Weakly Ionized Plasmas for Reconfigurable RF Systems

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Acknowledgments

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- Field ionization plasma switch:

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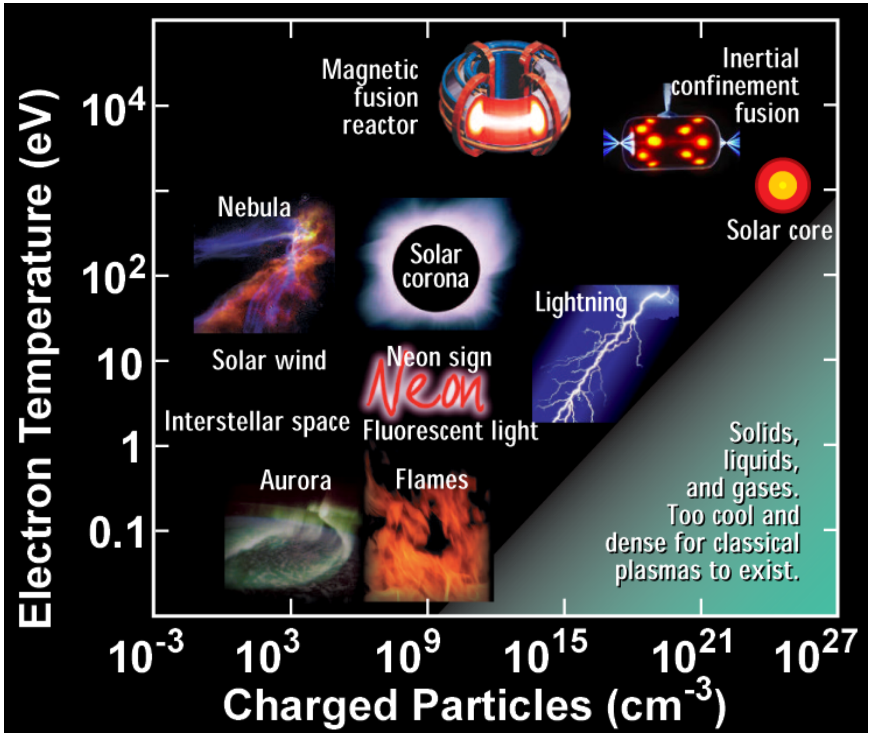
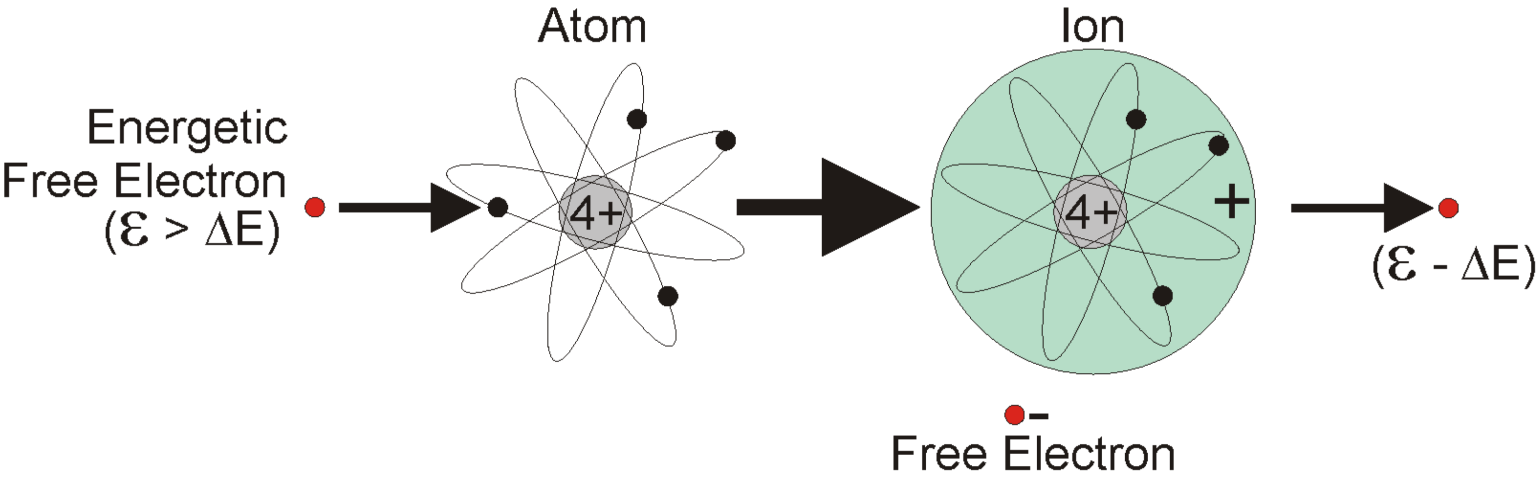
Low Temperature Plasmas

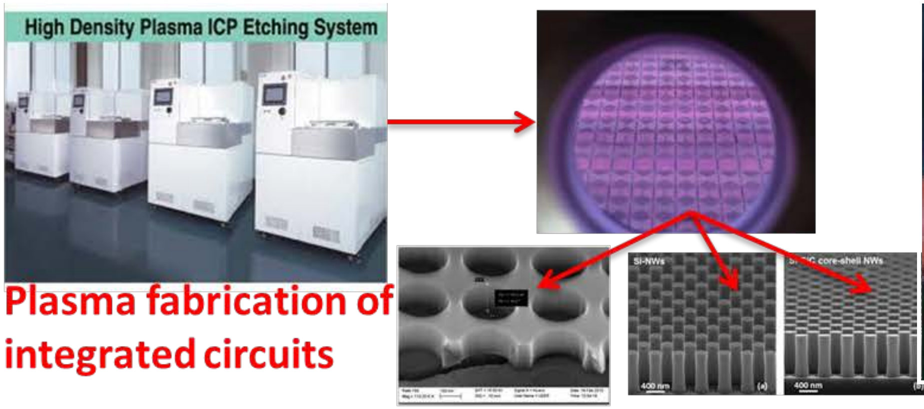
- Plasmas (ionized gases), the “fourth state of matter”, account for > 99.9% of the mass of the universe (dark matter aside).
- An energetic free electron collides with an atom, creating a positive ion and another free electron (also – photoionization)
- In cold plasmas, only 1 atom in a 1,000 – 10,000,000 is ionized, gas is cold (~room temperature), but electrons are very hot (1-10 eV)





Cold Plasmas: Applications


Compact Fluorescent Lamp

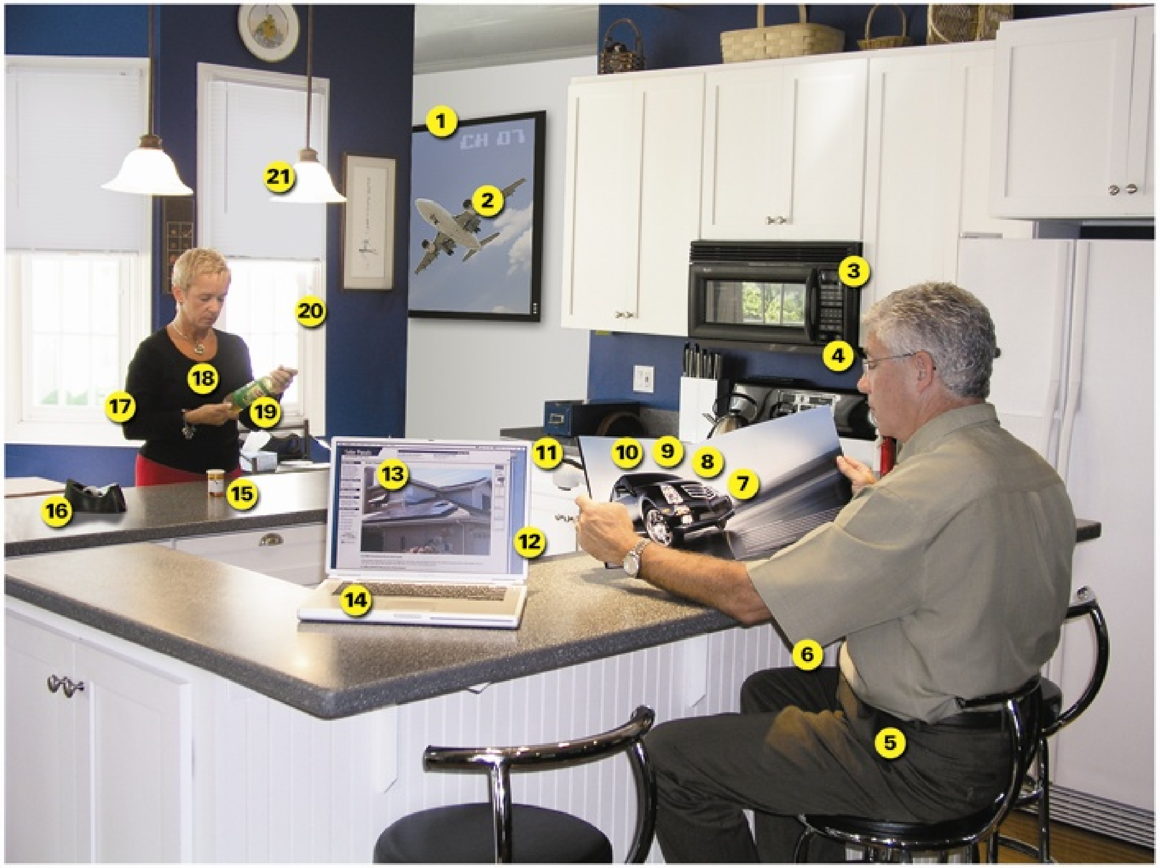


Plasma fabrication of integrated circuits


Jet Engine Spray Coatings

- **Low Temperature Plasma (LTP) -** ionized gas in extreme thermodynamic nonequilibrium: room temperature gas, but very hot (10,000 – 100,000 K) electrons and very high populations of excited atomic and molecular states.
- 2012: 12% of US electricity was expended by lighting; ~2/3 of that was used in LTP lighting sources.
- The entire current and future information technology (IT) infrastructure owes its very existence and Moore's Law development (transistor number in a dense IC doubles every 2 years) to LTPs.
- Renewable energy sources such as solar cell arrays, cannot be economically produced without deposition and etching by LTPs.
- High efficiency jet engines, military and commercial, would not exist in the absence of thermal barrier coatings produced by LTPs.
- Spacecraft rely on propulsion from LTP thrusters.
- The estimated impact on the US economy **$650 billion – 1.2 trillion** today

Cold Plasmas: Societal Benefits



01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
16—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp

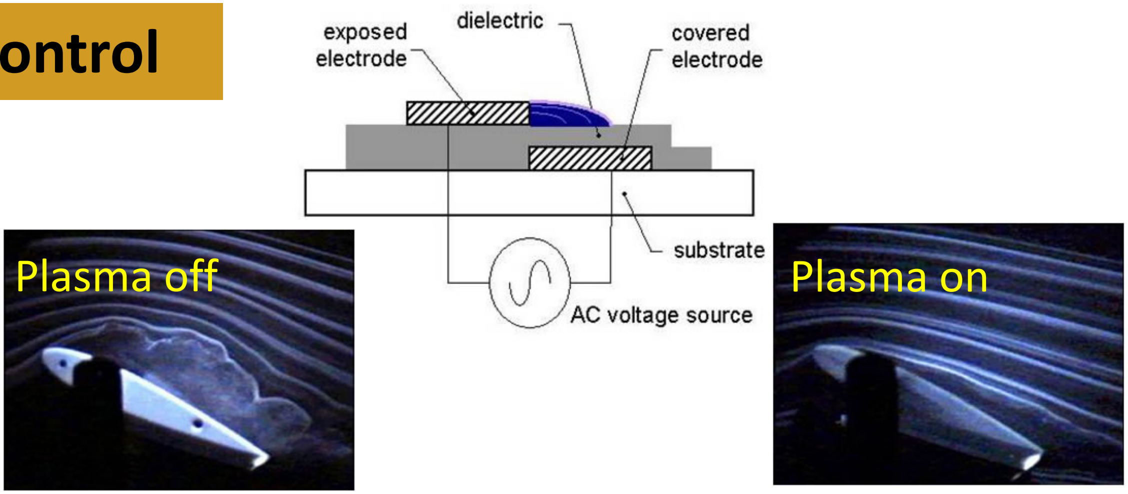
Ref:
“Plasma Science: Advancing Knowledge in the National Interest”, US National Research Council, 2007.

Cold Plasmas for Aerospace

Aerodynamics and Flow Control

Cold microplasma arrays:

- Low-power tunable actuation → ***30-50% higher fuel efficiency and range:*** military apps; potential est. **$15B savings in US airline industry**
- aircraft noise suppression.



Hypersonics

X-51: Mach>5 for 210 sec (2013)

Plasma would increase hypersonic lift-to-drag ratio by 30-50% and would also enable scramjet ignition and stable combustion

Plasma-Assisted Combustion & Cold Plasma Micropropulsion

Nanosecond-pulsed cold plasma sources:

- Tune in/out specific molecular and atomic processes → ***Ultimate control of chemistry***
- Chemistry activation and quenching control → ***less fuel, lower temperature, higher speeds***
- **Novel plasma microthrusters**: enabling orbital control and maneuvering for nanosatellites

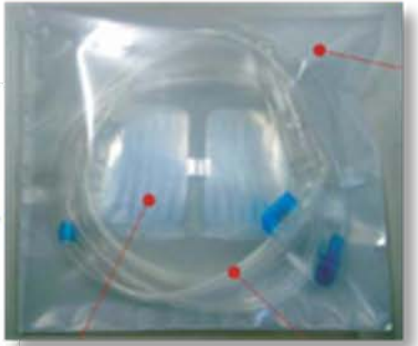
Food/Medical Technology

Kevin Keener
(Food Science & ABE)

Purdue invention:
30-120 kV atmospheric cold plasma technology

Medical Device Sterilization

$100B annual market opportunity



Food Safety

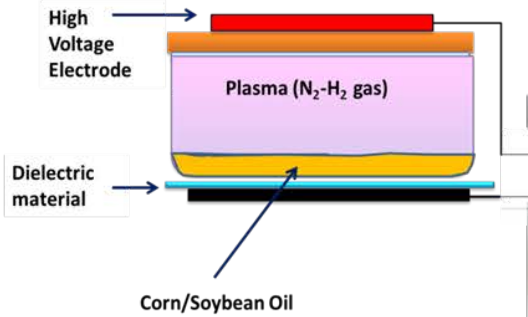
Cold plasma extends shelf-life by 4 weeks
$140M annual loss prevention – fresh tomatoes

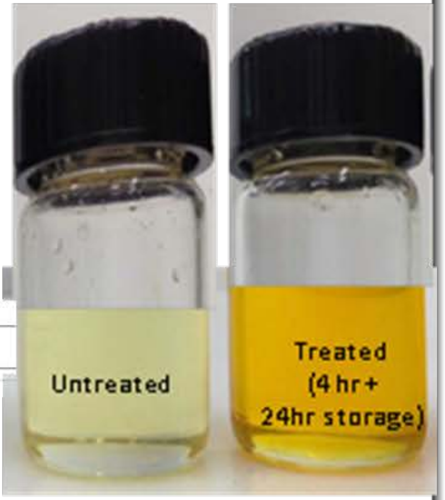
Industrial Processing

Food Oil Hydrogenation

a. No catalyst required
b. Trans-fat free
c. Low energy

Food Oil $28B annual market value





Plasmas for RF Electronics

Why it is important:

The next 20-30 years will demand completely **reconfigurable RF electronics** due to congested/contested EM spectrum.

Plasmas offer the ultimate platform for novel electronics.

Vision: plasma-based switches, reconfigurable antennas, transistors.

Added benefit: can **handle much higher power** than semiconductor electronics

Past

Static antennas

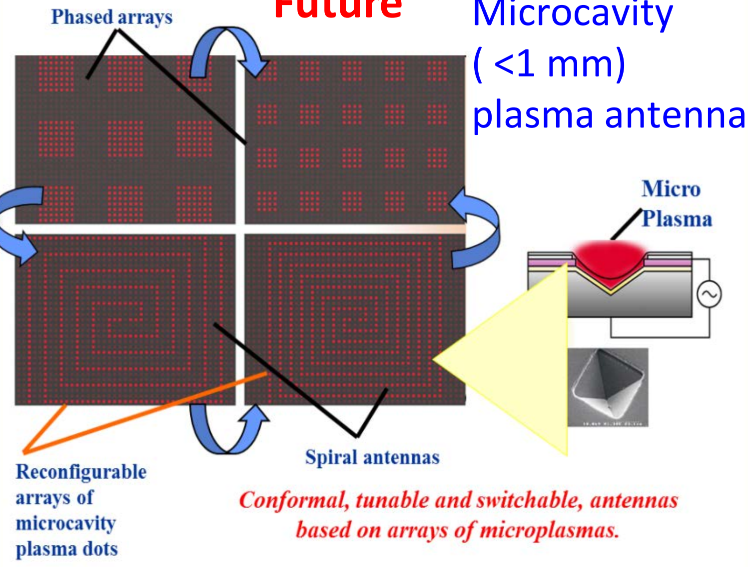
Present

Bulky (1 meter) plasma antenna

http://www.antentop.org/004/plasma.htm

Future

Microcavity (<1 mm) plasma antenna

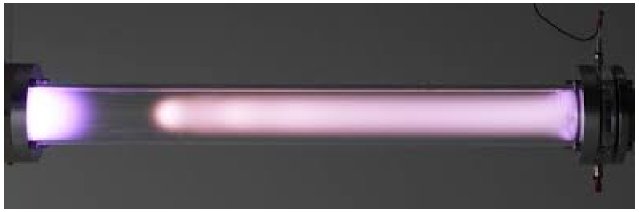


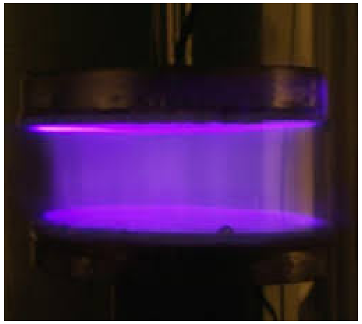
Conformal, tunable and switchable, antennas based on arrays of microplasmas.

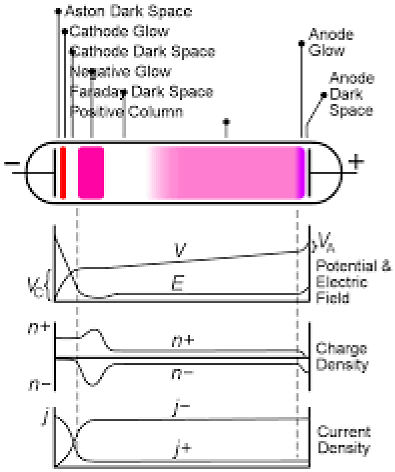
Impact:

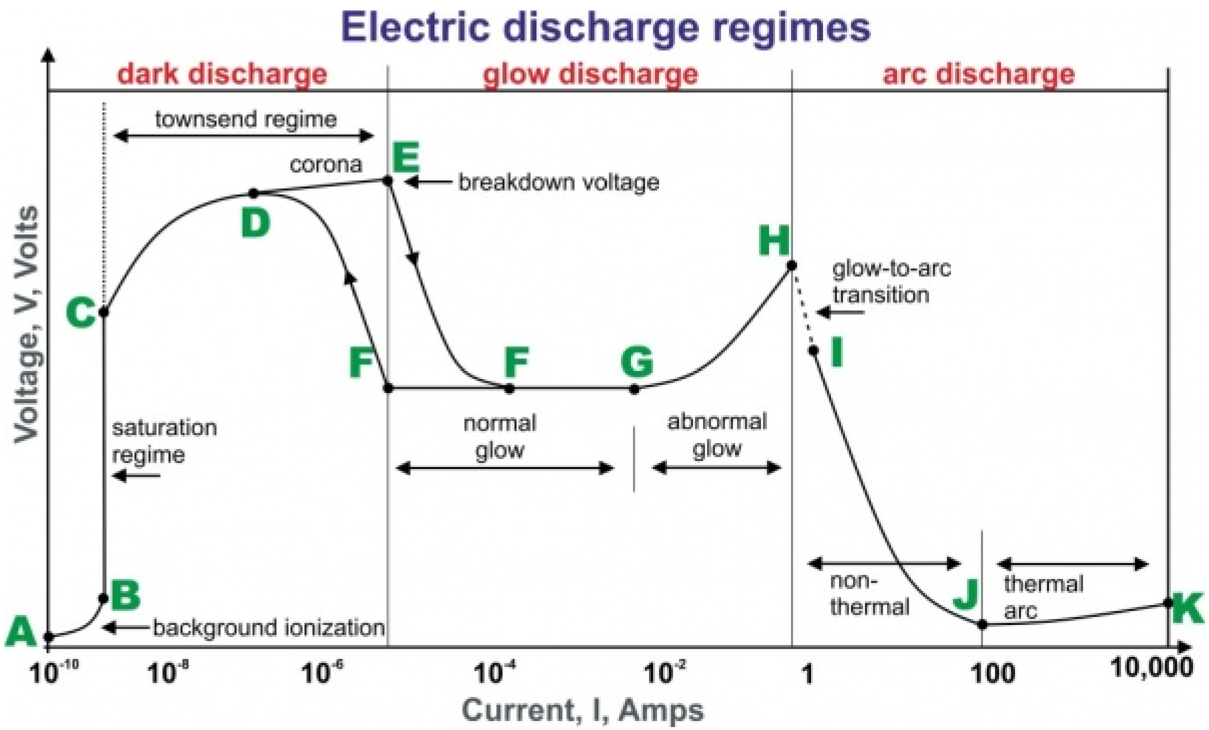
- Reconfigurable antennas and amplifiers for future mobile devices
- Modern airplanes (e.g. F-22) have ~100 antennas, strongly affecting design
    - Miniaturizing and combining antennas would open new design space

Electric Discharges: Complex Structure and Properties









Plasma as Tunable Dielectric

$$\varepsilon_r = \left(1 - \frac{\omega_p^2}{\omega^2 + \nu_m^{\;2}}\right) - j \cdot \frac{\nu_m}{\omega} \cdot \frac{\omega_p^2}{\omega^2 + \nu_m^{\;2}};$$

$$\omega_p = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m}} \text{ - plasma frequency}$$

ν_m - electron collision frequency; n_e - electron number density

- Plasmas are unique
    - Plasmas are both dielectrics and conductors
    - The real part of permittivity is always <1 and can be negative.
- By varying the gas pressure and the electron density, the collision frequency and the plasma frequency can be changed, thus tuning both real and imaginary parts of ε.

Microplasma Capacitor

$$\varepsilon_r = \left(1 - \frac{\omega_p^2}{\omega^2 + \nu_m^{\ 2}}\right) - j \cdot \frac{\nu_m}{\omega} \cdot \frac{\omega_p^2}{\omega^2 + \nu_m^{\ 2}};$$

$$\omega_p = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m}} \text{ - plasma frequency}$$

ν_m - electron collision frequency; n_e - electron number density

- When permittivity is negative, plasma capacitor is equivalent to tunable inductor:

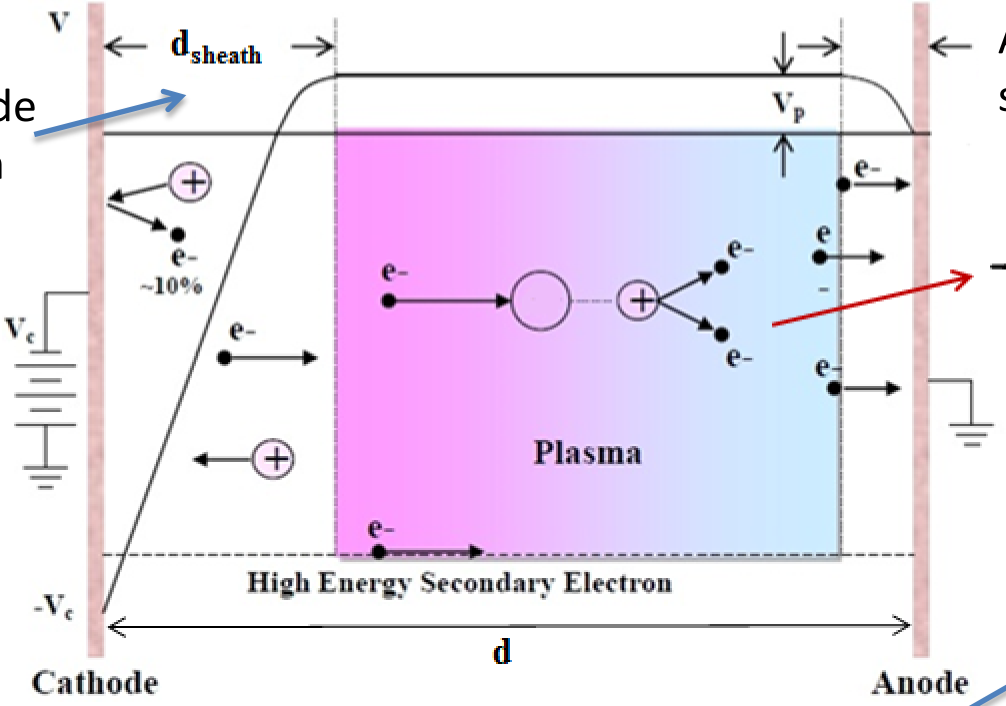
$$\varepsilon_r \approx 1 - \frac{\omega_p^2}{\omega^2} \approx -\frac{\omega_p^2}{\omega^2}, \quad \text{if } \frac{\omega_p^2}{\omega^2} \gg 1.$$

$$\text{Capacitance: } C = C_0 \varepsilon_r \approx -C_0 \frac{\omega_p^2}{\omega^2}.$$

$$\text{Impedance:} \quad Z_C = \frac{1}{j\omega C} = j\omega L_{eff}, \quad \text{where } L_{eff} = \frac{1}{C_0 \omega_p^2} \propto \frac{1}{n_e}$$

Electric Discharge Plasmas: Complex and Tunable Electromagnetic Properties

Cathode sheath



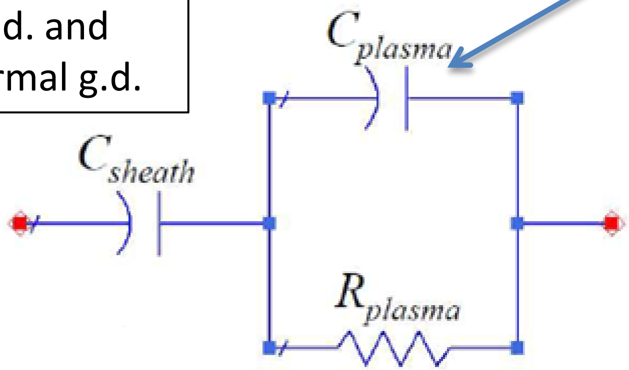
Anode sheath

$$\begin{cases} \varepsilon_{rp}(V) = 1 - \dfrac{e^2\, n_e(V)}{m\, \varepsilon_0\, (\omega^2 + v_m^2)} \\[2ex] \sigma_p(V) = \dfrac{e^2\, n_e(V)\, v_m}{m\, (\omega^2 + v_m^2)} \end{cases}$$

C_{plasma} becomes negative, equivalent to inductor, at high electron density, when $\varepsilon_{rp}<0$

d_{sheath} is constant in normal g.d. and reduces with current in abnormal g.d.

$$C_{sheath}(V) = \varepsilon_0 \frac{A}{d_{sheath}(V)}$$

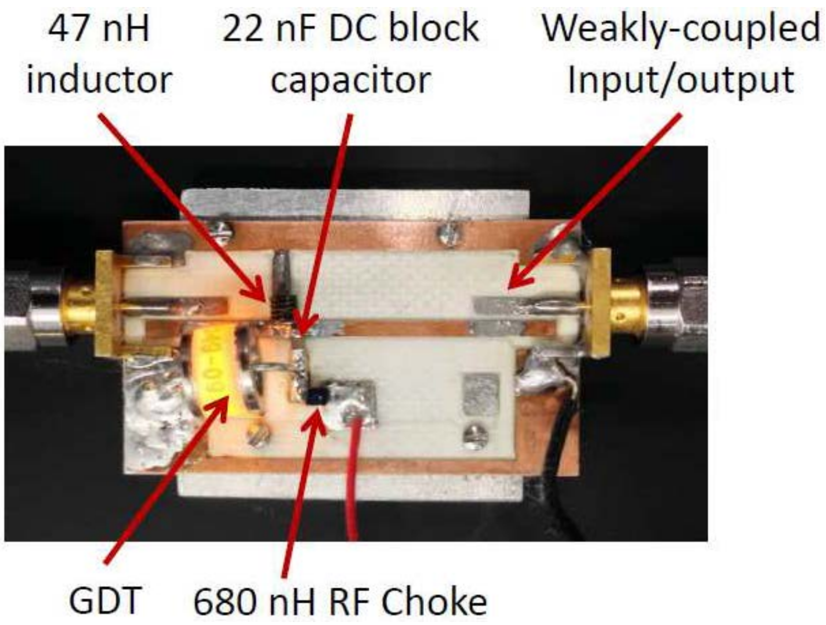


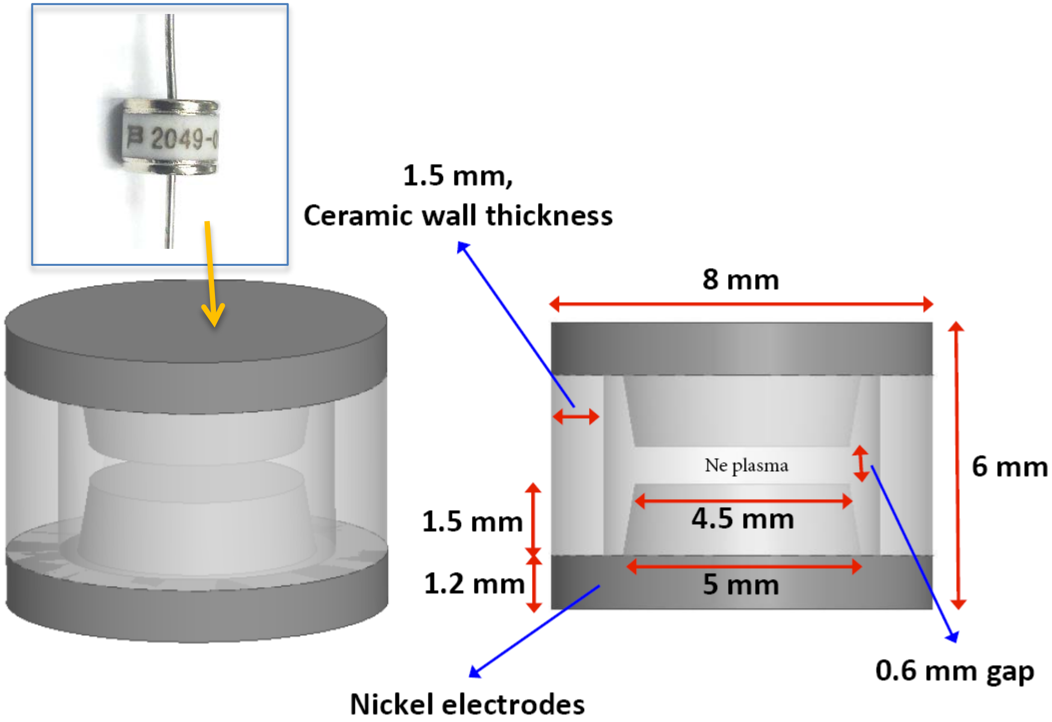
$$C_{plasma}(V) = \varepsilon_0\, \varepsilon_{rp}(V) \frac{A}{d - d_{sheath}(V)}$$

$$R_{plasma}(V) = \frac{1}{\sigma_p(V)} \frac{d - d_{sheath}(V)}{A}$$

Plasma discharges have complex and tunable resistive/capacitive/inductive properties

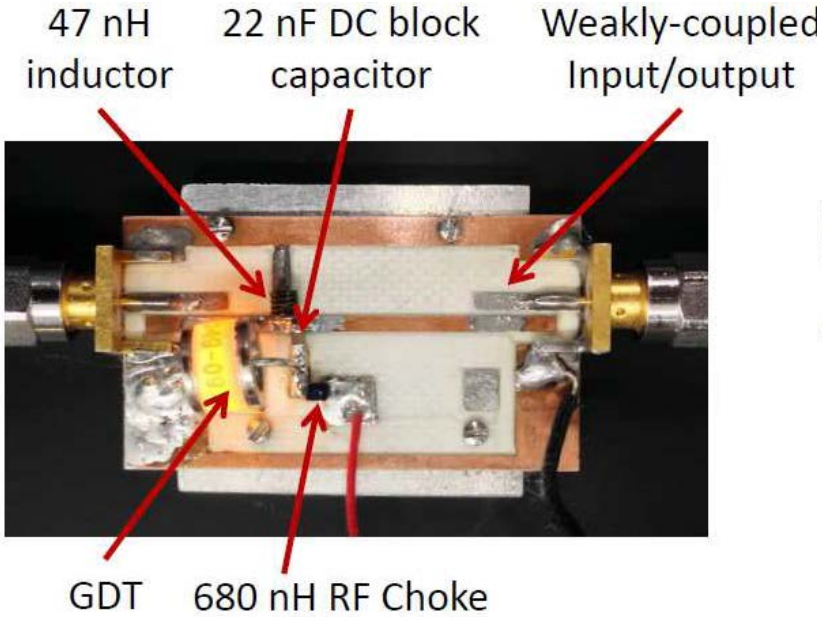
GDT Tunable LC Resonator

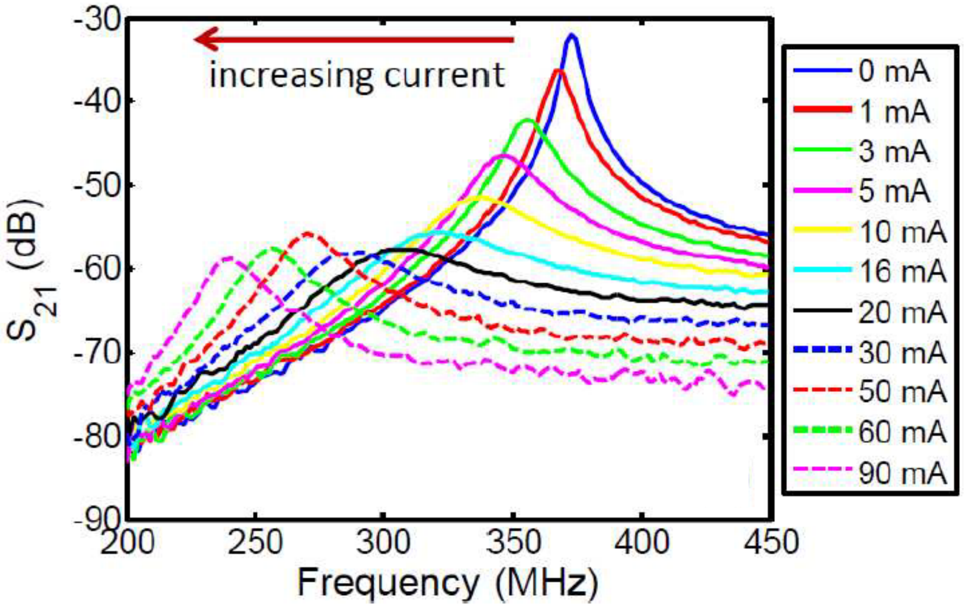




- Gas Discharge Tube (GDT) – inexpensive surge-protection device
- We use it as the capacitor in LC resonator

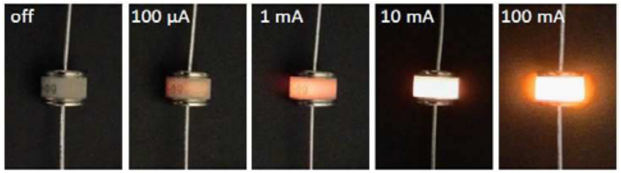
GDT Tunable LC Resonator



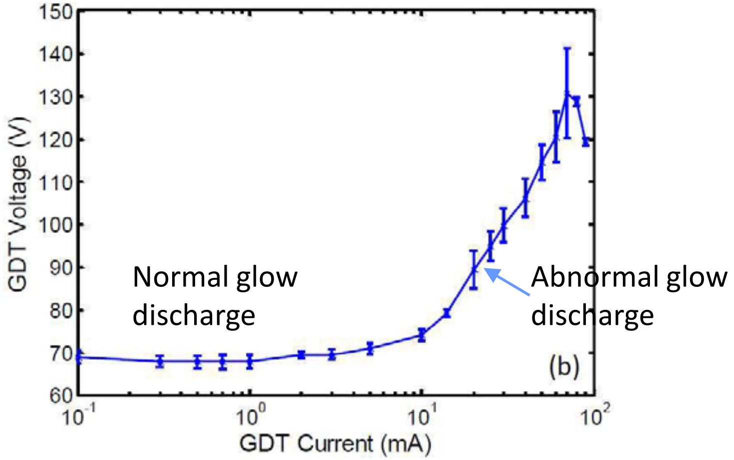


- Gas Discharge Tube (GDT) is the capacitor in LC resonator
- 55% of resonant frequency tunability in VHF/UHF range when I_{tube} = 0 – 90 mA
- Q_u = 62 - 10 for the same range

V-I Characteristic, Tuning, and Q Factor

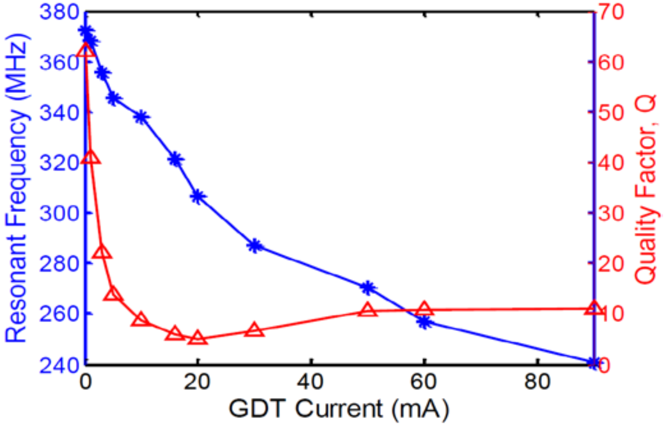


(a)



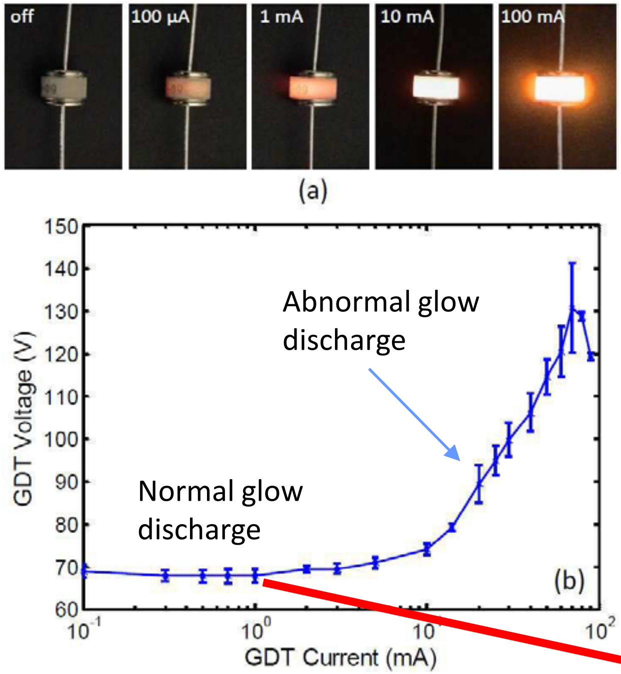
Normal glow discharge

Abnormal glow discharge



- Substantial change in capacitance starts with onset of abnormal glow discharge
- This indicates key role of cathode sheath
- Normal glow discharge: constant voltage, constant cathode sheath thickness, very little change in capacitance and thus in resonant frequency.
- Abnormal glow discharge: cathode sheath shrinks as the current increases, thus increase in capacitance and decrease in resonant frequency.

Determining Discharge Parameters

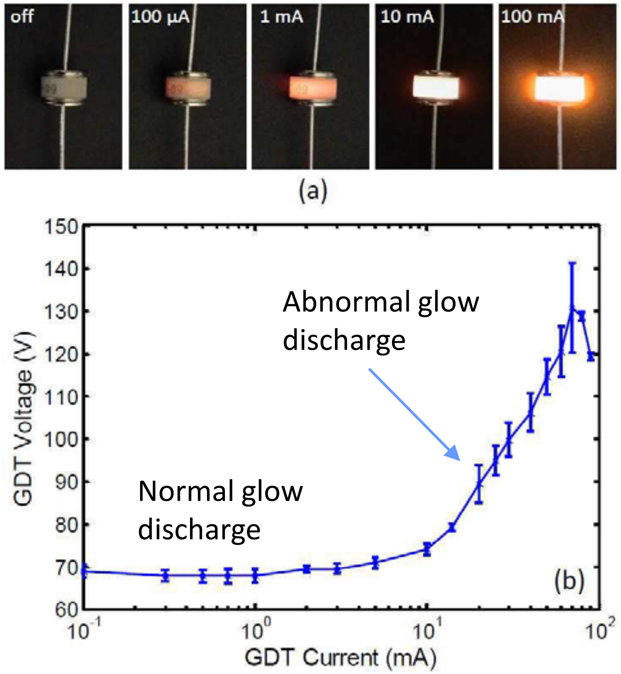


From interelectrode gap (d=0.6 mm), ignition voltage (90 V) and normal glow discharge voltage, we can determine the gas, pressure, secondary emission coefficient, and normal current density using Townsend breakdown theory and the theory of normal cathode sheath

gas cathode	air	Ar	He	H_2	Hg	Ne	N_2	O_2	CO	CO_2
Al	229	100	140	170	245	120	180	311	–	–
Ag	280	130	162	216	318	150	233	–	–	–
Au	285	130	165	247	–	158	233	–	–	–
Bi	272	136	137	140	–	–	210	–	–	–
C	–	–	–	240	475	–	–	–	526	–
Cu	370	130	177	214	447	220	208	–	484	460
Fe	269	165	150	250	298	150	215	290	–	–
Hg	–	–	142	–	340	–	226	–	–	–
K	180	64	59	94	–	68	170	–	484	460
Mg	224	119	125	153	–	94	188	310	–	–
Na	200	–	80	185	–	75	178	–	–	–
Ni	226	131	158	211	275	140	197	–	–	–
Pb	207	124	177	223	–	172	210	–	–	–
Pt	277	131	165	276	340	152	216	364	490	475
W	–	–	–	–	305	125	–	–	–	–
Zn	277	119	143	184	–	–	216	354	480	410
glass [a]	310	–	–	260	–	–	–	–	–	–

Normal cathode voltage fall V_n, Volts [Yu.P. Raizer, Gas Discharge Physics, Springer 1991]

Determining Discharge Parameters



Paschen breakdown minimum:

$$V_{min} = \frac{\bar{e}B}{A}\ln\left(1+\frac{1}{\gamma}\right);\ \ (pd)_{min} = \frac{\bar{e}}{A}\ln\left(1+\frac{1}{\gamma}\right).$$

Normal cathode voltage fall: $V_n = 1.1V_{min}$

For V_n=68 V, secondary emission coefficient:

$$\ln\left(1+\frac{1}{\gamma}\right) = 0.91;\ \ \gamma = 0.674$$

The values of *pd* corresponding to the Paschen minimum and to the normal cathode sheath:

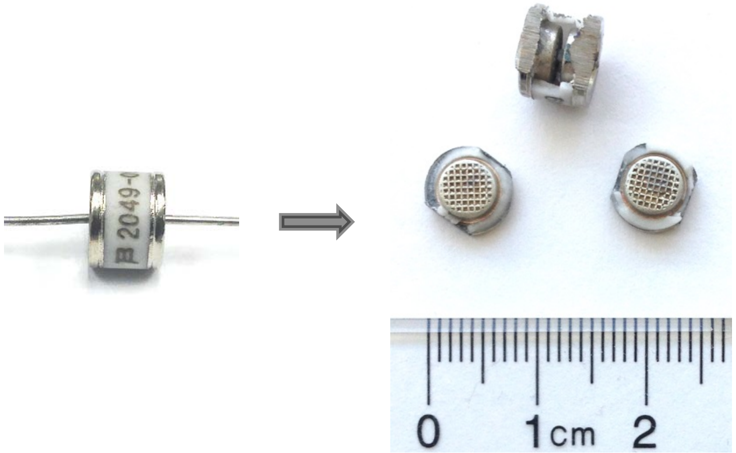
$$(pd)_{min} = 0.618\ \text{cm·Torr};\ (pd)_n = 1.4\ (pd)_{min} = 0.865\ \text{cm·Torr}$$

Gas pressure: For a pressure of <u>*p*=30 Torr</u>, d_n=300 micron, and with *d*= 0.6 mm, *pd*=1.8, breakdown voltage V_t is close to the nominal 90 V.

Normal current density: $\frac{j_n}{p^2} = 1.8(1+\gamma)\varepsilon_0(\mu_+ p)V_n^2/(pd)_n^3 \quad = \quad 9.53\frac{\mu\text{A}}{\text{cm}^2\cdot\text{Torr}^2}$ - consistent with Ne discharges.

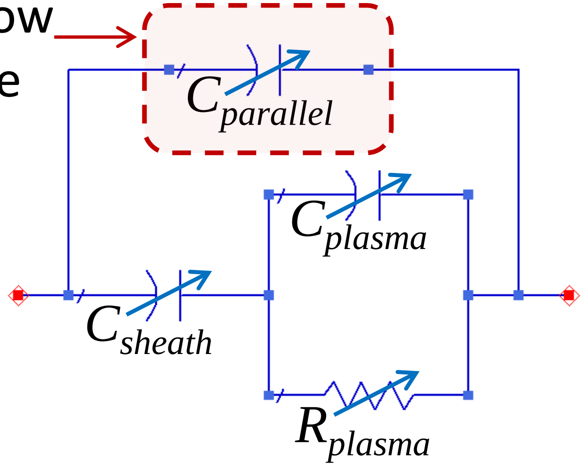
Current corresponding to onset of abnormal discharge at *p*=30 Torr is ≈1.4 mA, consistent with experimental data.

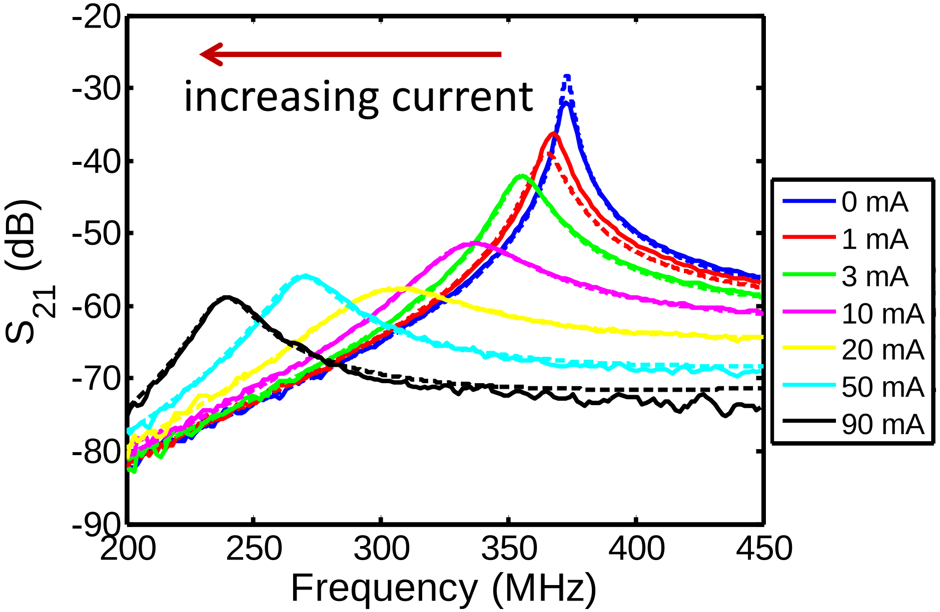
GDT Modeling

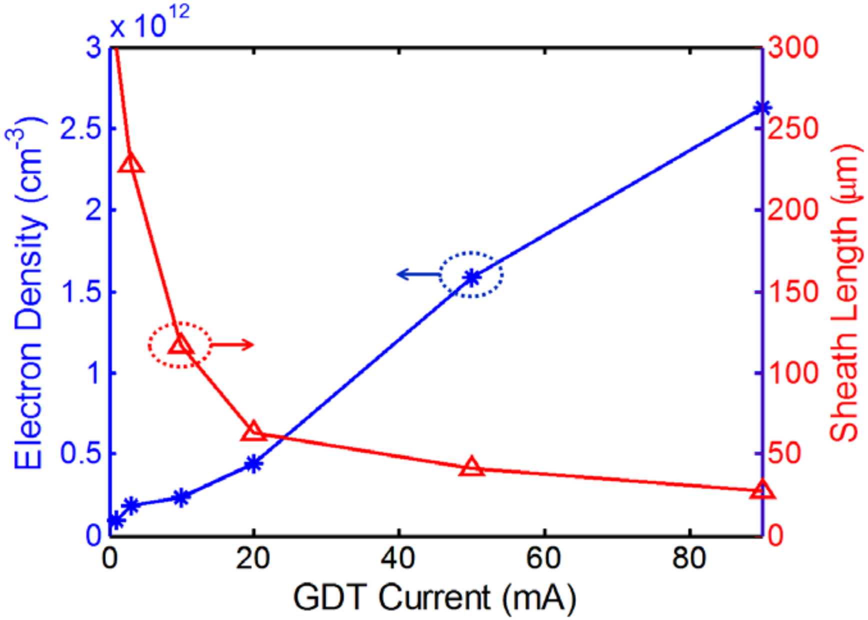


≡

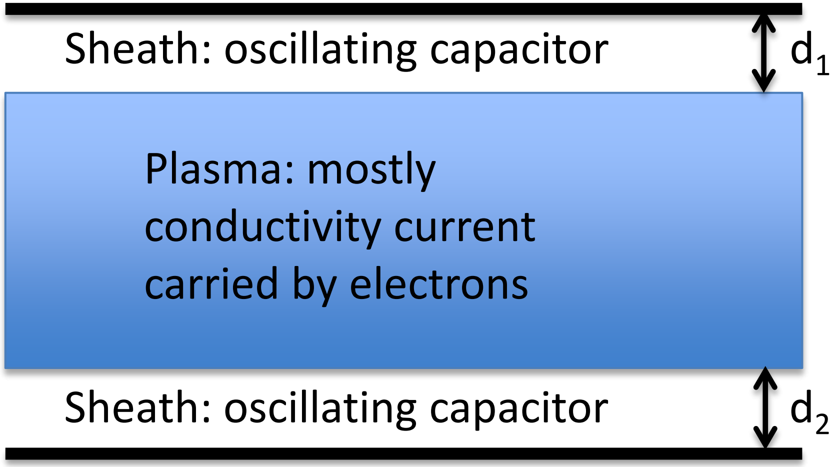
just for normal glow discharge regime







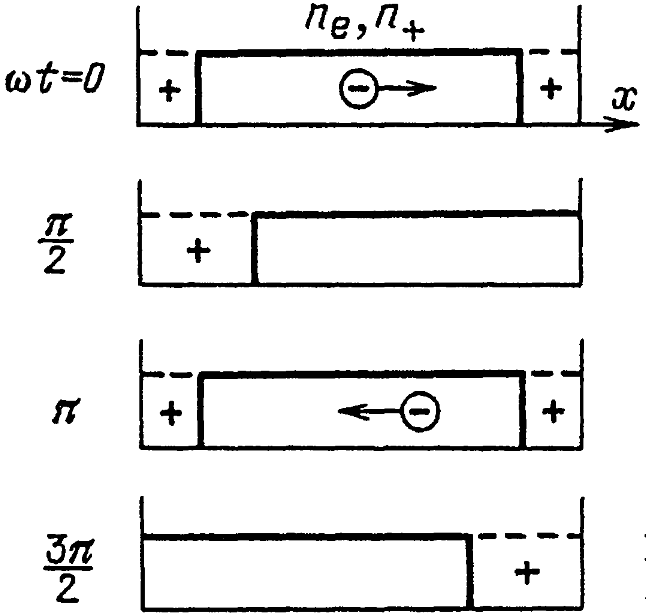
New Concept: Tuning LC Resonator by Varying Plasma-Driving Frequency



Sheath: oscillating capacitor d_1

Plasma: mostly conductivity current carried by electrons

Sheath: oscillating capacitor d_2

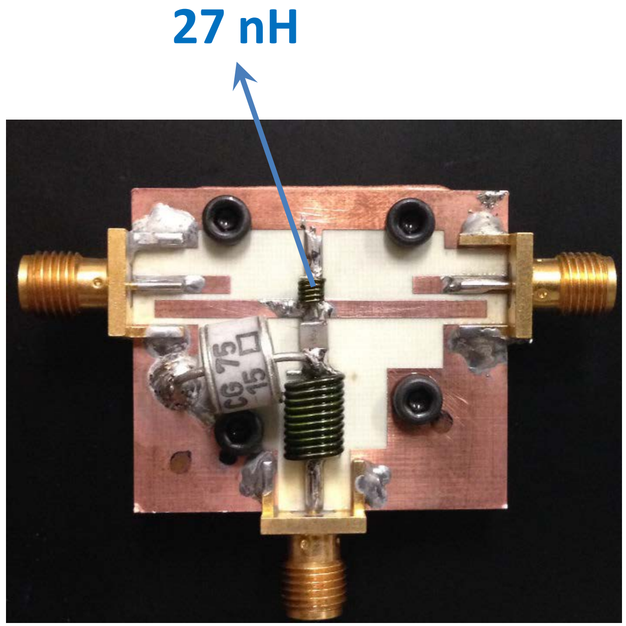


$$d_1 + d_2 = 2A = 2\frac{\mu_e E_a}{\omega}, \quad \text{where } A = \frac{\mu_e E_a}{\omega} \text{ is the electron oscillation amplitude}$$

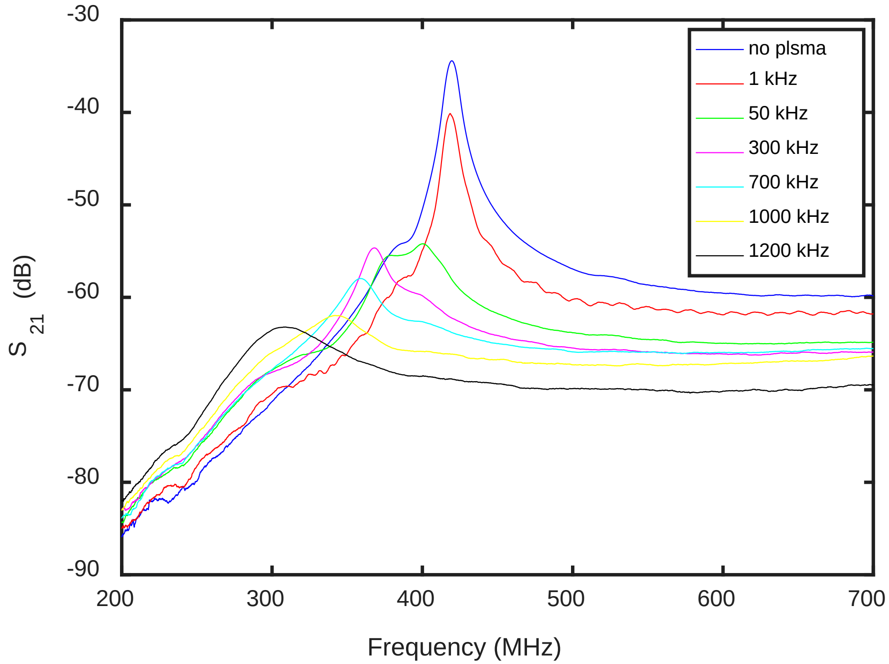
The effective plasma capacitance is proportional to the generator frequency. Thus, by varying the generator frequency, e.g., in 1-100 MHz range, LC resonant frequency in a different frequency range, e.g., 200-800 MHz or 1-6 GHz, can be tuned .

Tuning LC Resonator by Varying Plasma-Driving Frequency

kHz-controlled LC resonator in 300-500 MHz range



Voltage: 100 V amplitude kHz-range AC plus 40 V DC bias



Next steps: driving plasma at 1-100 MHz (α discharge) and reducing losses

Reducing Losses: Low Pressure Operation

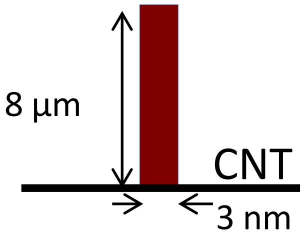
- For low loss tangent, $\tan\delta \approx \frac{\sigma\omega}{\varepsilon_0\omega_p^2} = \frac{\nu_m}{\omega} \leq 10^{-3}$, need very low collision frequency, thus low pressure (<10 mTorr)
- Need electron density $>10^{11}$ cm^{-3} for tunability in RF regime
- How can a plasma with substantial electron density be sustained at $p \leq 10$ mTorr and $d \leq 100$ µm, i.e. at $pd \leq 0.0001$ cm × Torr, with virtually no electron-atom collisions?
- Need completely new way of plasma generation:
  - Electrons are generated by field emission (FE) from CNTs or similar emitters
  - Ions are independently generated in tunneling field ionization (FI)

Field Emission and Field Ionization

Fowler-Nordheim Field Emission

$$j_{FN} = \frac{A_{FN}\beta^2 E^2}{\phi_w t^2(y)} \exp\left[-\frac{B_{FN}\phi_w^{\frac{3}{2}} v(y)}{\beta E}\right]$$

j_{FN} = field emission current density
E = electric field
ϕ_w = work function
β = field enhancement factor
A_{FN}, B_{FN} = Fowler-Nordheim constants
$v(y) \approx 0.95 - y^2$; $t^2 \approx 1.1$
$y = 3.79x10^{-4}\sqrt{\beta E}/\phi_w$



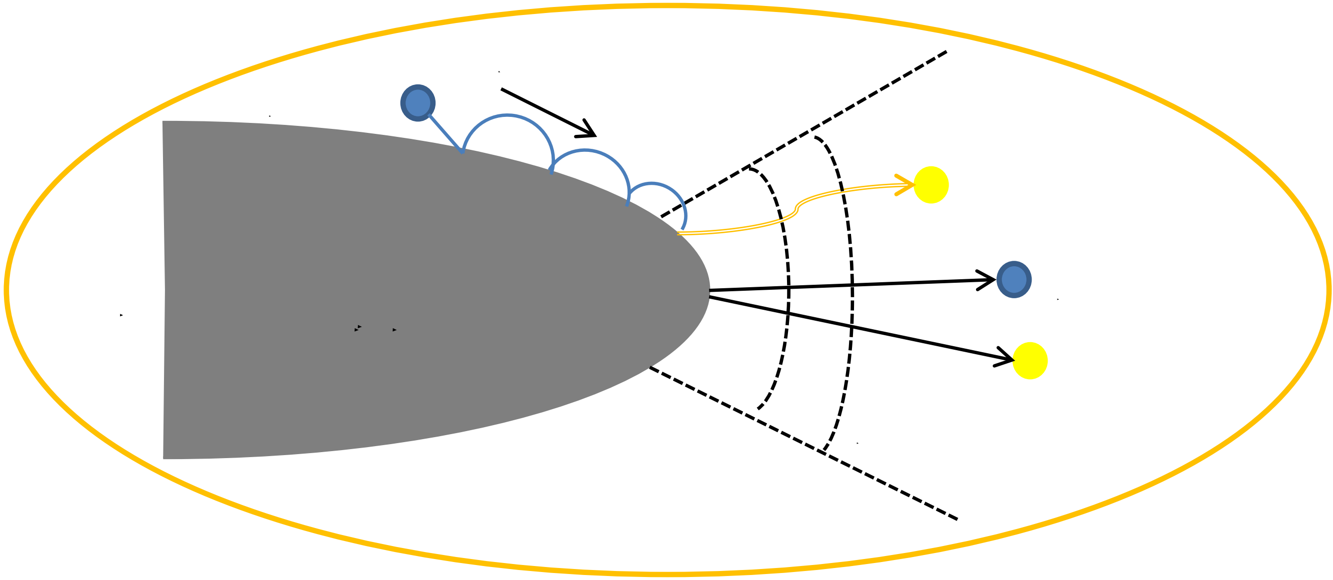
Field enhancement factor
β = H/0.7d (aspect ratio)

For field emission, need fields ~3×10^7 V/cm. For field ionization, need ~3×10^8 V/cm, thus curvature radius ~0.1 nm (atomic sharpness)

Field ionization:

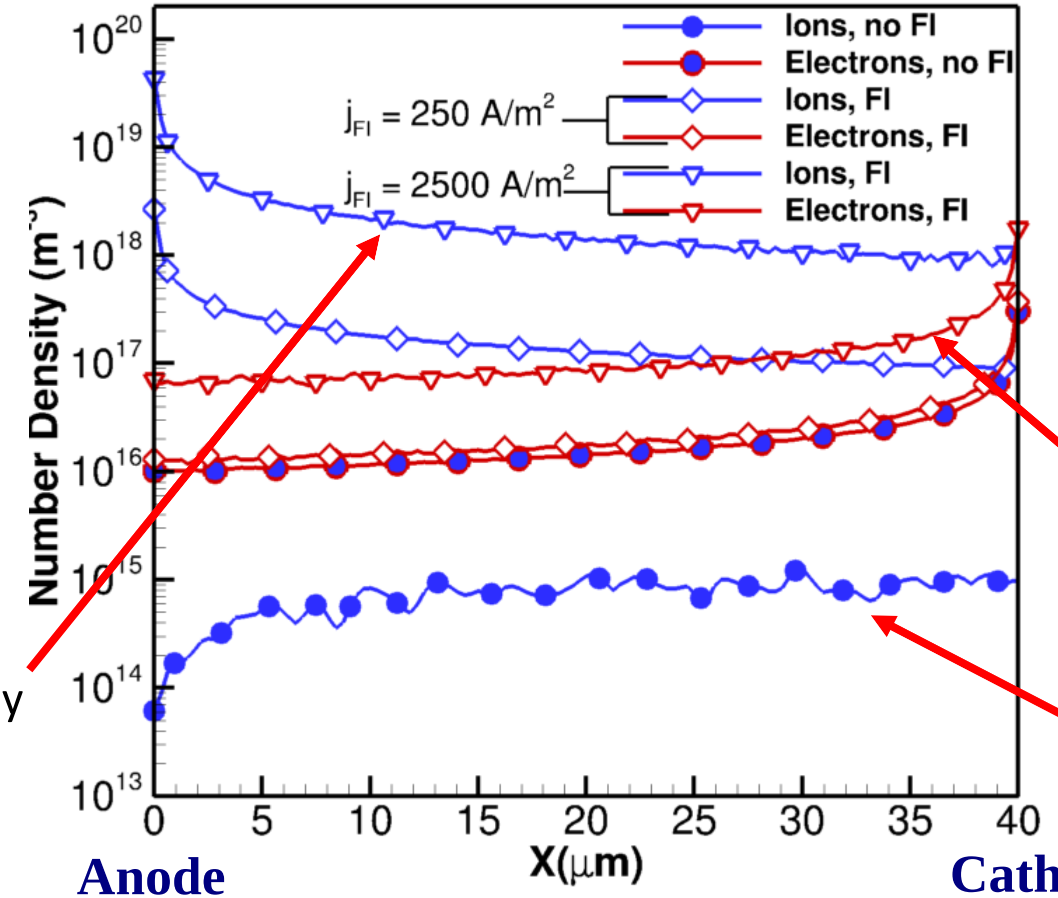
(Used in atom-probe microscopy and mass spectrometry)

Liu and Orloff (2005) model includes tunneling ionization and gas supply function



PIC/MCC Simulation Results

$\Phi = 63$ V
$d = 40\ \mu m$
$\beta = 2667$
$P = 7.5$ mTorr



Anode

Cathode

Electrons produced by ion-enhanced Field Emission

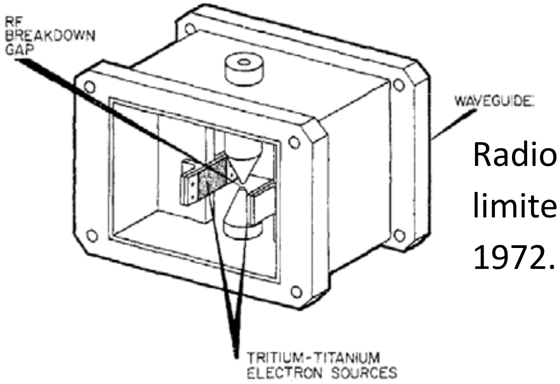
Ions produced by Field Ionization

Ions produced by electron-impact ionization

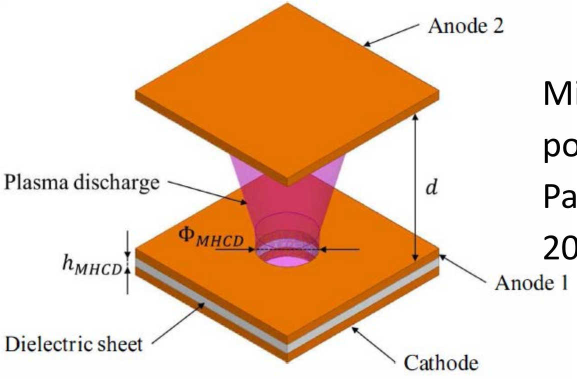
- **Effective electron collision frequency (collisions w/ wall) ~5×10^{10} s^{-1} – too high.**
- **But the device can be a fast switch: ignition time ~20 ps to get n_e~10^{10} cm^{-3} (electron time of flight) and ~4 ns to reach n_e~10^{12}-10^{13} cm^{-3} (ion time of flight)**

Power Limiters

- Required to protect sensitive circuits against high-power incoming waves
- Solid-state limiters based on PIN diodes, Schottky diodes, and FETs
  - ✓ Low loss, small, low cost, fast and tunable
  - × Too wideband, parasitics and nonlinearities in the off (non-limiting) mode
- Ferrite materials
  - ✓ absorptive with frequency selectivity
  - × high insertion loss, large size, expensive, no power tunability
- Existing plasma limiters (high-power signal ignites plasma which reflects the signal)
  - ✓ Works up to very high frequencies and power levels
  - × Not frequency-selective, expensive and complicated, short lifetime, high threshold power, and transient spike leakage



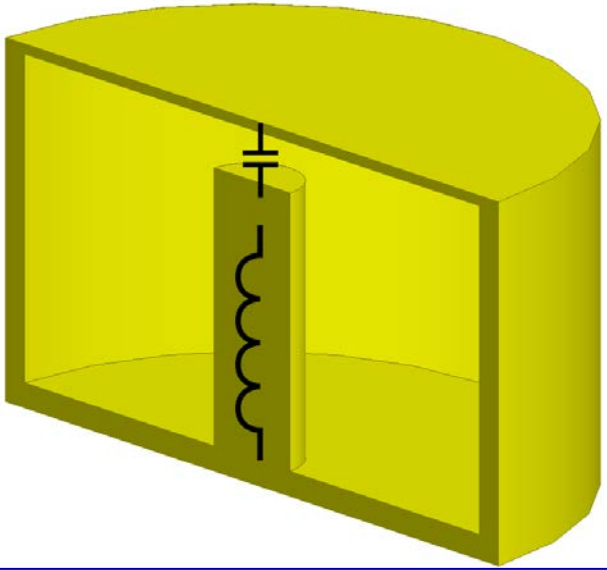
Radioactive plasma limiter, Goldie, 1972.



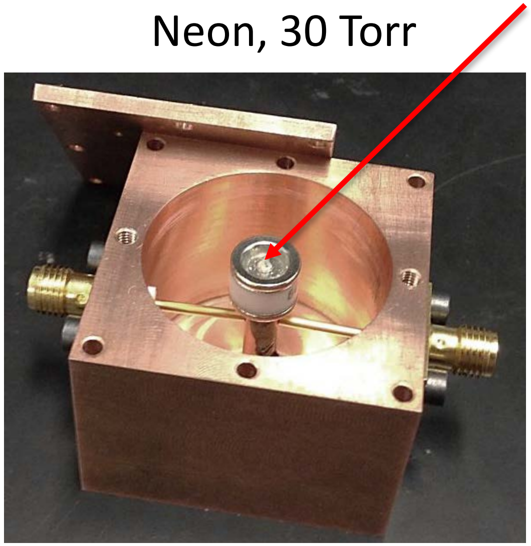
Microplasma power limiter, Pascaud *et al.*, 2015.

Plasma Power Limiter: Our Approach

- Employing a plasma cell inside a high-*Q* 3D resonator for both frequency selectivity and reduced threshold power
- Plasma behaves as a conducting barrier for the propagating EM waves.



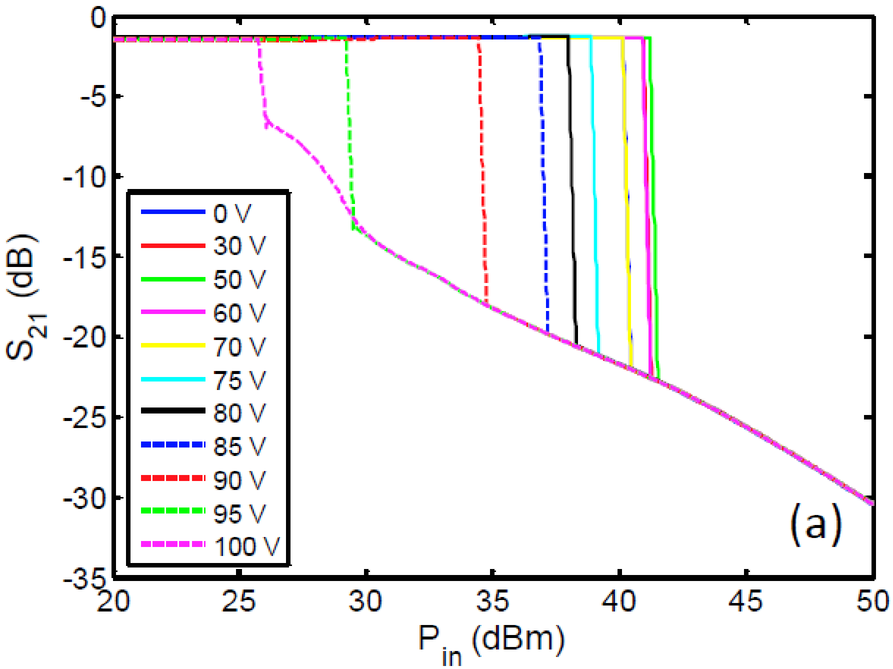
90 V Gas Discharge Tube (GDT)
Neon, 30 Torr

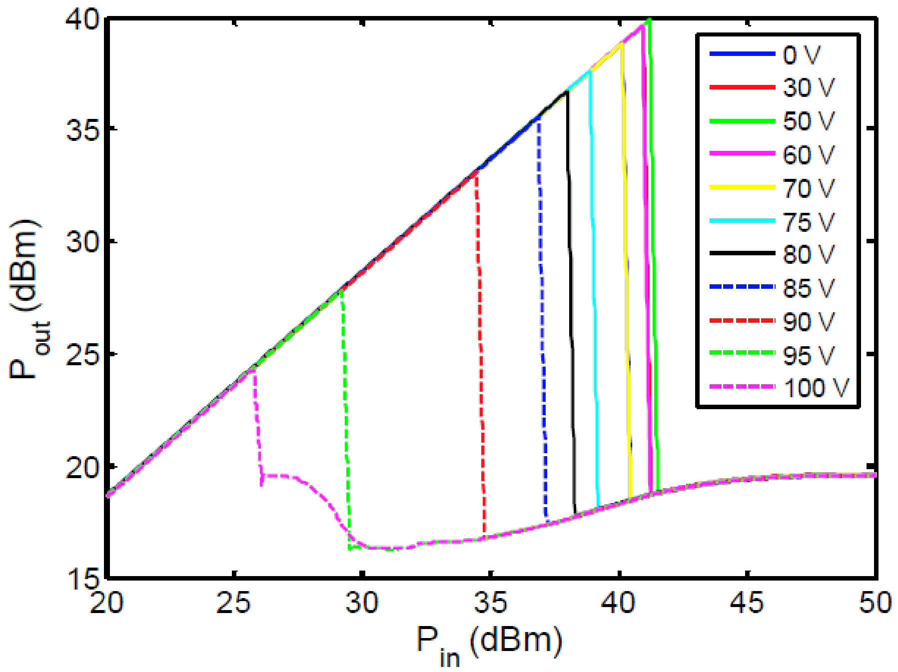


Evanescent-Mode Cavity Resonator

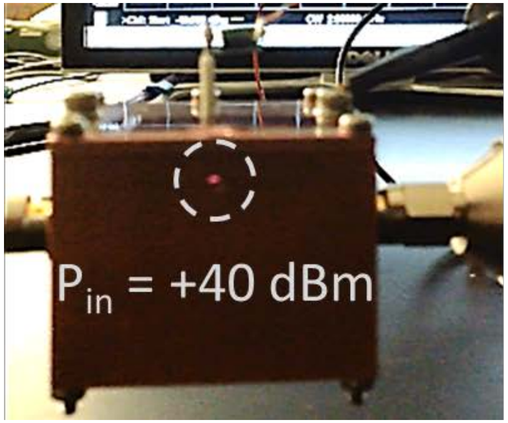
- High-*Q* (> 500 - 1,000)
- Widely Tunable (> 2:1)
- Highly-Linear (> 60 dBm)
- Scalable from sub-GHz to over 100 GHz
- Mobile form factor

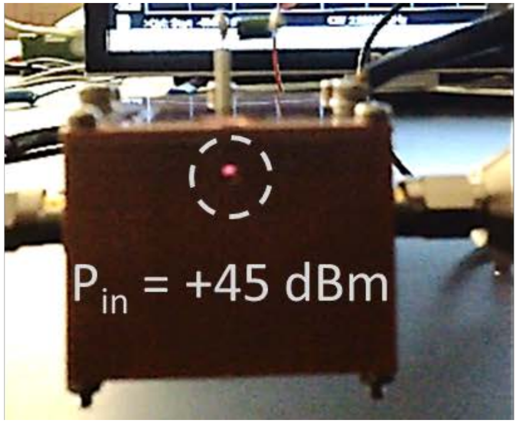
90 V GDT With Stand-By Bias

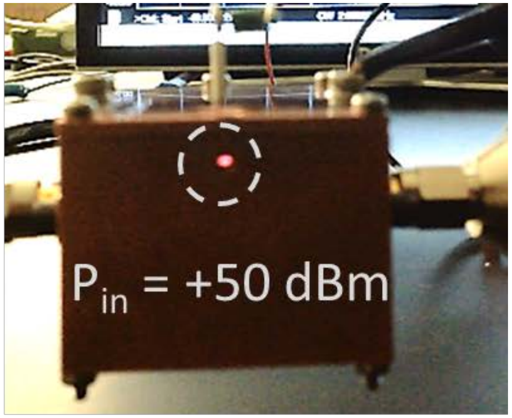




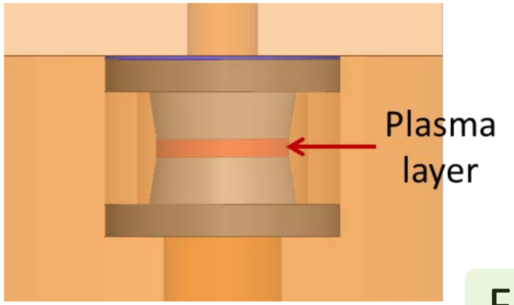
in no-bias case:



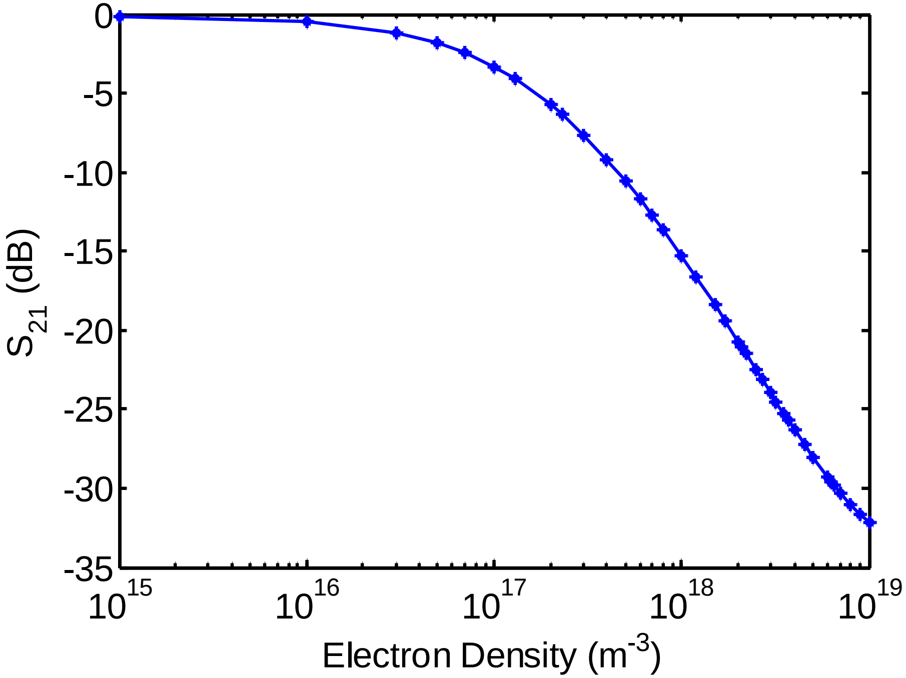




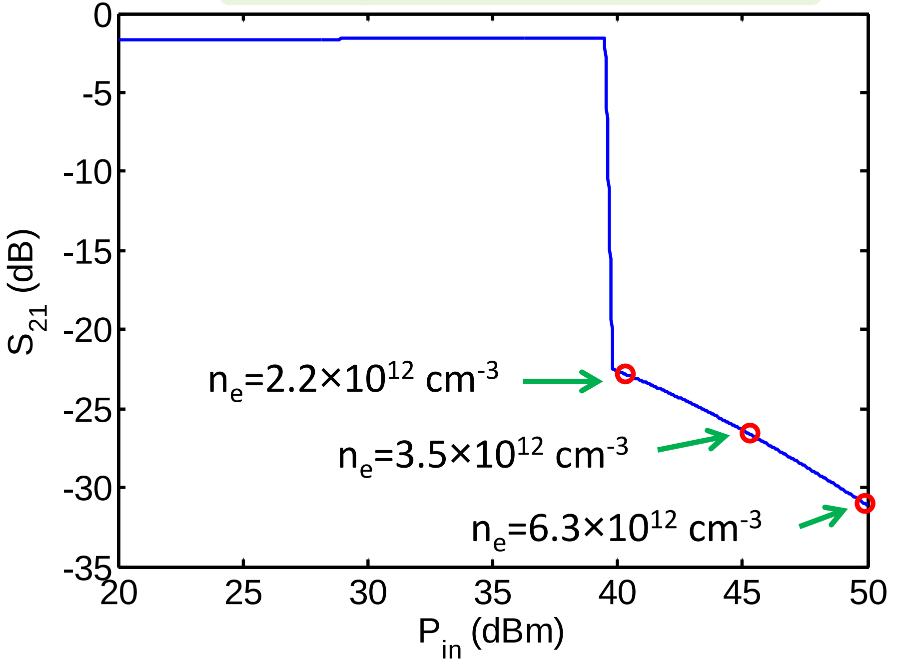
Inferred Electron Density



HFSS Simulation

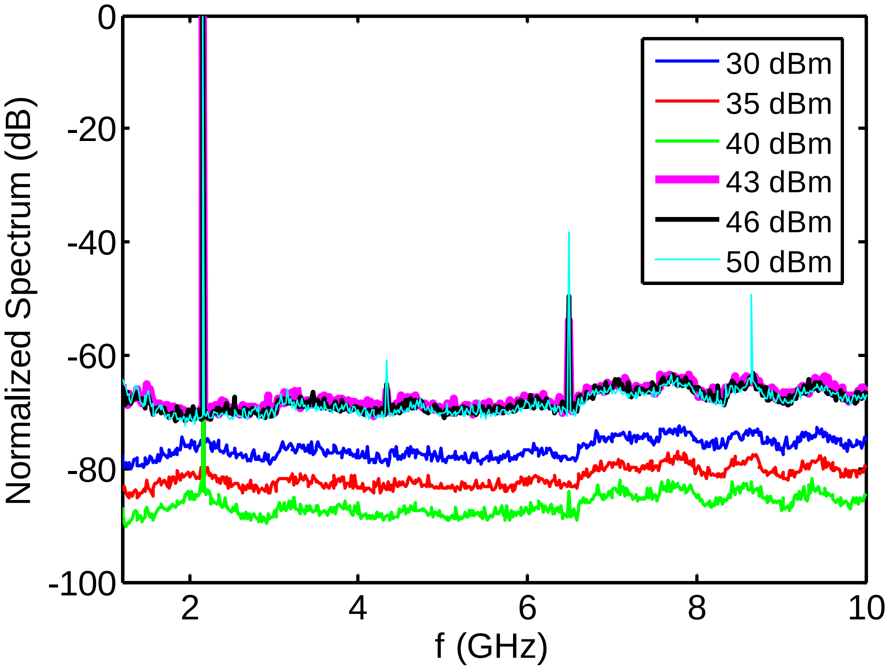


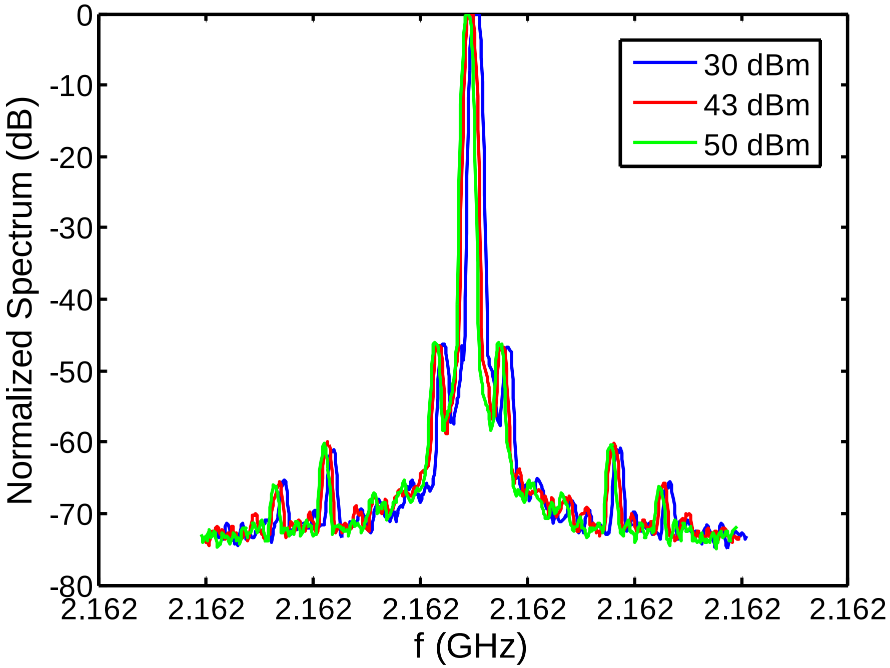
Fitting to Measurements



✓ Electron density is in the order of 10^{12} cm^{-3}

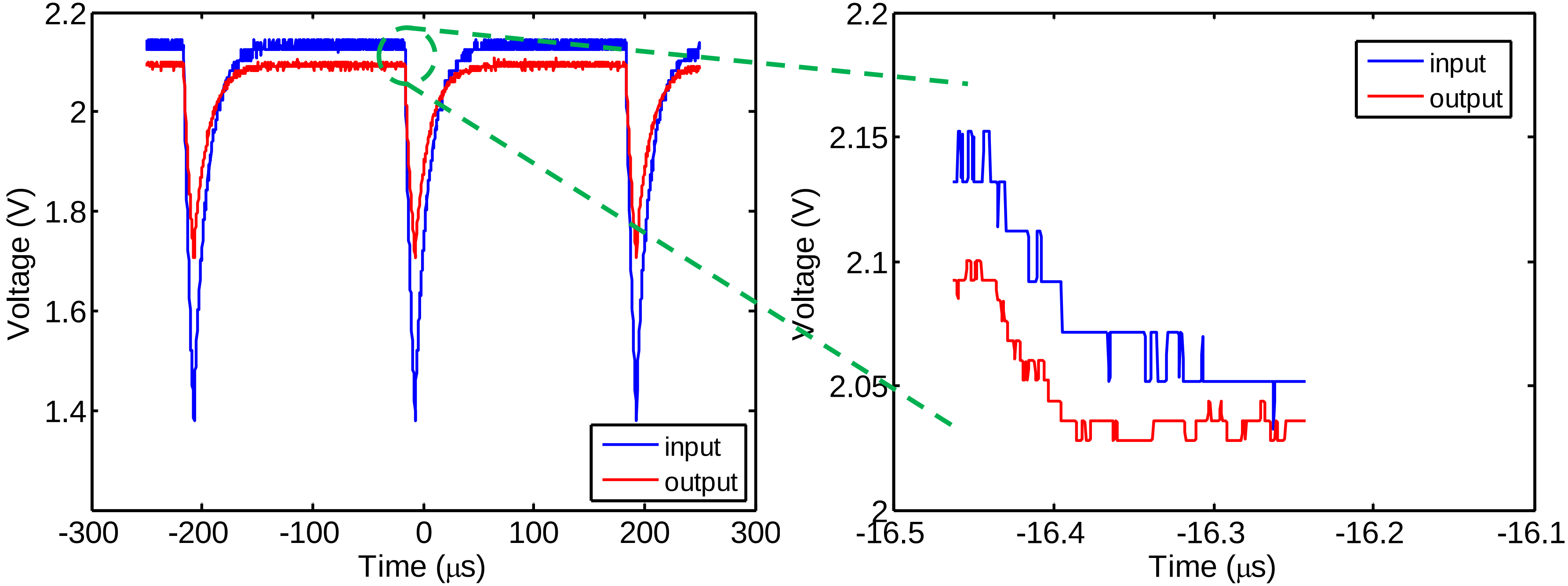
Linearity





- ✓ Harmonics less than 40 dB
- ✓ Almost no effect of intermodulation terms

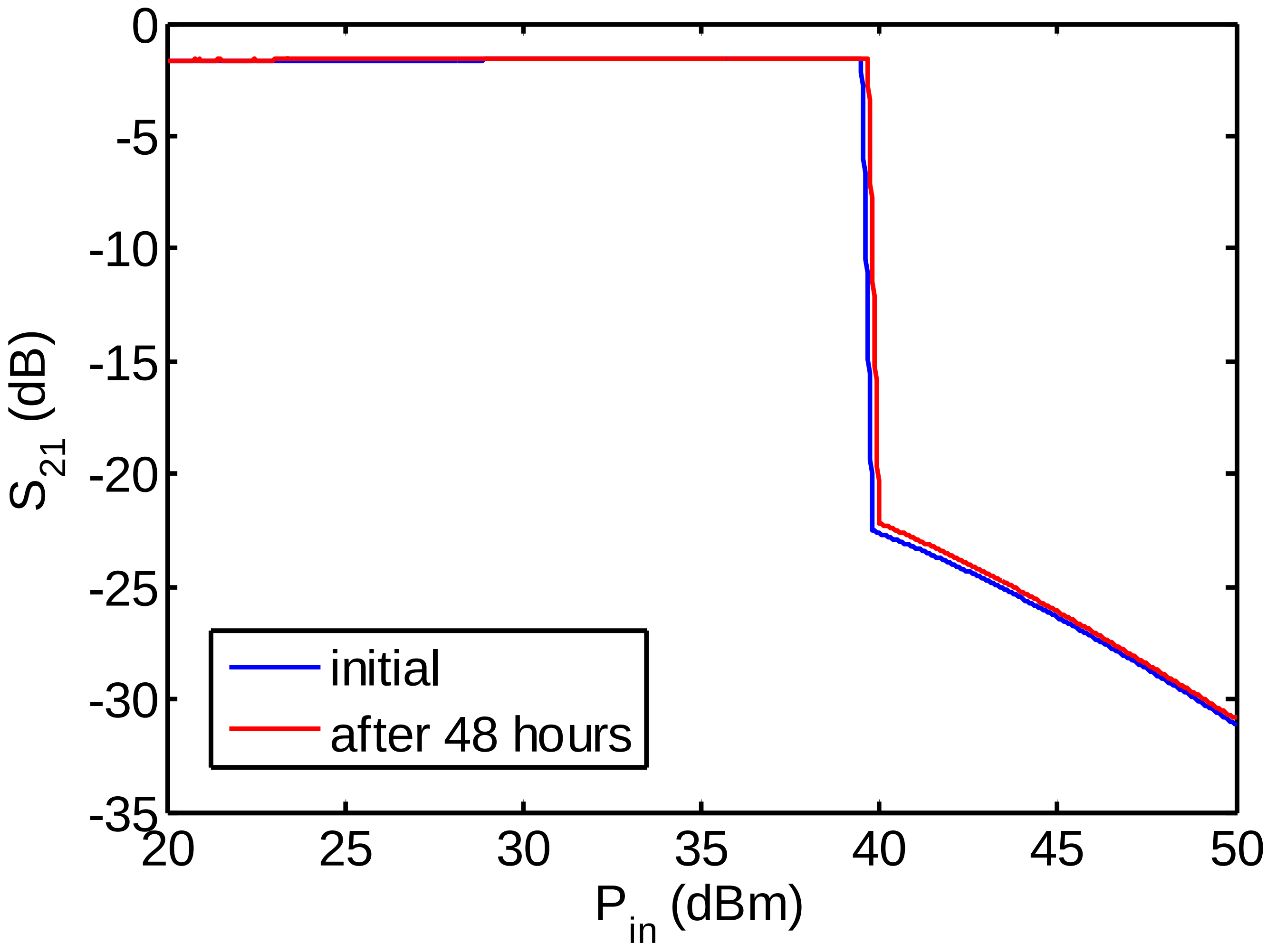
Response/Recovery Time



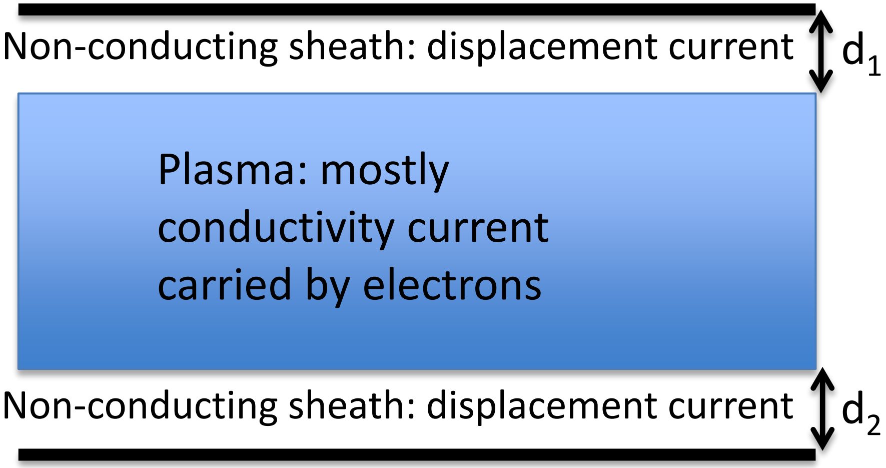
Response time: ≤ 10 ns (probably ~1 ns)

Performance Stability

90 V GDT loaded under 20 W



Operation at High Frequency: α-Discharge



Non-conducting sheath: displacement current d_1

Plasma: mostly conductivity current carried by electrons

Non-conducting sheath: displacement current d_2

Displacement current density in the sheath:

$$j = \varepsilon_0 \frac{\partial E}{\partial t} \cong \varepsilon_0 \omega \frac{V_0}{d};\ d \approx A = \frac{\mu_e E_a}{\omega},$$

$$\text{then} \quad j \approx \varepsilon_0 \frac{V_0}{\mu_e E_a} \omega^2$$

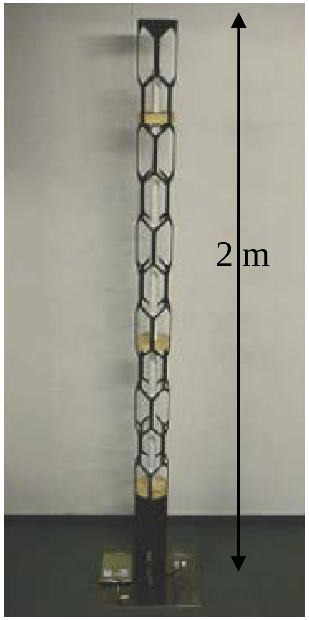
At high ω (f=1-10 GHz), sheath is only ~1 μm thick, and a low sheath voltage, V_0<10 V, is sufficient to close the circuit by matching the displacement current in the sheath to conduction current in the plasma.

This regime has no electrode sputtering and heating problems, in contrast to DC where V_0~100-300 V results in high heat flux and ion-impact sputtering.

Plasma Antennas: Background

**First patent on plasma antennas: J. Hettinger, "Aerial Conductor for Wireless Signaling and Other Purposes,"
US Patent 1,309,031, issued July 8, 1919 (filed June 4, 1917)**

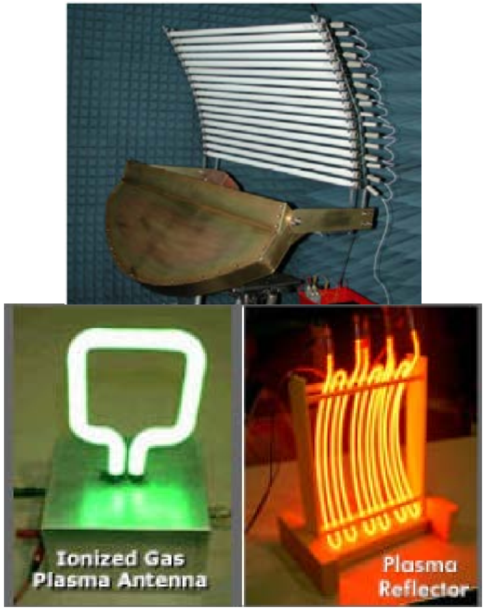
Australian Nat'l University



Surface wave driven plasma antenna

- **RF driven, 30 MHz**
- **Argon at 1 Torr**
- **$n_e = 5.3 \cdot 10^{11}$ cm^{-3}, σ=28 S/m**

University of Tennessee / Haleakala Inc.



Large glow discharge plasma antennas

- **500 MHz–20 GHz performance similar to Cu wire**
- **Flexible plastic tubes for mechanical robustness**
- **Switchable**
- **Bulky**

Macroscale discharge antennas: good, but bulky and noisy

Plasma vs. Metallic Antennas

@ RF frequencies of 100 MHz – 10 GHz

	Electron Density (cm^{-3})	Electrical Conductivity (S/m)	Collision Frequency (s^{-1})	Skin Depth (μm)
Metal	10^{22} - 10^{23}	3×10^{5} - 3×10^{6}	~ 10^{22}	0.7 - 30
Plasma	10^{12} - 10^{16}	3×10^{1} - 3×10^{3}	~ 10^{11} - 10^{12}	10^{4}

- Higher resistivity leads to higher losses in a plasma conductor; thus, lower gain
- Cross-coupling between plasma elements in arrays is weaker then for metallic elements
- Johnson-Nyquist thermal EM noise can be lower in plasma antennas than it is in metallic antennas:
  - Transmitting antenna (emitted noise): Since $R_p \leq \delta$, EM field is not in equilibrium with plasma, and therefore the effective noise temperature is << plasma temperature (Wort 1962, Manheimer 1994). This is similar to optically thin media where radiation escapes before reaching thermal equilibrium, so that the emissivity is << that of blackbody.
  - Receiving antenna: Thermal stochastic noise is due to electron scattering, but the electron scattering (collision) frequency in plasma is 3-8 orders of magnitude lower than it is in metals (Anderson 2002).

Dipole Plasma Vs. Metallic Antennas

Calculations: A. Semnani

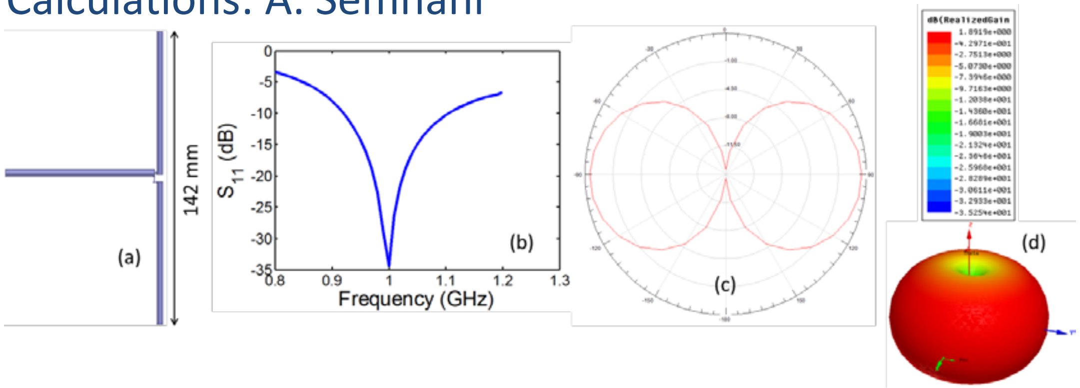


Fig.1. (a) **Metallic dipole antenna** at 1 GHz and the simulation results of (b) S_{11}, (c) radiation pattern at ϕ=90 deg, and (d) 3-D radiation pattern.

Gain$_{max}$=1.1 dBi

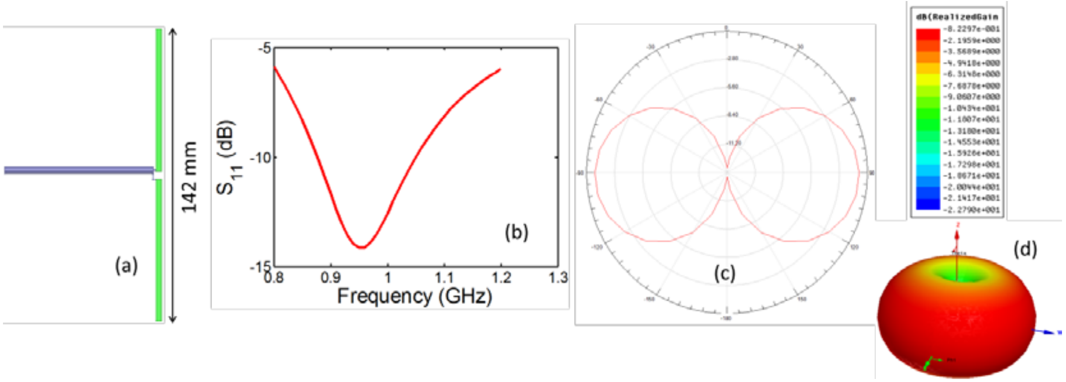


Fig.2. (a) **Plasma dipole antenna** at 1 GHz and the simulation results of (b) S_{11}, (c) radiation pattern at ϕ=90 deg, and (d) 3-D radiation pattern.

Gain$_{max}$=-2.3 dBi

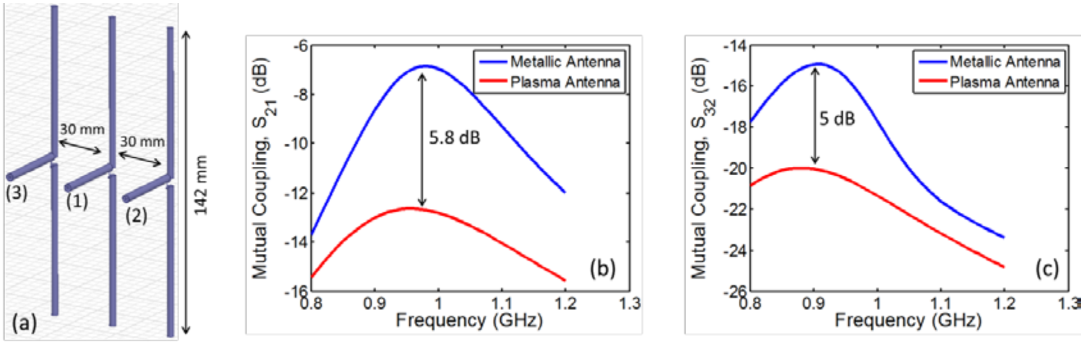


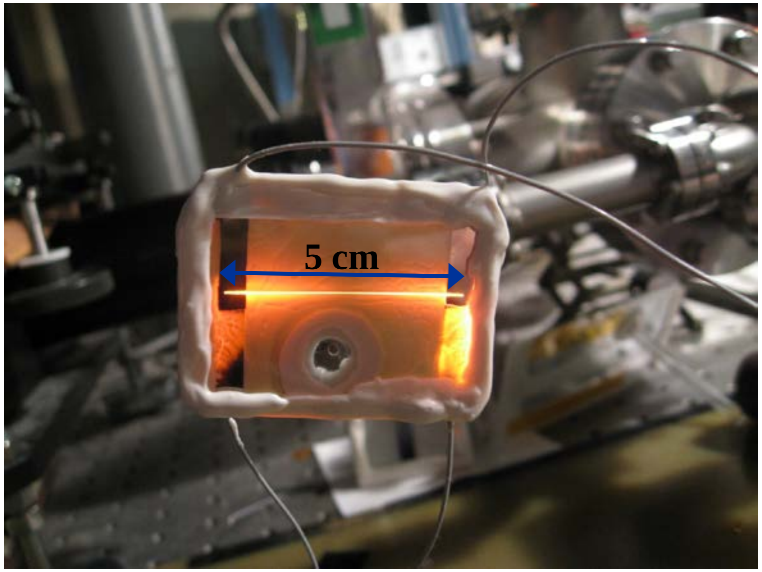
Fig.3. (a) **Three dipole antennas** with distance of λ/10=30 mm from each other. (b) S_{21}, (c) S_{32}.

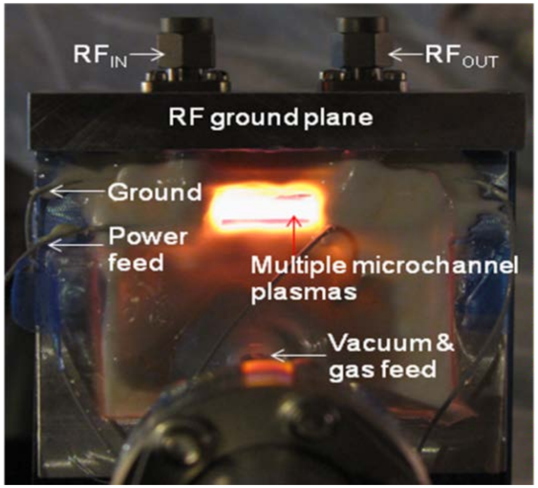
Higher loss (2.7 dB) in the plasma dipole is due to its lower electrical conductivity.
But the mutual coupling between plasma dipoles is 5-6 dB less than those in metallic dipoles

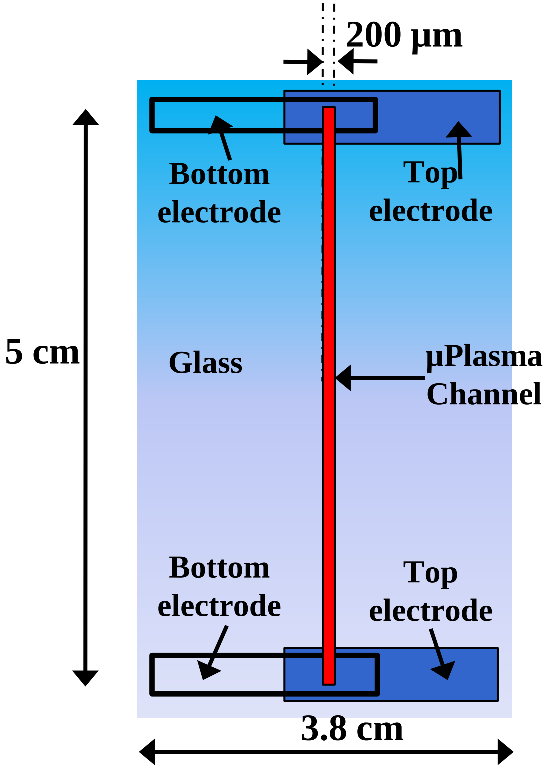
Microchannel Plasma Dipole Antenna

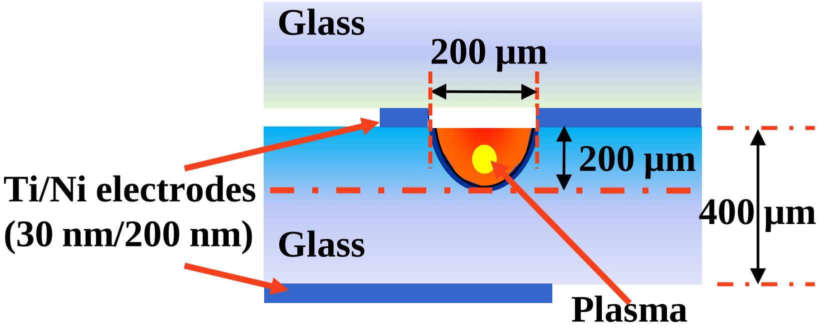
University of Illinois
Laboratory for Optical Physics and Engineering

380 Torr Neon, 1.7 kVAC, 20 kHz





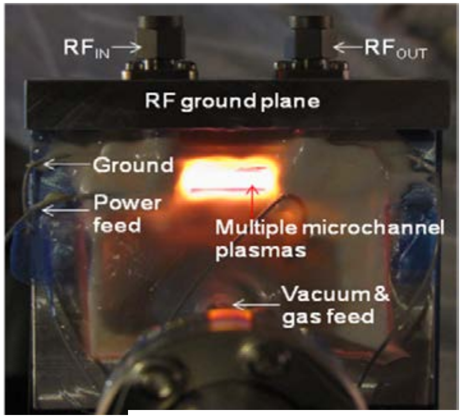




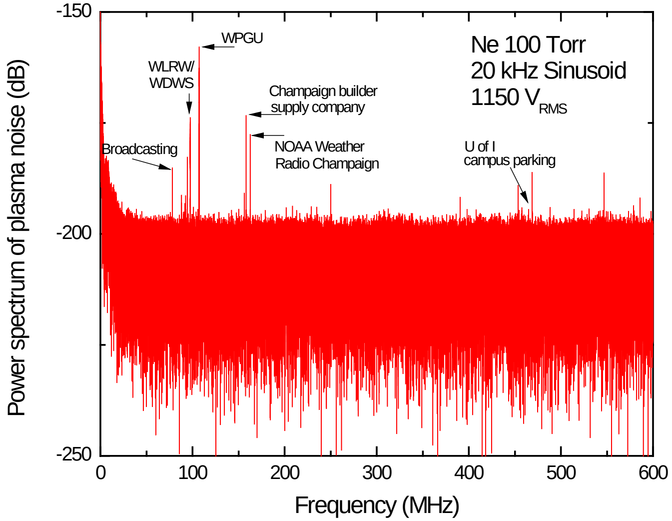
Microplasma Dipole Antenna

University of Illinois
Laboratory for Optical Physics and Engineering

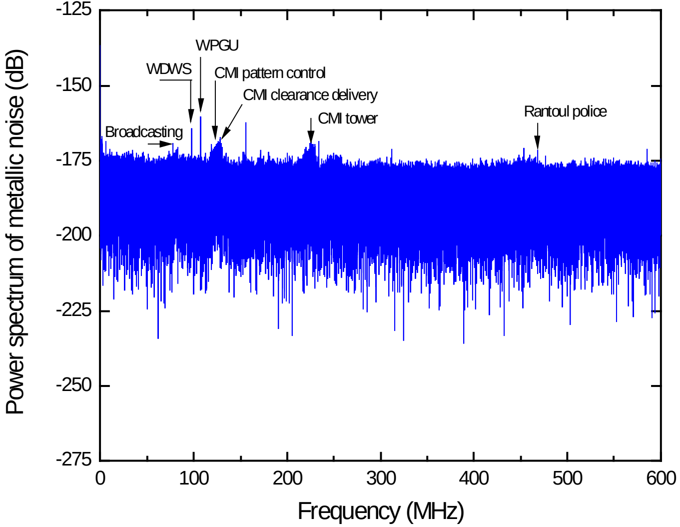
Multichannel plasma devices in glass: antenna reception measurements



Plasma antenna noise is 23 dB lower than that of copper wire, probably due to low duty cycle and power



Plasma antenna resolves local FM stations



Copper wire antenna performance

Electrically small μ-plasma antennas: low noise; resolve FM stations

Approved 10/18/2013 by DARPA for public release with distribution unlimited

Approved for public distribution AER201401002, 1-10-14

Low Noise Plasma Antennas

- Johnson-Nyquist thermal EM noise power per unit bandwidth:

$$P_{noise}/\Delta f \ = \frac{4kT_e}{1+\frac{\omega^2}{\nu^2}}$$

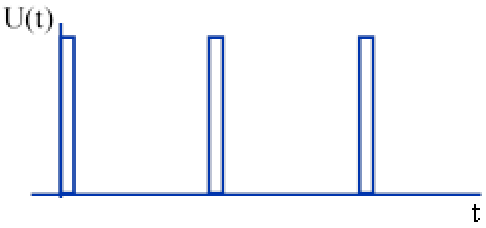
- In metals, $T_e = T, \ \omega \ll \nu$, thus $P_{noise}/\Delta f \ = 4kT$.
- In conventional plasmas, $T_e = 10{,}000 - 30{,}000 \ K$, thus high noise at low frequencies
- For low noise plasma antennas, need
  - Low T_e, ensuring that even at low frequency , $\omega \ll \nu$, the noise is not higher than in metal
  - Low collision frequency (low p and T_e), ensuring that at $\omega \gg \nu$ the noise is lower than in metal
- Caution: high (ω/ν) would also reduce conductivity $\sigma = \frac{e^2 n_e}{m\nu\left(1+\frac{\omega^2}{\nu^2}\right)}$

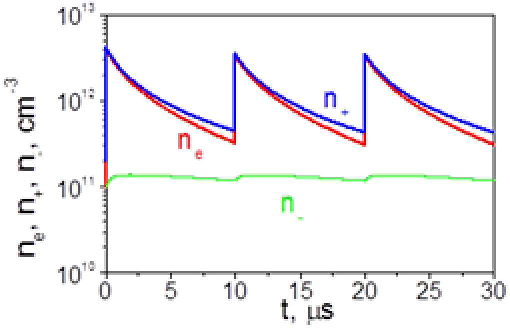
Low Noise Plasma Antennas

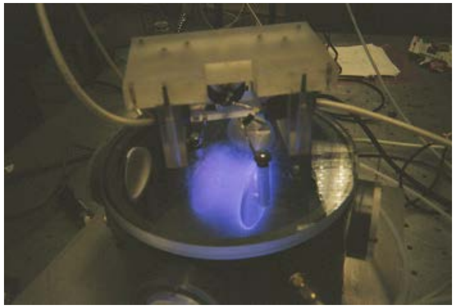
- $FOM = \frac{(G/T_{noise})_{plasma}}{(G/T)_{metal}} = \frac{T_e}{T} \frac{1+\frac{\omega^2}{\nu^2}}{1+\frac{R_0}{R_{rad}}\left(1+\frac{\omega^2}{\nu^2}\right)}$
- To get FOM>1, need low T_e and low collision frequency
- For example, if f=1 GHz, "cold" ($T_e = T = 300\ K$) plasma at p=20 Torr ($\omega \approx \nu$) with n_e=2 × 10^{13} cm^{-3} in a tube with R= 1 cm and L=λ/2 = 15 cm would produce $\sigma_0 \approx$100 S/m, $\delta \approx$1.15 mm, $R_{loss} \approx$15 Ω, and thus $\eta \approx$0.83 and FOM≈1.42.
- Creating cold-electron plasma (no E field):
  - Energetic photons or particle beams generated outside and injected into plasma volume: plasma electrons have low energy without E field
  - Repetitive short pulses: PRF should match plasma recombination time, electron temperature relaxation is much faster than recombination, thus between the pulses (i.e. most of the time) electrons are thermalized.
  - Low T_e also reduces electron collision frequency ν, further reducing noise
  - Low-noise plasma antenna would be equivalent to cryogenic systems without the actual cryogenics

Plasma Antennas: Getting High G/T_{noise}

- Plasma sustained by repetitive nanosecond pulses:
  - Strong E field very efficiently ionizes gas in ~1-10 ns
  - Pulse repetition frequency (PRF) is matched to recombination rate, thus little decay between pulses
  - Power budget is ~1000x lower that in conventional plasmas; suppressed heating; enhanced stability
  - Electrons cool faster than they recombine, thus low T_e and low collision frequency most of the time
  - Low collision frequency and low T_e ensure gain/noise is greater than that for metallic antenna
  - Purdue has 3 unique custom-built pulsers







Concluding Remarks

- Cold plasmas have unique and switchable/tunable properties for reconfigurable RF antennas, resonators, filters, limiters etc.
- Proof-of-principle experiments show viability of novel plasma tunable capacitors and plasma limiters
- Plasma antennas have lower gain but also can have weaker cross-coupling in array and potentially higher Gain/Noise than metallic antennas.
- Low-pressure plasmas sustained by nanosecond repetitive pulses can potentially yield low antenna noise.
- Plasma offers viable solutions in high-power and harsh-environment applications where conventional semiconductor devices fail.