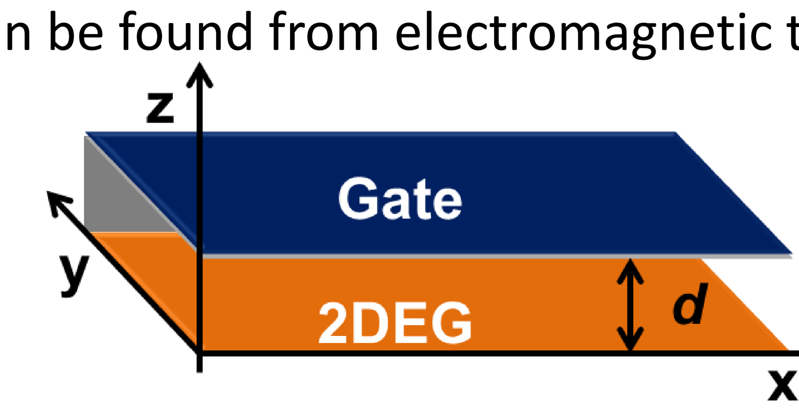
(fully screened limit) ***(unscreened limit)***

-Gated 2DEG in the screened limit has a gate-channel parallel plate capacitance (Burke *et. al.*, APL (2000))

-Unscreened 2DEG has a circuit capacitance that depends on plasmon wavevector (Rana, IEEE Trans. on Nano. (2008))

Generalized Plasmonic TL Model

In general the plasmon is screened and does not satisfy the above limits. A self-consistent plasmonic TL model can be found from electromagnetic theory:



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

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

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

-Voltage and current are superposition of backward and forward propagating waves consistent with TL

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

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

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

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

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

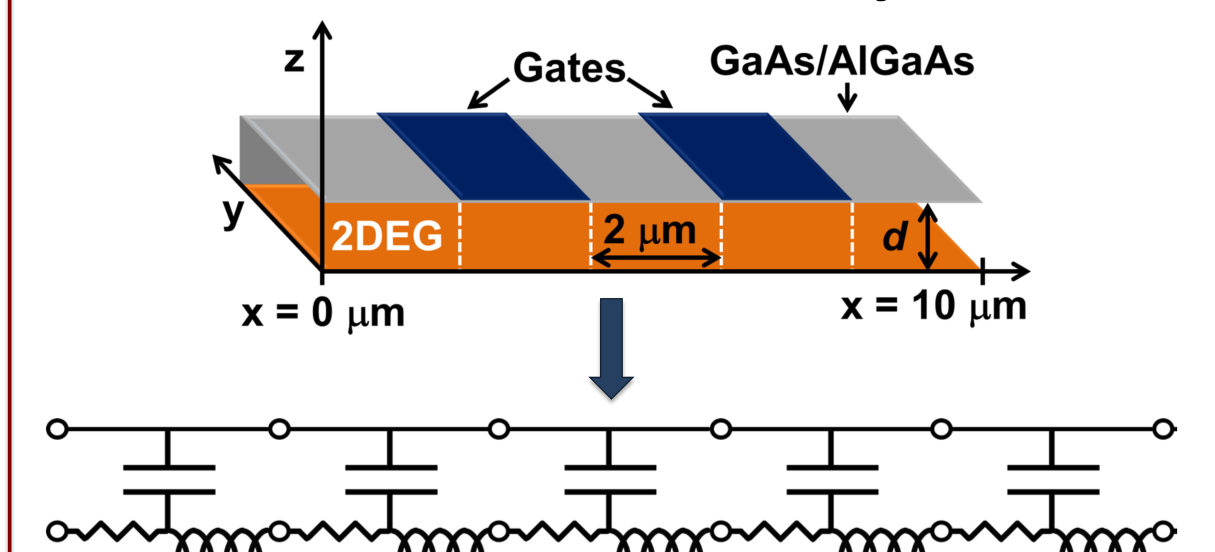
Defining effective V, I and Z for TL maintains continuity of potential and conserves energy.

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

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

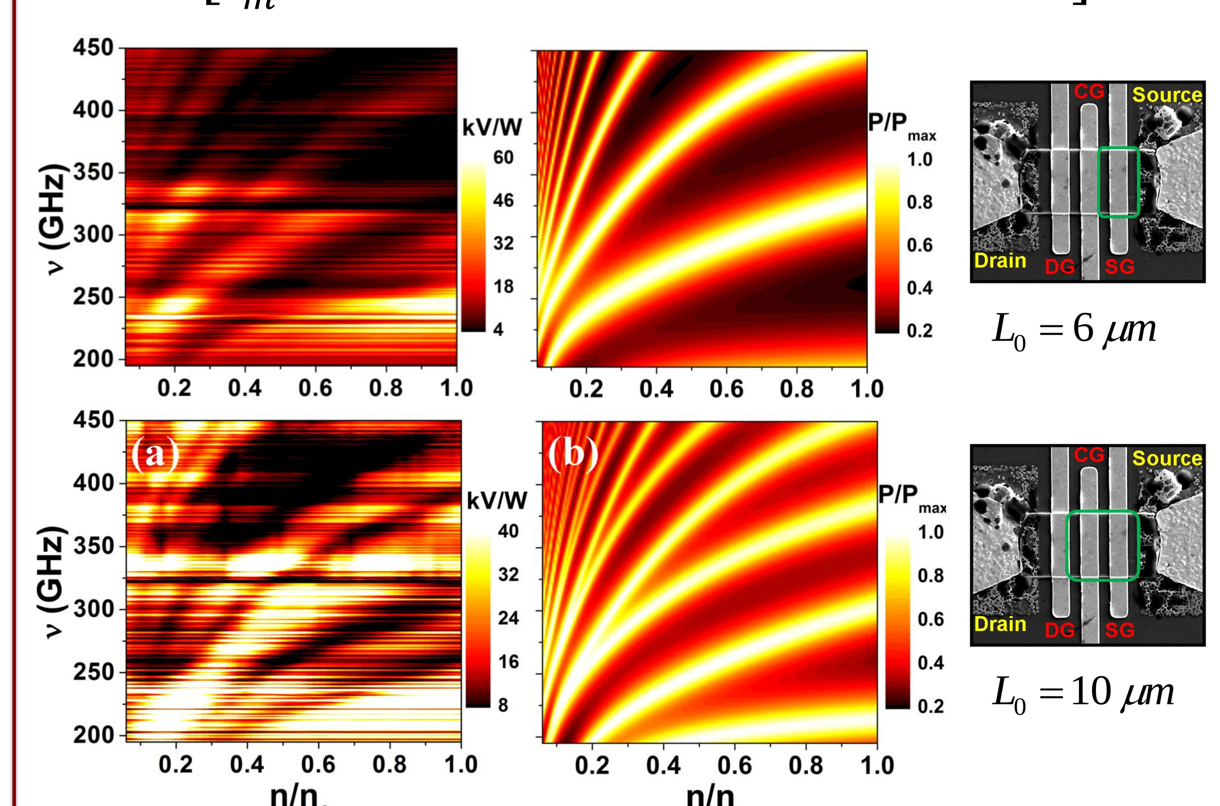
$$\tilde{Z}_0 \equiv \frac{Z_0}{\xi(\omega,d)}$$

Finite Plasmonic Crystal



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

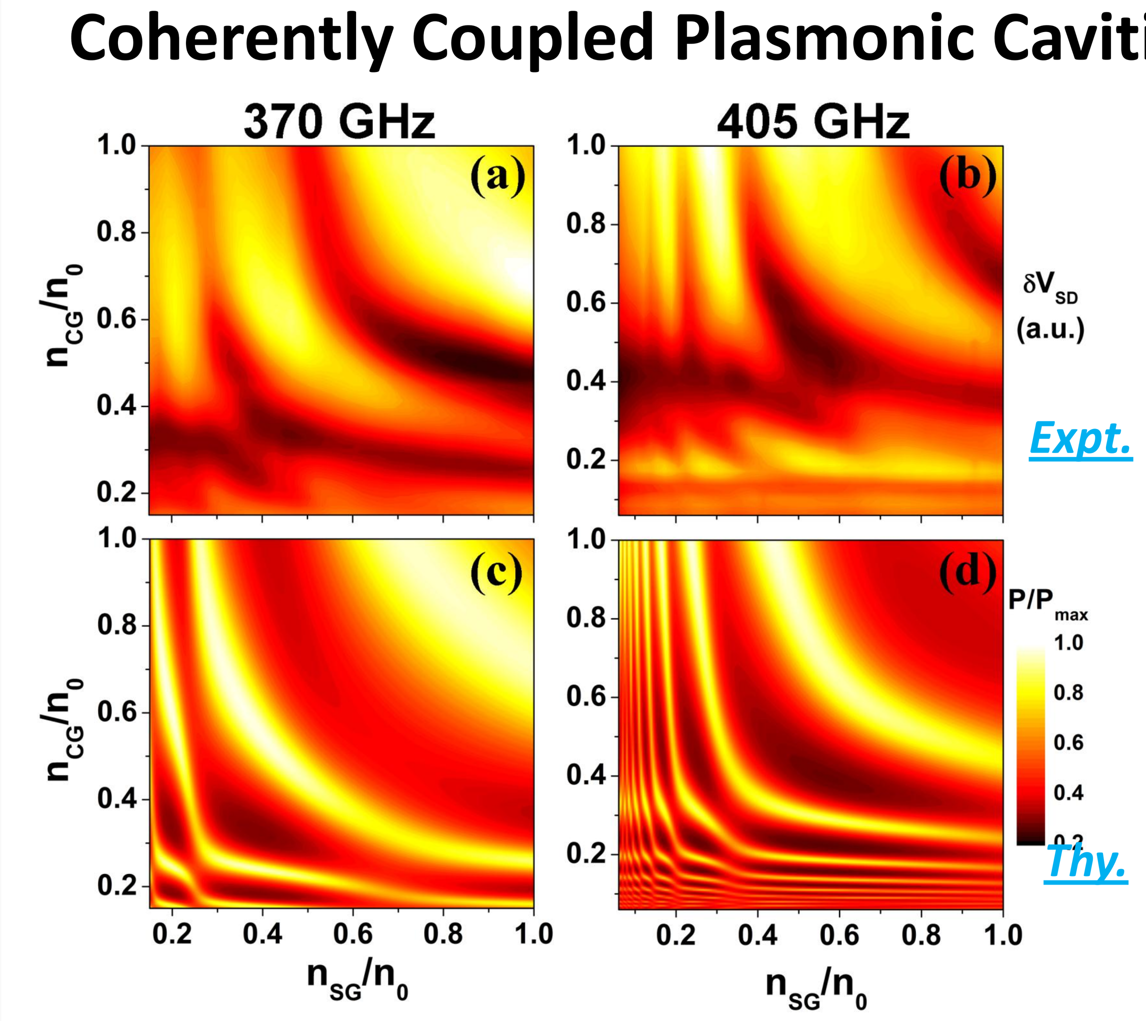
$$\begin{pmatrix}\tilde{V}_m \\ \tilde{I}_m\end{pmatrix} = \left[\prod_m^n \begin{pmatrix} \cos[q_m a_m] & i\tilde{Z}_m \sin[q_m a_m] \\ i\sin[q_m a_m]/\tilde{Z}_m & \cos[q_m a_m]\end{pmatrix}\right]\begin{pmatrix}\tilde{V}_{n+1} \\ \tilde{I}_{n+1}\end{pmatrix}$$

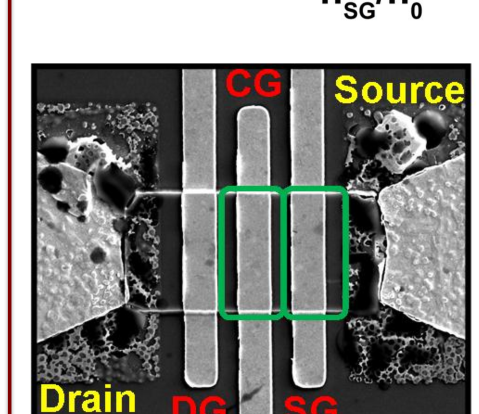


-Position of gate-induced bolometric sensor (CG vs. DG) determines plasmonic cavity size L_0

-SG and CG tuned identically: plasmonic band structure when 2DEG density modulation is strong

Coherently Coupled Plasmonic Cavities





Experiment and model show transition from plasmonic spectrum of a homogeneous cavity to coherent interaction of independently tuned sub-cavities below SG & CG

-2D plasmonic analogue of coupled quantum wells

-Repelled crossings of high order plasmonic eigenmodes in lower left quadrant

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