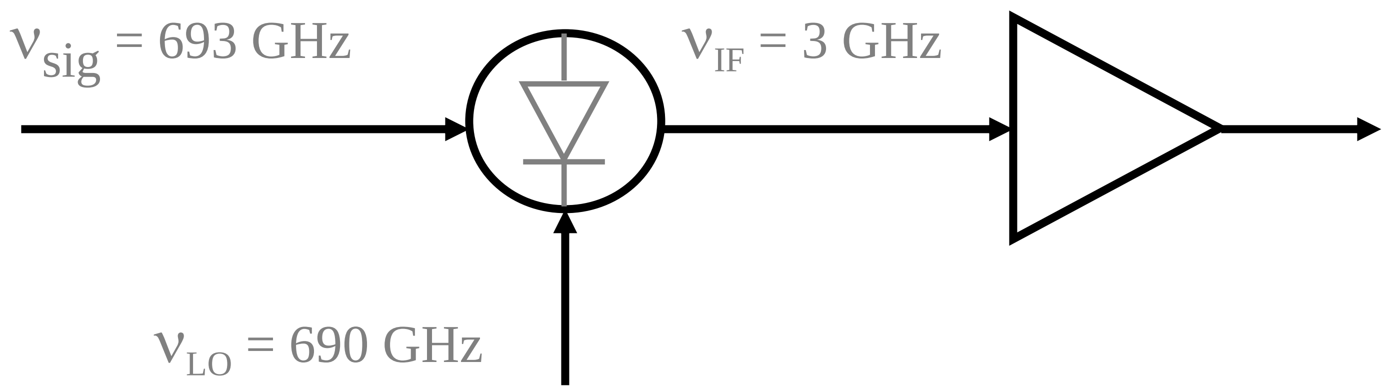
State-of-the-Art in Room-Temperature THz Mixers and Direct Detectors

Broadband Mixers

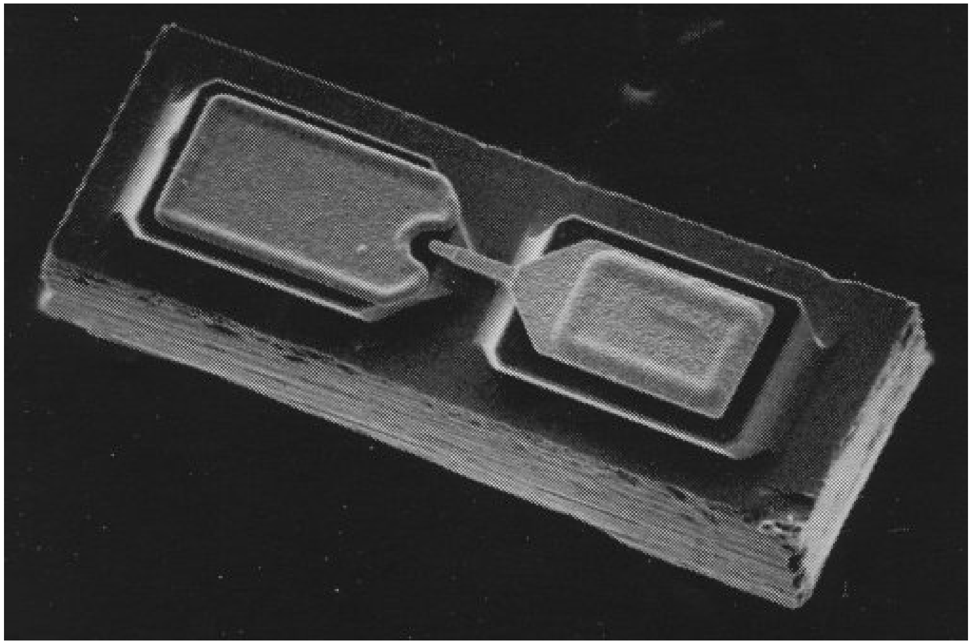
A frequency mixer – mix a high frequency signal with a local oscillator reference to generate a copy of the signal at a lower frequency for spectral analysis.



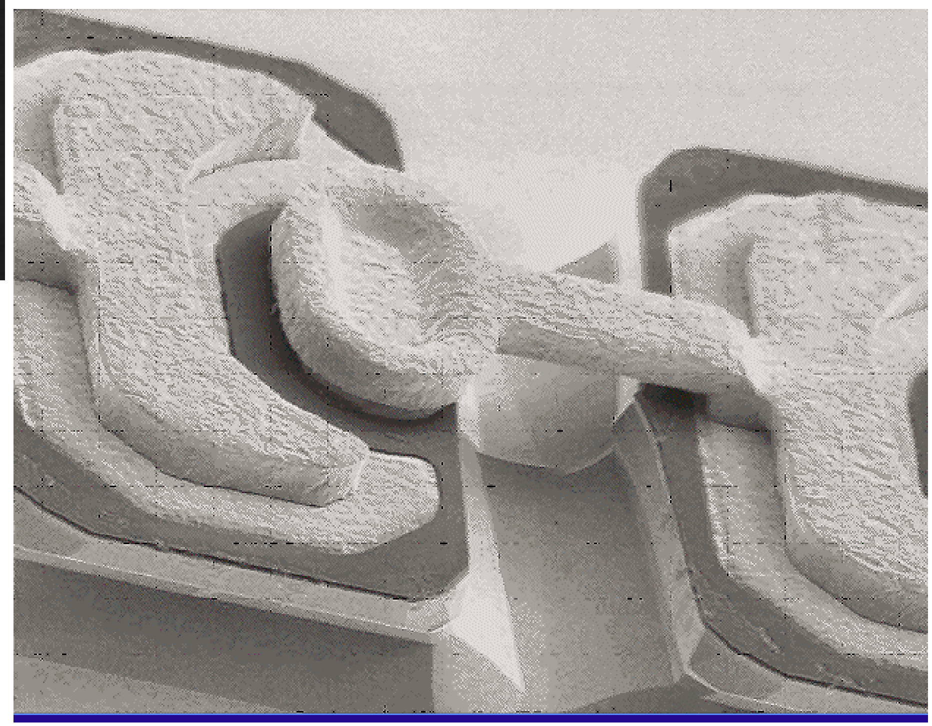
Goals - Optimize input, LO and IF coupling, reduce noise, filter other frequencies, reduce LO power required, increase bandwidth, ….

Schottky diodes at RT, but Superconductors yield far better sensitivity when cooled!

Airbridge Processing



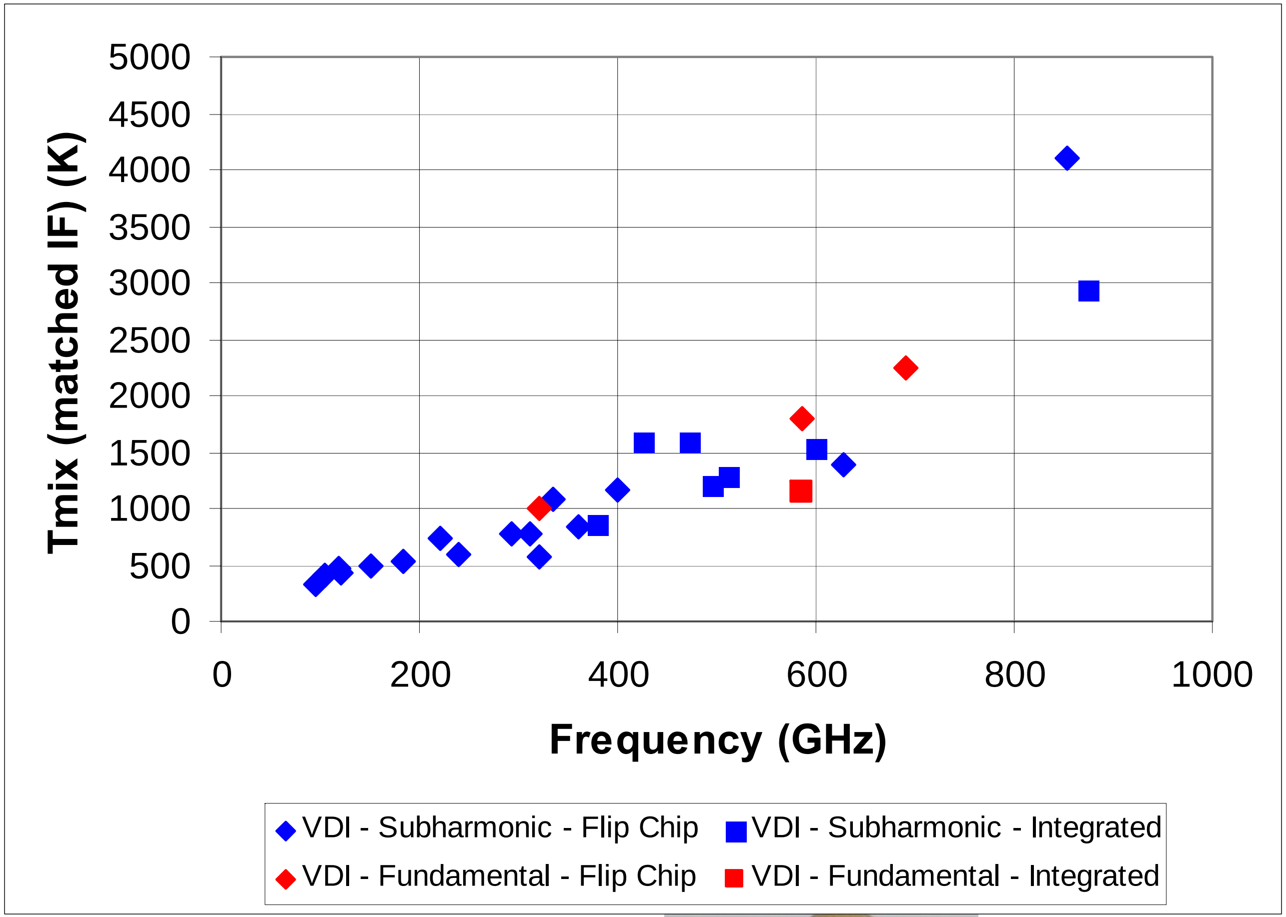
Reduce parasitic capacitance



Make metallizations as thick as possible to reduce series resistance

Broadband Mixers

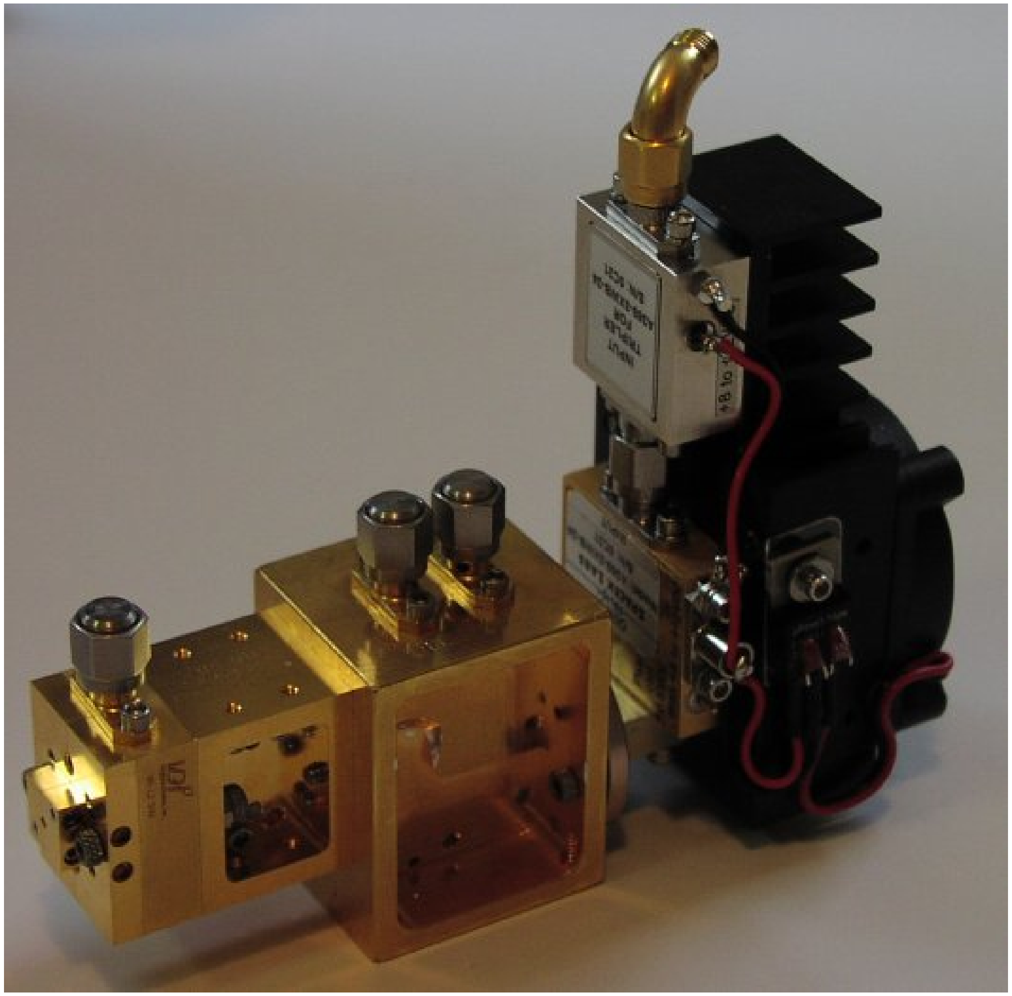
- **Low conversion loss**
  - **5 dB (DSB) at 100 GHz**
  - **10 dB at 640 GHz**
- **Broad IF bandwidth**
  - **> 40 GHz for mixer at 600 GHz**
- **LO Power 2-7 mW Typical**



440-660 GHz Mixer

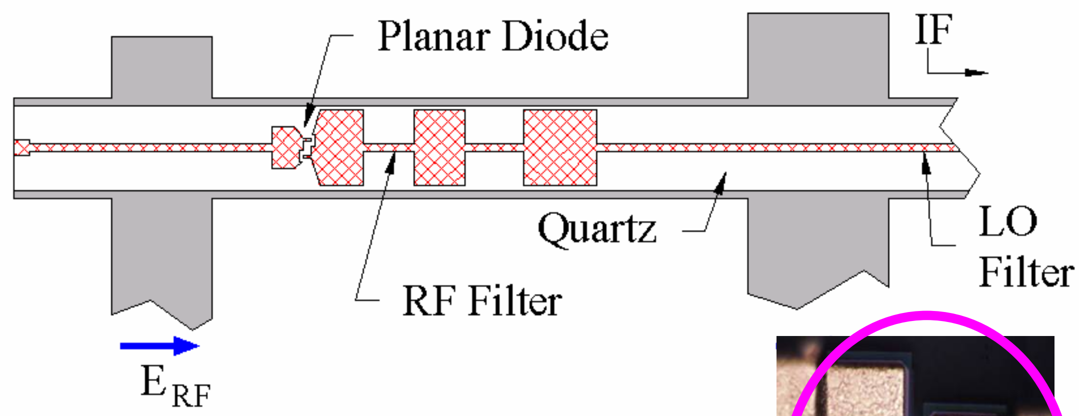
WR-1.2SHM – 870 GHz Mixer

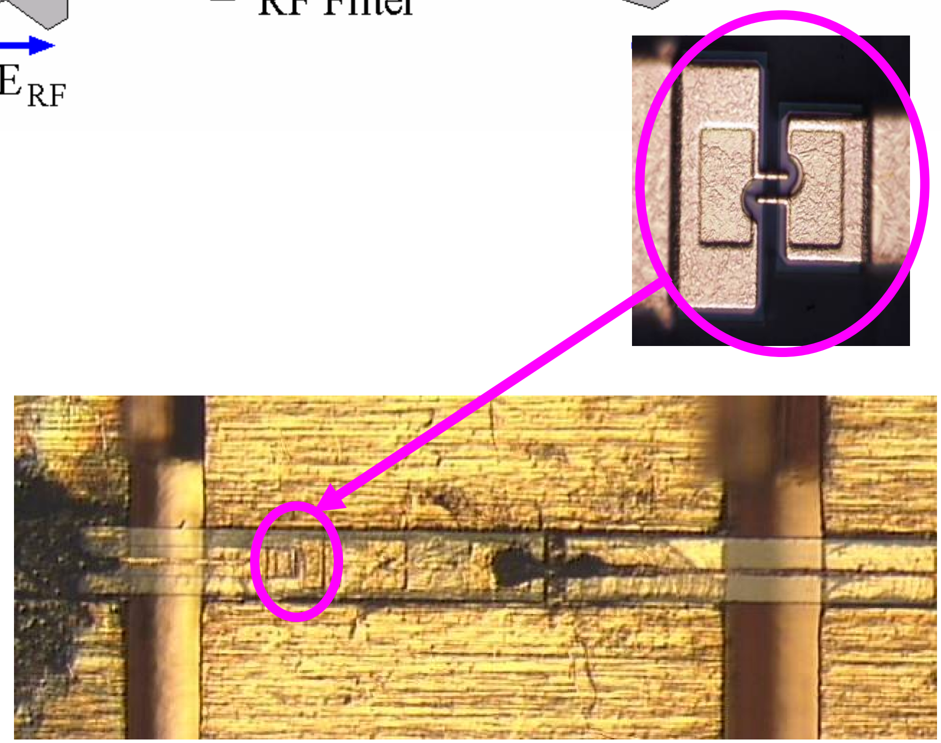
- Configuration Amp+X4+X3+SHM
  - Amp → 1W at 36.25 GHz
  - Q145 → 100 mW at 145 GHz
  - WR-2.2X3 → 2.5 mW at 435 GHz
- **T_{mix} = 3500 K (DSB)**
  - **IF SWR 2.25:1**
- **L_{mix} = 12 dB (DSB)**



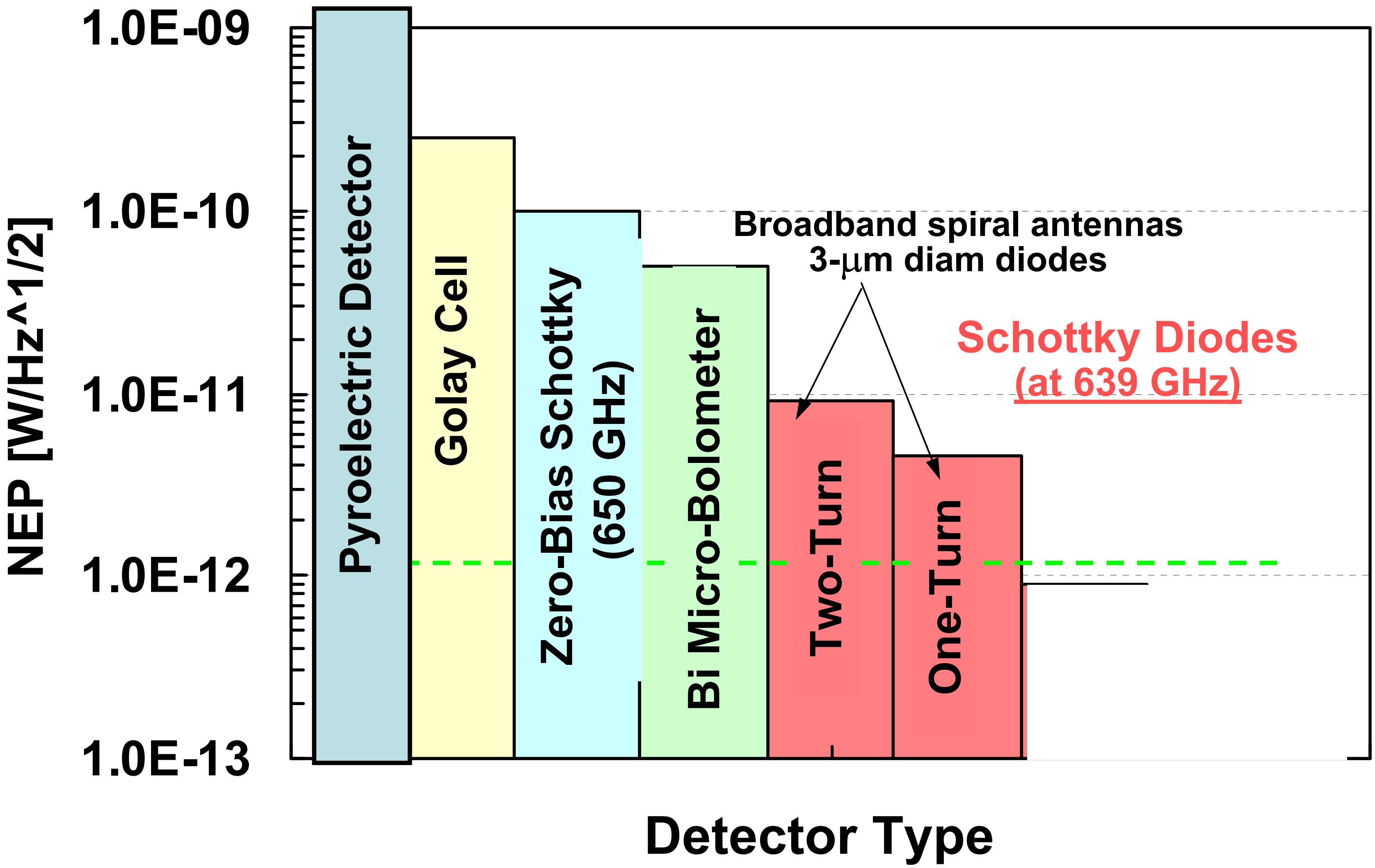
Subharmonic Mixer Design

- Use Tunerless Broadband Mixer Design
  - Broadband
- Anti-parallel Subharmonic Mixer
  - LO at ½ RF
  - No external diplexer needed
  - LO noise suppression
  - Relatively low IF impedance
- Disadvantages
  - requires larger LO power
  - difficult to bias diodes

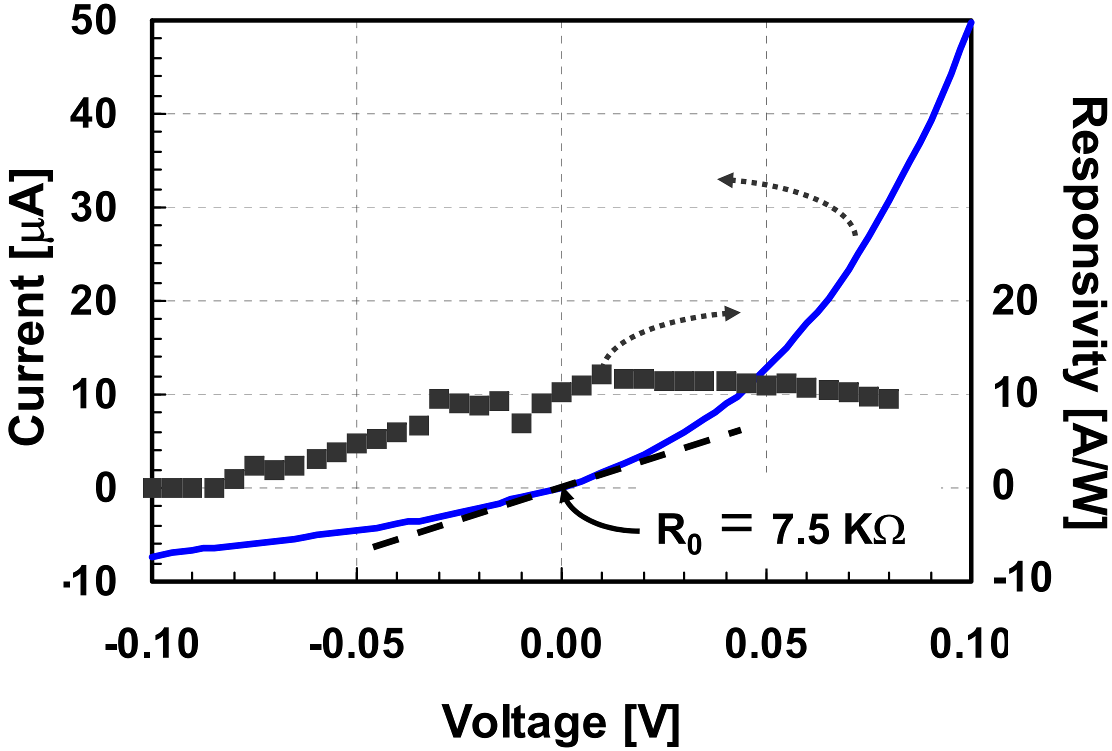




THz Direct Detectors



Rectifier Responsivity

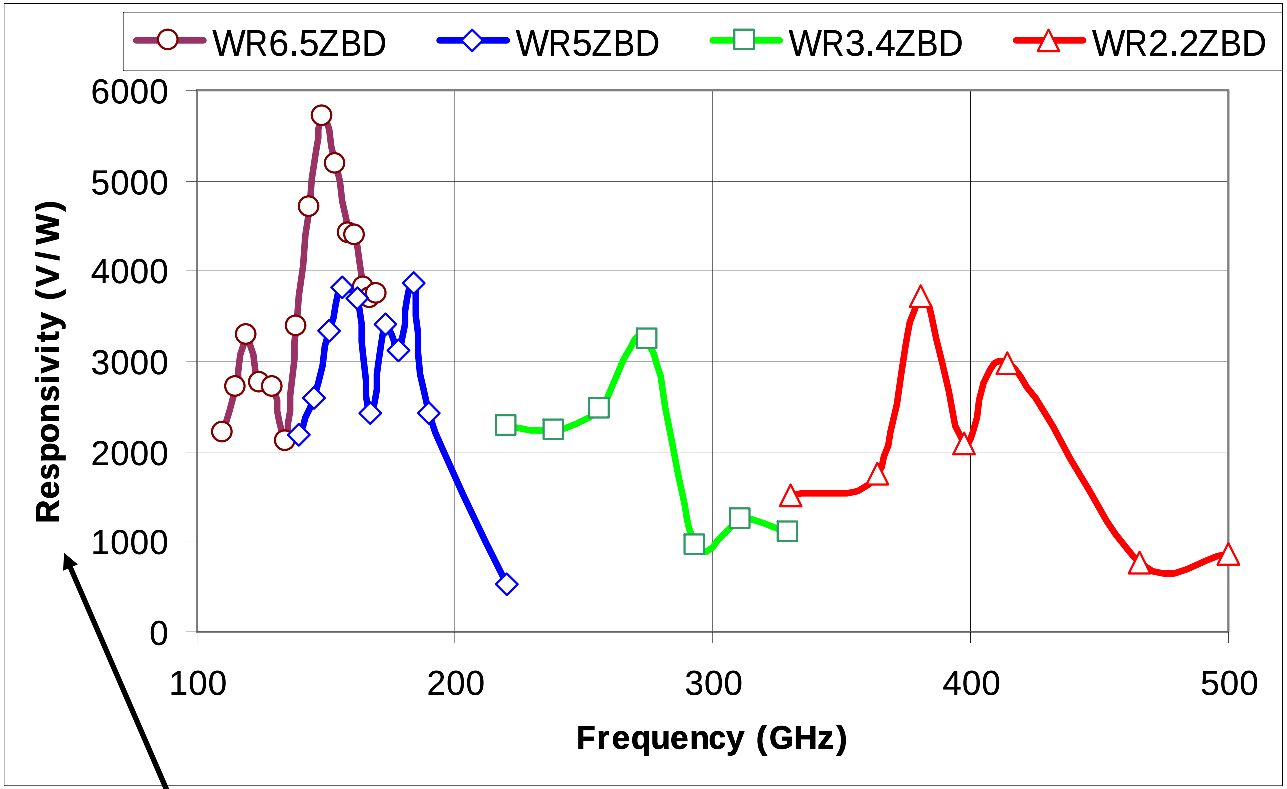


$$\Re_I = (1/2) \cdot \frac{d^2I/dV^2}{dI/dV} \cong 10 \text{ A/W}$$

$$\Re_V \cong S_I \cdot R_0 \cong 75 \text{ KV/W}$$

Broadband Zero-Bias Detectors

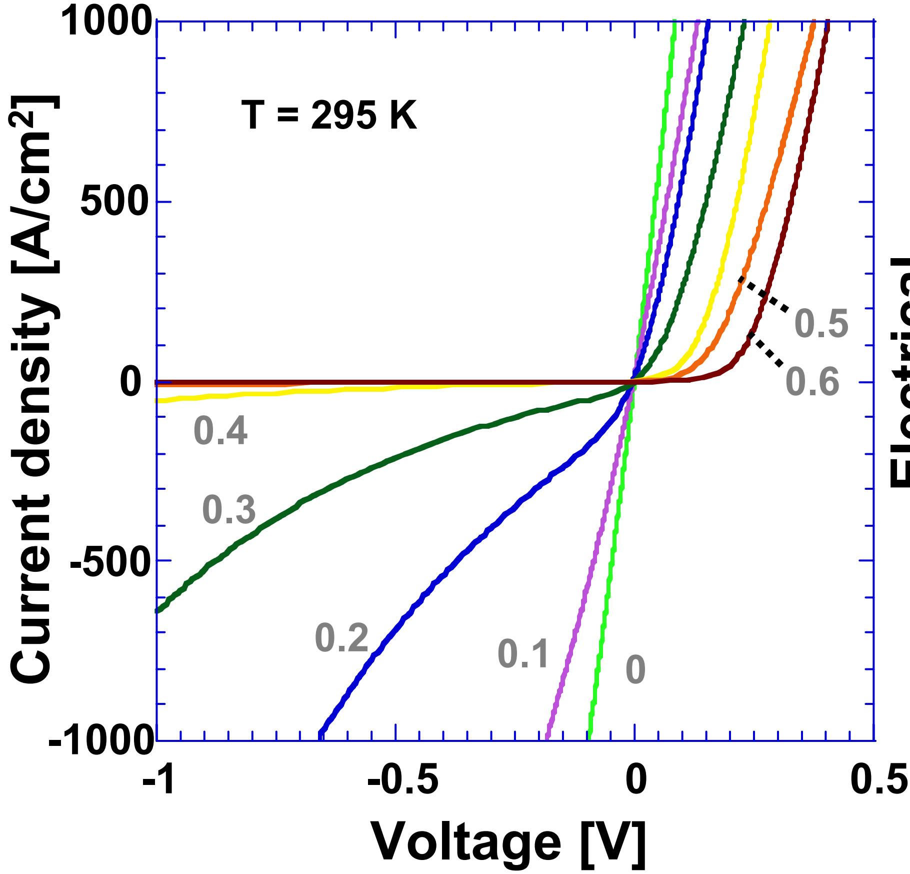
WR-6.5ZBD

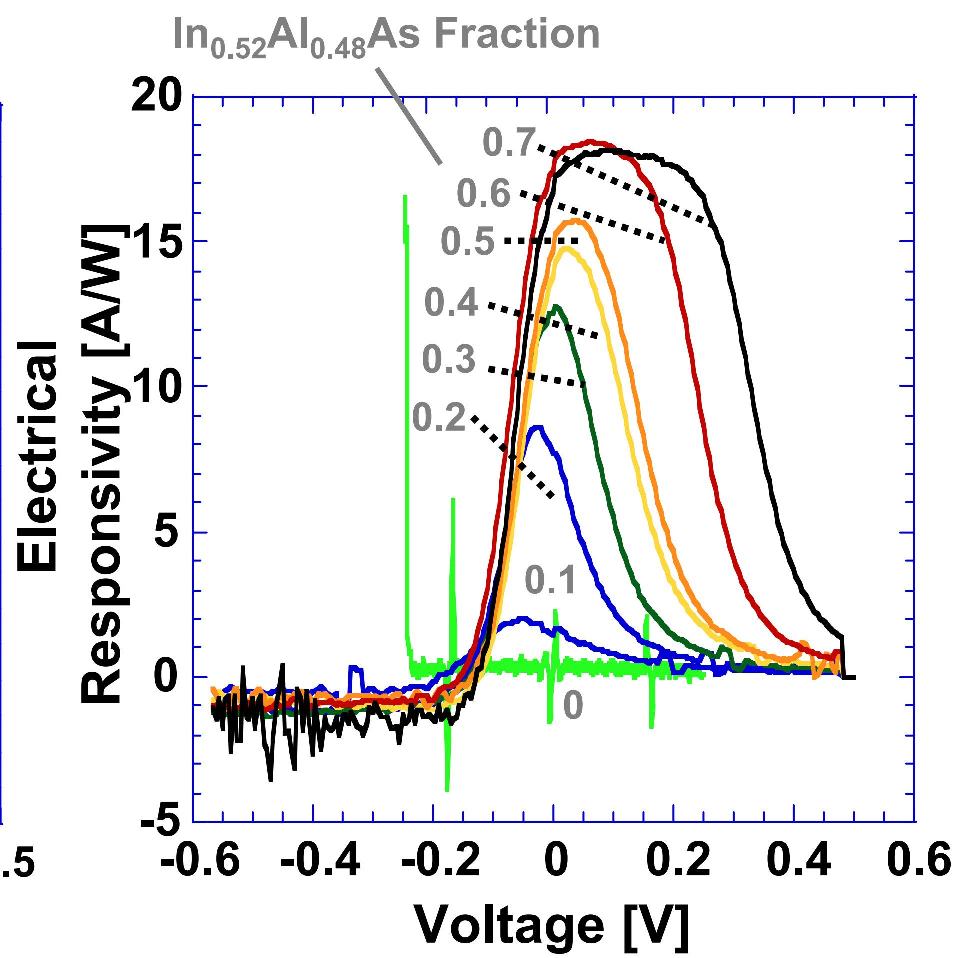


- Full waveguide band with excellent sensitivity
  - Tunerless
- NEP ~ 2-10 pW/Hz^0.5

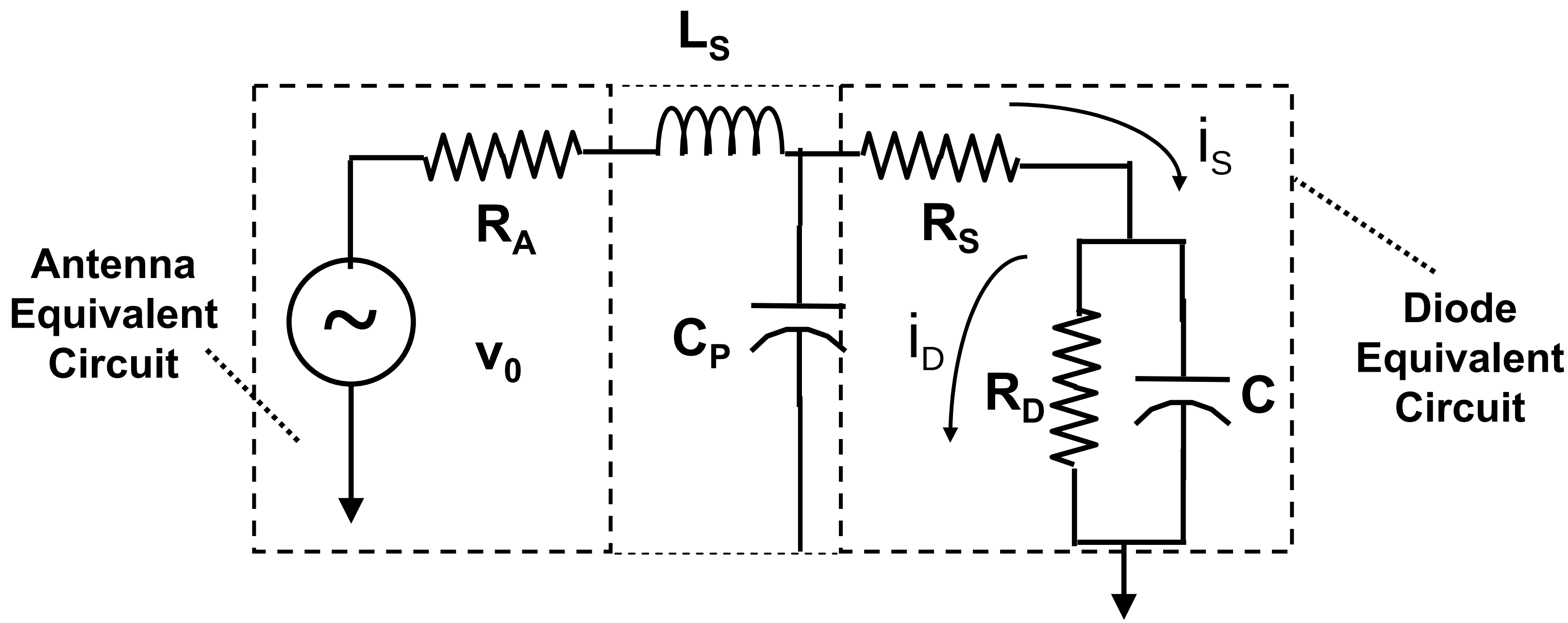
Note: this is external responsivity, including coupling factor

Single-Crystal ErAs-InAlGaAs Rectifier Diodes





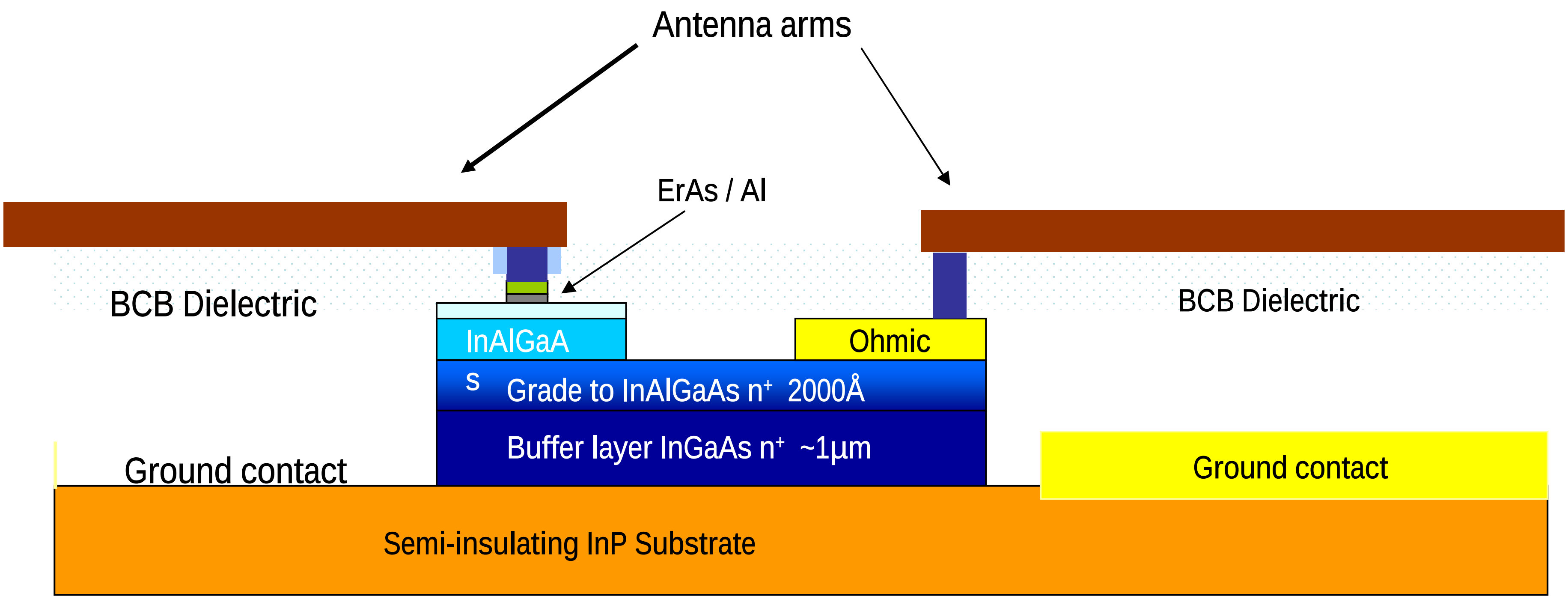
Big Challenge with Rectifiers: THz Impedance Matching



$$\eta \equiv \frac{P_D}{P_A} = \frac{4 \cdot R_D R_A}{(R_D + R_A + R_S - \omega^2 LCR_D)^2 + [\omega L + \omega R_D C(R_A + R_S)]^2}$$

Fully Planaraized Processing

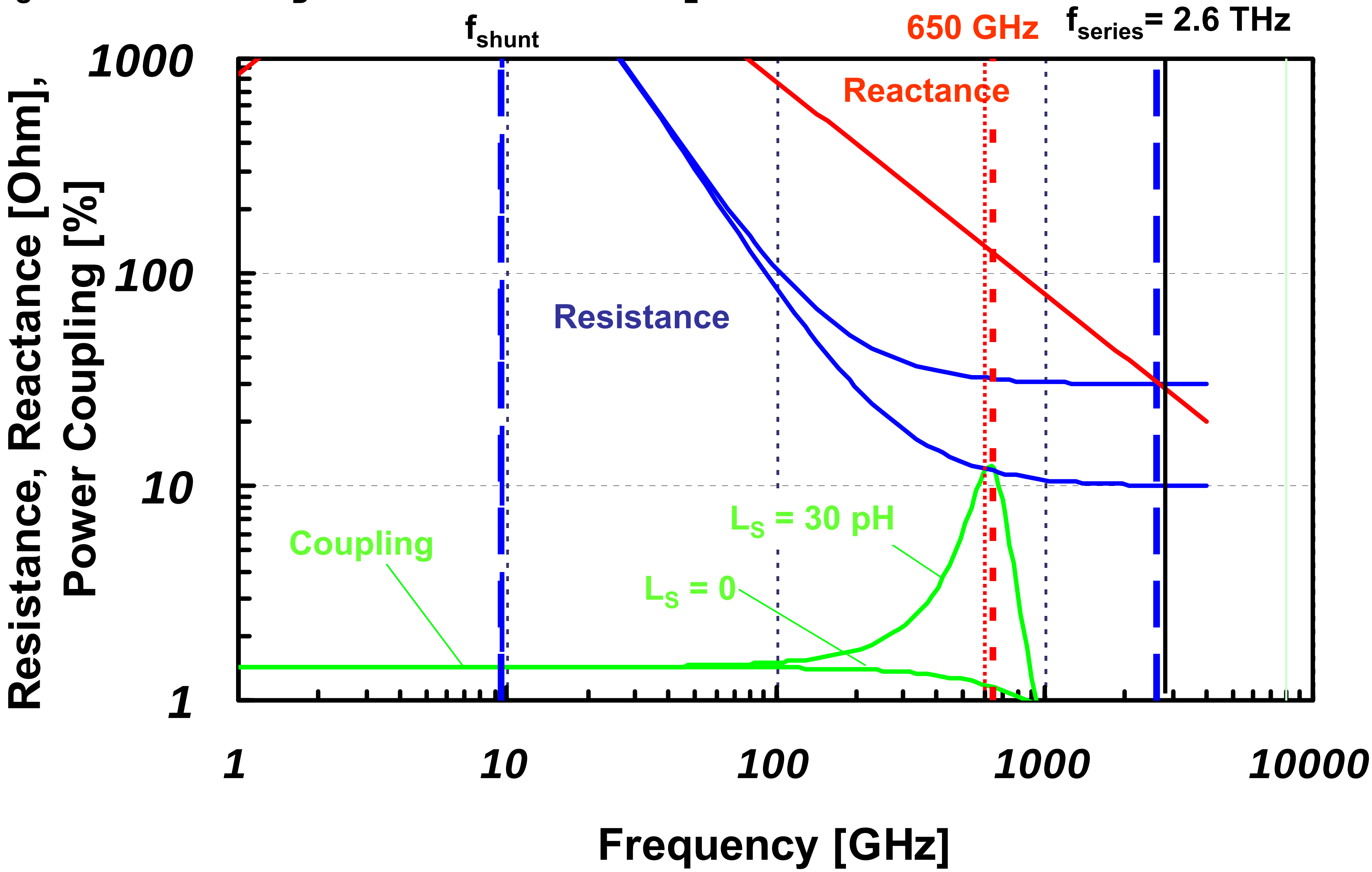
- **Fabricate Schottky diode in driving gap of planar antenna**



650 GHz Coupling: Effect of Inductance and Series Resistance

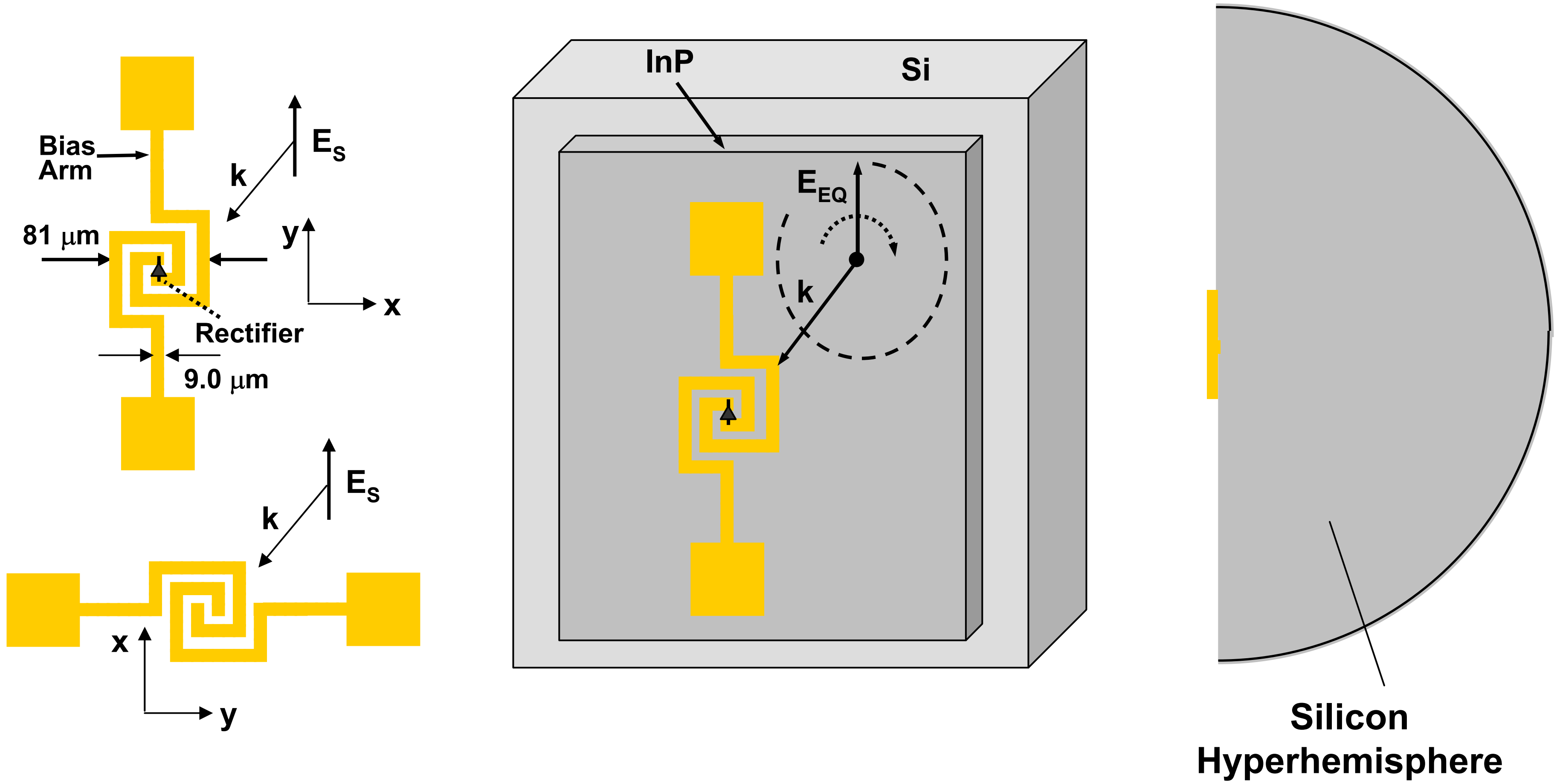
1-sq-micron devices

R_S = 30 Ω/10 Ω, R_D = 8300 Ω, C = 2 fF, R_L = 50 Ω

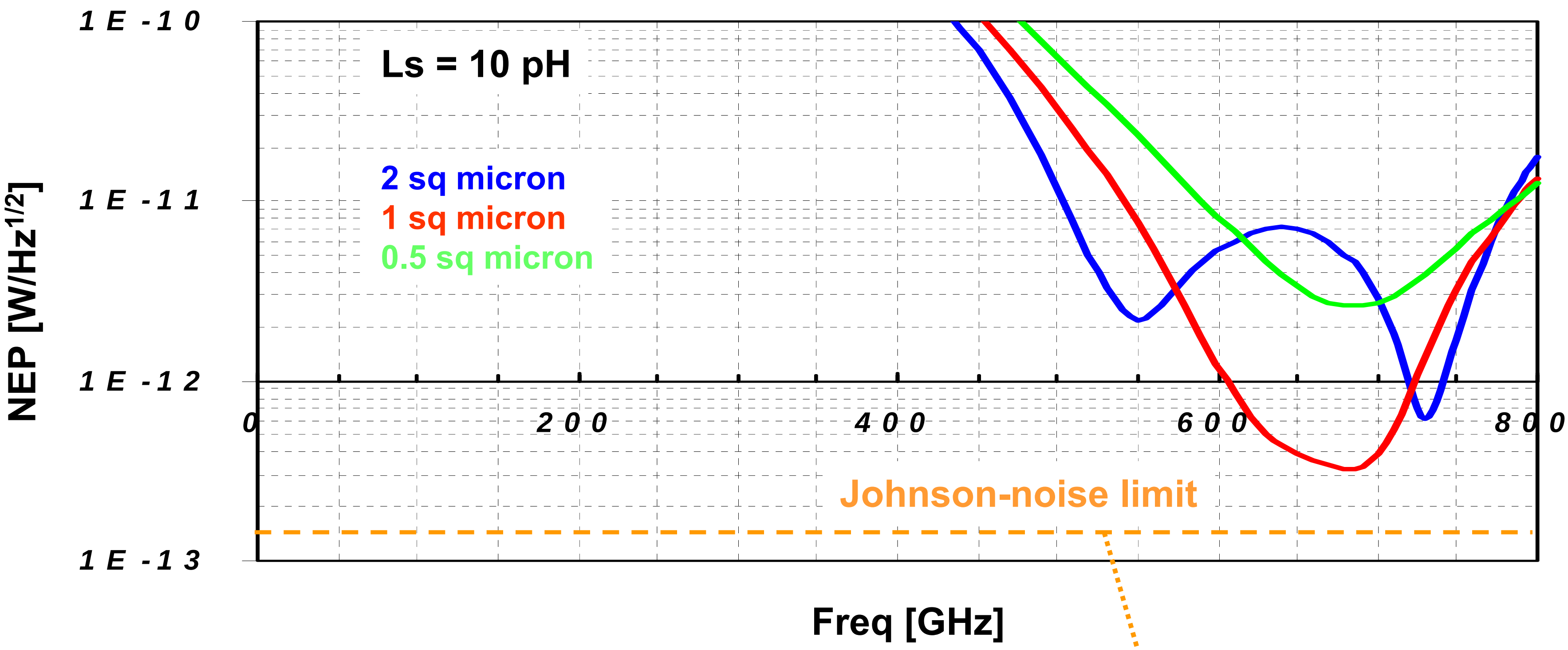


Planar Antenna Coupling

(Antenna must be very small)

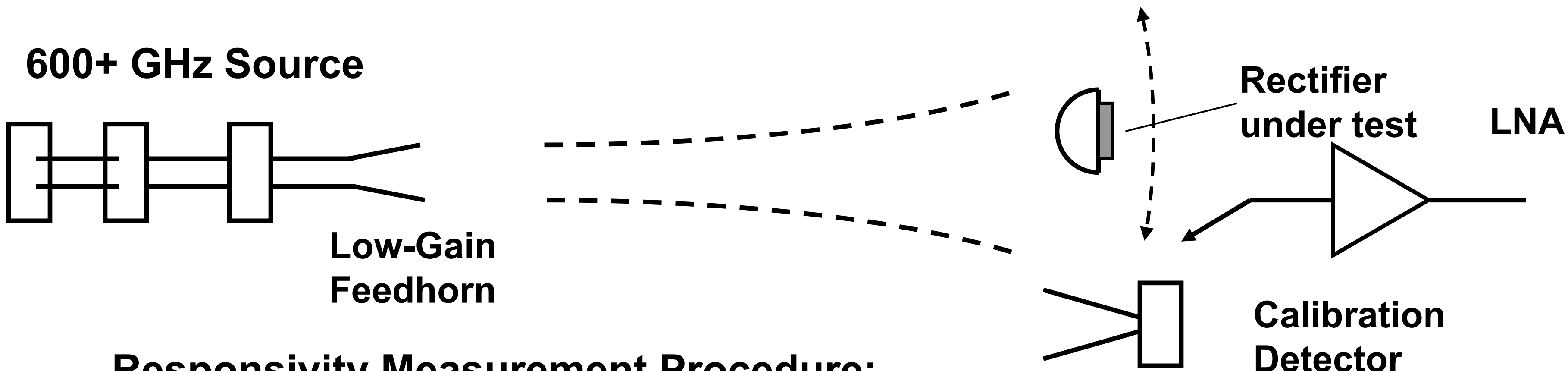


The Ultimate Potential of Rectifiers



$= 4k_B T \cdot R/(75 \times 10^3 \text{ V/W})$

Optical Responsivity & NEP Measurement



Responsivity Measurement Procedure:

Step 1: Measure response vs angle of rectifier-under-test

Step 2: Deconvolve test horn pattern (if necessary)

Step 3: Compute rectifier directivity with respect to entire pattern

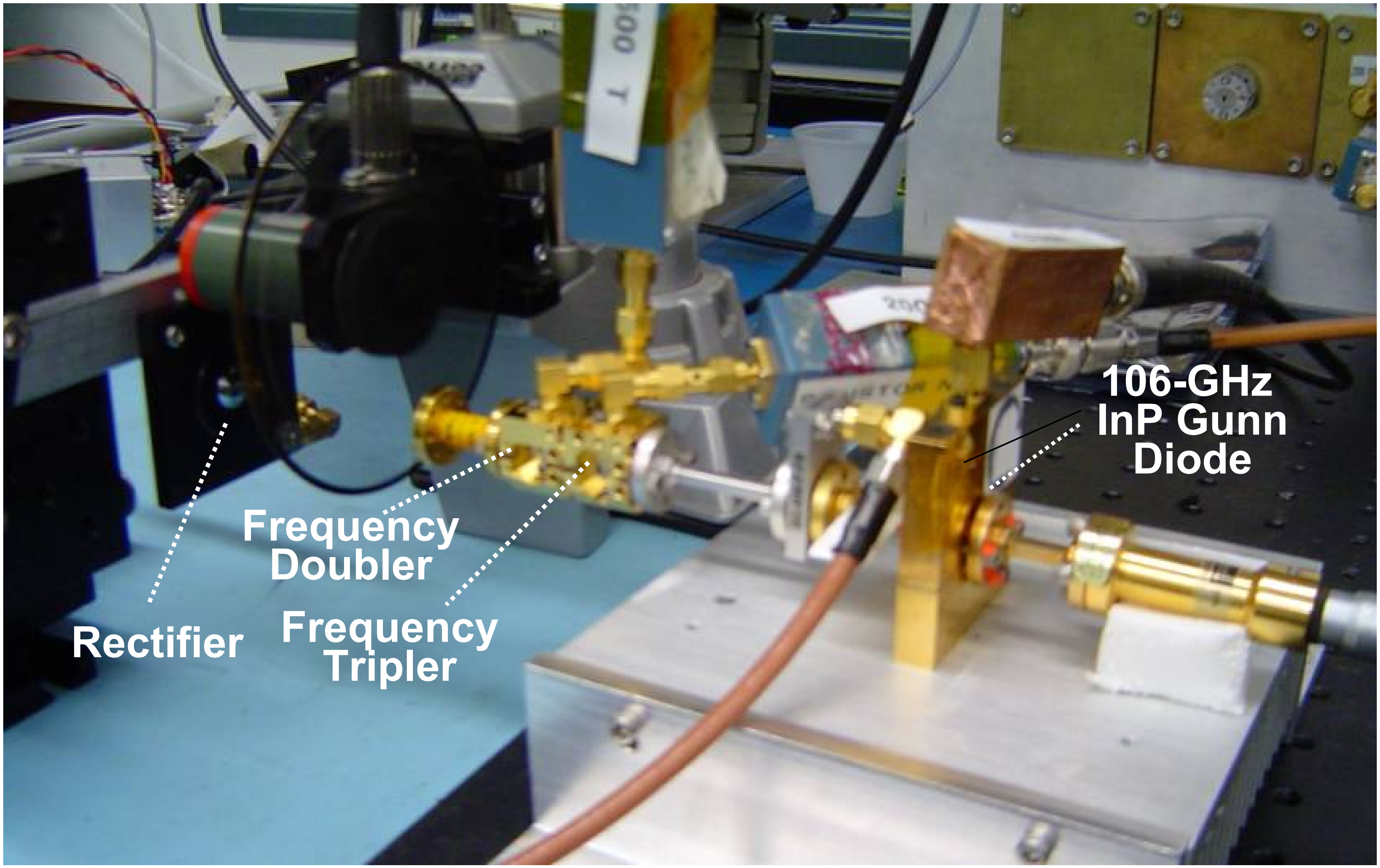
Step 4: Compute $A_{eff} = \lambda^2 D/4\pi = \lambda^2 / \Omega_B$ $\Omega_B \rightarrow$ beam solid angle

Step 5: Compute available power, $P_{avail} = I_{Tx} A_{eff}$

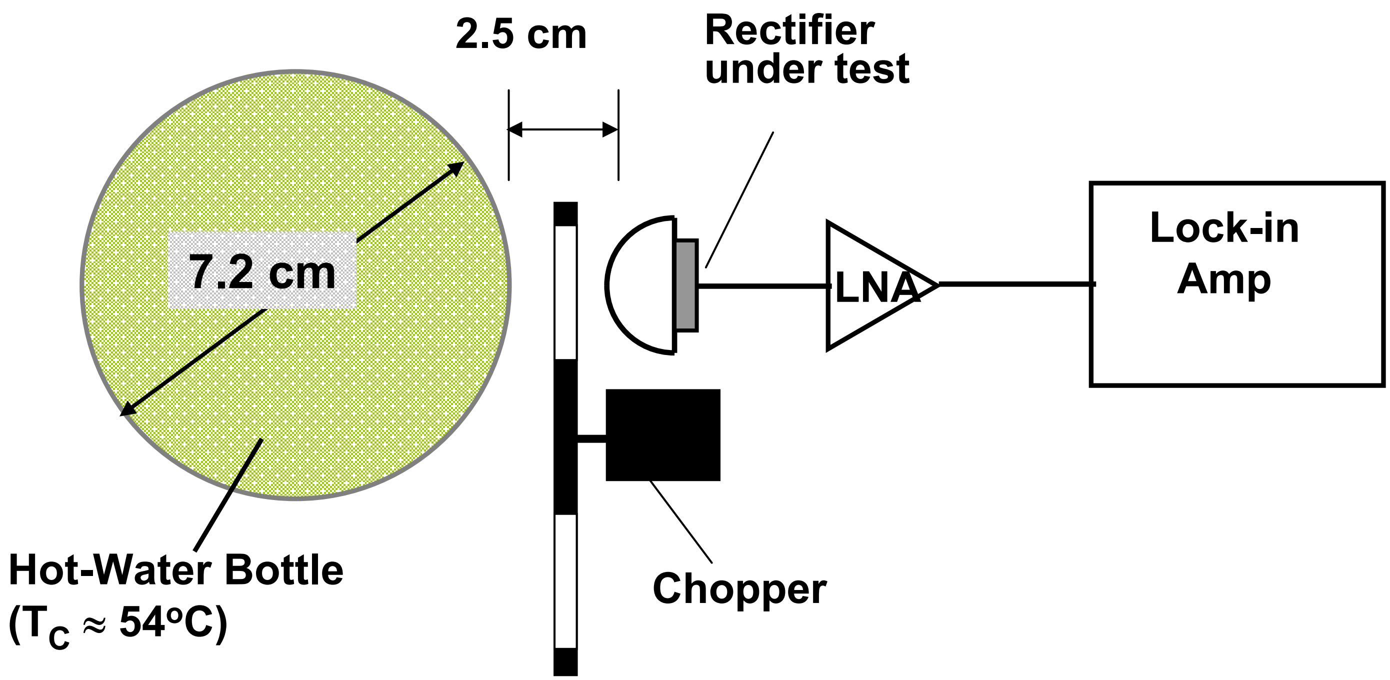
Step 6: Compute responsivity, $S_V = V_{out}/P_{avail}$

Step 7: Compute NEP = V_{noise}/S_V $[V_{noise}] = V/Hz^{1/2}$

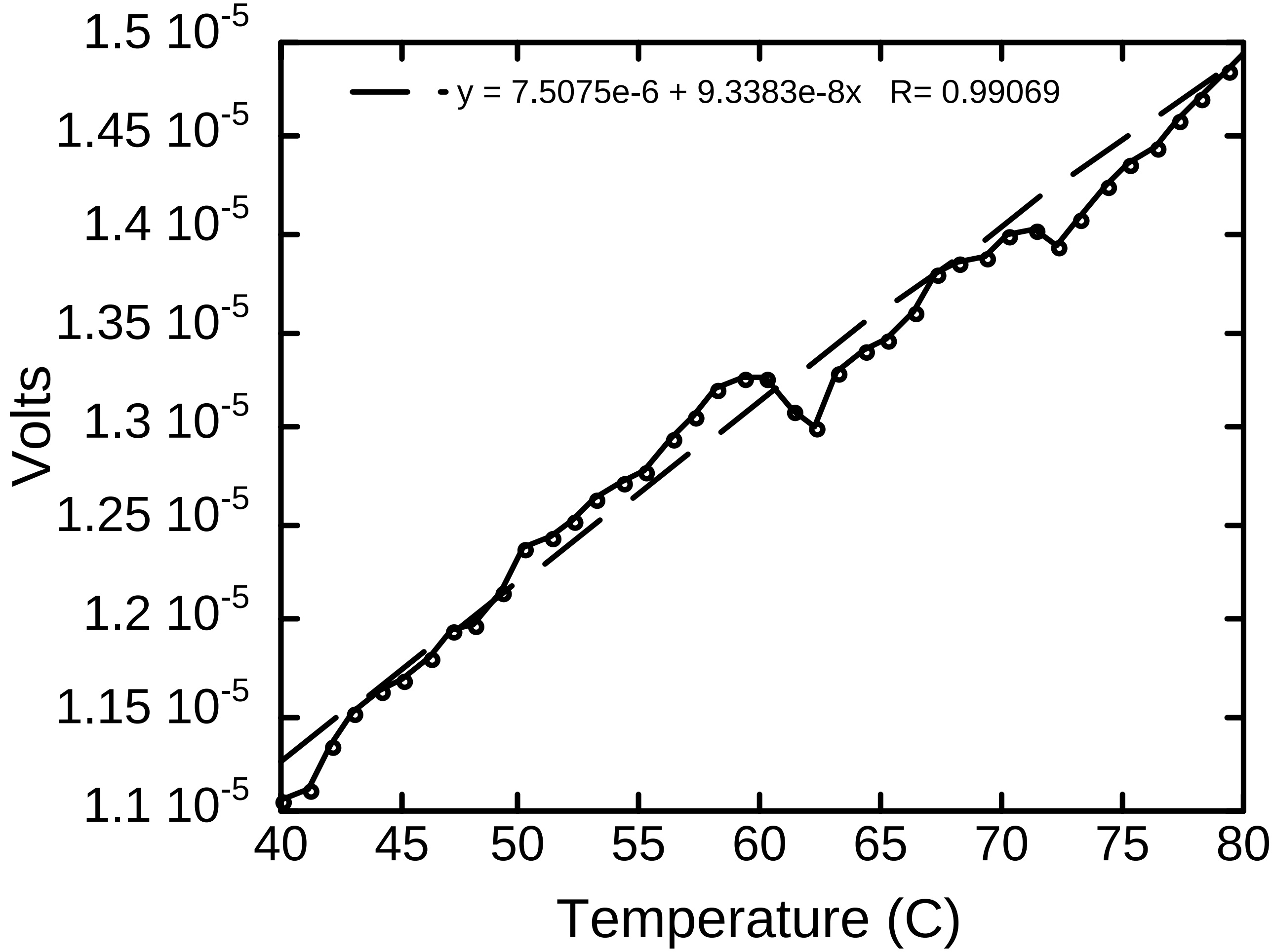
650-GHz Plane-Wave Set-UP



NEΔT Set-Up


2.5 cm
Rectifier under test
7.2 cm
LNA
Lock-in Amp
Hot-Water Bottle
($T_C \approx 54^oC$)
Chopper

Measuring NEΔT



NEΔT ~ 0.12 K

THz Thermal Detectors

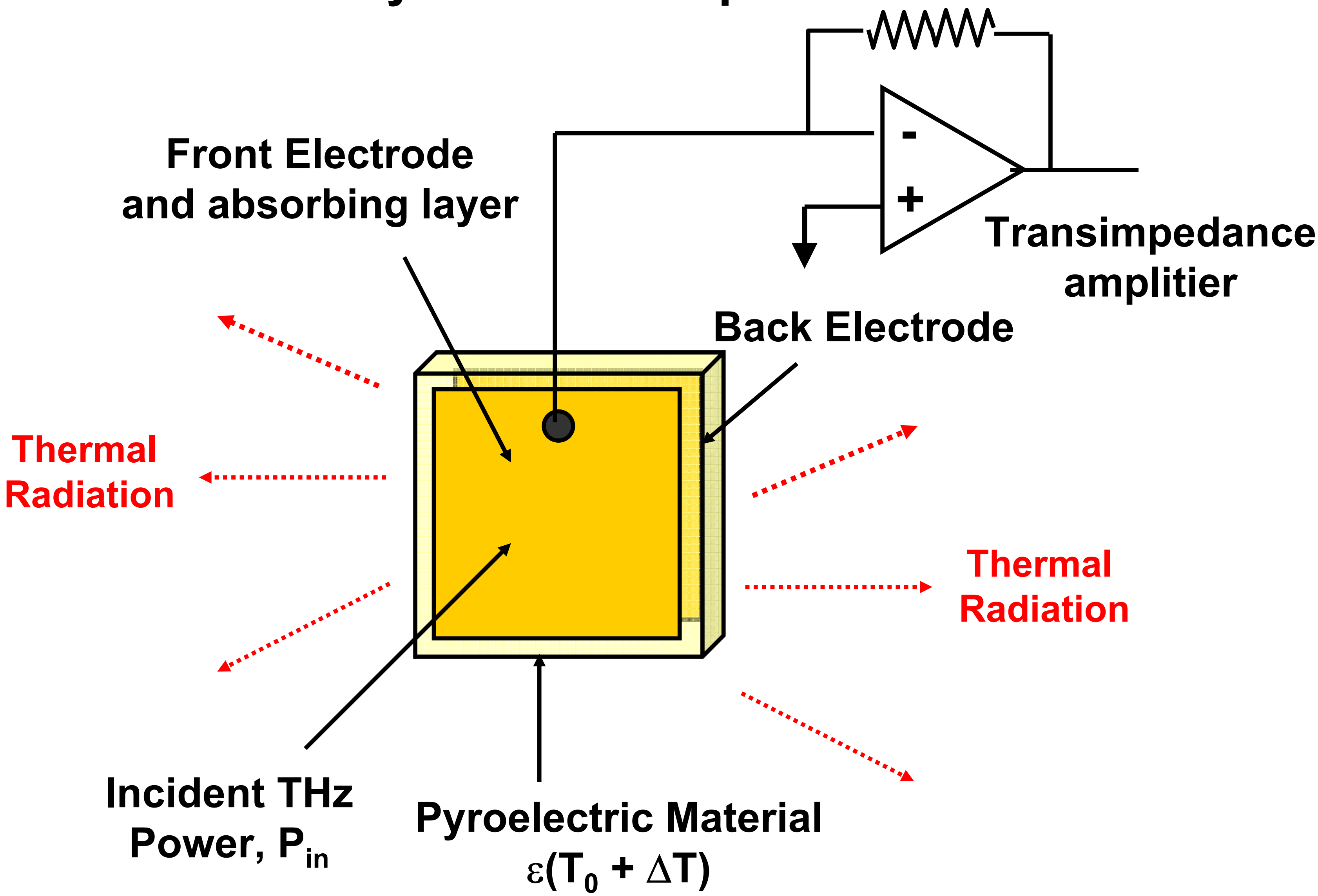
- **All of these utilize the change in some physical property caused by the temperature rise associated with absorption of radiation.**

- **(1) Bolometer: change in resistance of a solid: (1/R) dR/dT**
  (2) Golay cell: change in volume of gas
  (3) Pyroelectric detector: change in dielectric constant:
  $\kappa_P = dP_e/dT$ **,** P_e **being the macroscopic electric polarization**

- **These thermal detectors must be electrically biased.**

- **Big challenge at THz frequencies in the terrestrial environment is the ubiquitous background infrared radiation.**

Pyroelectric Capacitor



Pyroelectric Detector Analysis

• **Inherently an AC effect since it depends on polarization current, dP_E/dT**

$$i = A\frac{dP_E}{dT}\cdot\frac{dT}{dt} \equiv A\cdot\kappa_P\cdot\frac{dT}{dt} = A\cdot\kappa_P\cdot\frac{d\Delta T}{dt}$$

• **For *slow* sinusoidally modulated input power, $P_{in}(\omega) = P_0 \sin(\omega t)$, we expect sinusoidal temperature deviation $\Delta T(t)$ as well**

$$i = A\cdot\kappa_P\cdot\omega\cdot\Delta T\cos(\omega t)$$

• **Assume that in steady state the rise in temperature caused by absorbed THz radiation P_{in} , is matched by a thermal radiation to background (mostly in the IR region for T_0 = 300 K). Hence**

$$\Delta T = \frac{P_{in}}{G}$$

Where G is the radiative thermal conductance

Pyroelectric Detector Analysis (cont)

- **So the instantaneous signal and**

$$i_s = \frac{A \cdot \kappa_P}{G} \cdot \frac{dP_{in}}{dt} = \frac{A \cdot \kappa_P \cdot \omega P_0}{G} \cos \omega t \qquad \overline{i_s^2} = \frac{(A \cdot \kappa_P \cdot \omega P_0)^2}{2G^2}$$

- **Noise terms: (1) thermal noise from generalized Nyquist, and (2) radiation fluctuations expressed as temperature**

$$< (\Delta i)^2 >= \frac{4k_B T_N}{R} + (A \cdot \kappa_P \omega)^2 < (\Delta T)^2 >$$

Johnson Nyquist,
$T_N \Rightarrow$ noise temp including TIA

Temperature Fluctuations

- **But any body close to thermal equilibrium with a bath at temp T_0 has fluctuations (upcoming HW problem)**

$$< (\Delta T)^2 > \approx \frac{4k_B T_0^2}{G} \Delta f$$

where Δf is the electrical bandwidth

Pyroelectric Detector Analysis (cont)

- So the electrical signal-to-noise ratio becomes

$$SNR = \frac{\overline{i_s^2}}{<(\Delta i)^2>}$$

$$= \frac{P_0^2}{4k_B T_N BG^2 /[R(\kappa_p A\omega)^2] + 4k_B T^2 GB}$$

- Solving for the NEP, we get

$$NEP = \sqrt{4k_B T_0^2 G\{1 + [T_N G / T_0^2 R(\kappa_p A\omega)^2]\}}$$

- This is a very interesting expression with a fundamental leading term that is the limiting value with ω, κ_P, or both, are large enough

$$NEP \rightarrow \sqrt{4k_B T_0^2 G}$$

Radiative Thermal Conductance Limit

- **So thermal-noise limit can be computed for a best-case scenario of thermal radiative transfer only: Stefan-Boltzman law**

$P_{rad} = \varepsilon A\sigma T^4$ $\quad \sigma \Rightarrow$ Stefan Constant (5.67×10^{-8} [MKSA])

$$\frac{dP}{dT} \equiv G = 4e\sigma A T^3$$

$= 1.5\times10^{-4}$ W/K (assuming emissivity e = 1.0, and A = 0.25 cm^2)

- **So** $$NEP \rightarrow \sqrt{4k_B T_0^2 G}$$ **$= 2.8\times10^{-11}$ W/Hz$^{1/2}$**

- **Bolometers are already operating near this value, but pyroelectric detectors have a ways to go**

Effect of Thermal Time Constant

- A disadvantage of all THz thermal detectors (compared to rectifiers) is that they have a thermal time constant which generally limits the electrical bandwidth to relatively low values and introduces a sensitivity-bandwidth tradeoff.

- Where does thermal time constant come from ? Fourier's Law, and conservation of energy: $\overrightarrow{J_Q} = -K\vec{\nabla}T \qquad -\vec{\nabla}\cdot\overrightarrow{J_Q} = C_V\frac{\partial T}{\partial t} - \rho_Q$

K = thermal conductivity; C_V = specific heat capacity; ρ_Q = heat generation density

- In simplest cases, thermal time constant, $\tau_T = (C_V \cdot V)/(K \cdot L_{th}) \equiv C_T/G$ where V is the volume of the thermal device, L_T is the thermal path length, C_T is the thermal capacitance, and G is the thermal conductance

- What happens to a pyroelectric detector when the input power modulation frequency approaches $1/\tau_T$?
- Intuitively, we expect signal and the temperature-related fluctuations to roll-off in classic "single-pole" fashion.

Correction to NEP

- **Hence:** $$\overline{i_s^2} = \frac{(A \cdot \kappa_P \cdot \omega P_0)^2}{2G^2} \rightarrow \frac{(A \cdot \kappa_P \cdot \omega P_0)^2}{2G^2(1+\omega^2\tau_T^2)}$$

$$(A \cdot \kappa_P \omega)^2 < (\Delta T)^2 > \rightarrow \frac{(A \cdot \kappa_P \omega)^2}{1+\omega^2\tau_T^2} < (\Delta T)^2 >$$

- **But the Johnson-Nyquist noise is not affected, so that the NEP becomes:**

$$NEP = \sqrt{4k_B T_0^2 G \left\{ 1 + \frac{T_N G(1+\omega^2\tau^2)}{T_0^2 R(\kappa_p A\omega)^2} \right\}}$$

- **This has a more useful (and realistic high-frequency limit)**

$$NEP \rightarrow \sqrt{4k_B T_0^2 G \left\{ 1 + \frac{T_N G\tau^2}{T_0^2 R(\kappa_p A)^2} \right\}} = \sqrt{4k_B T_0^2 G \left\{ 1 + \frac{T_N C_T^2}{T_0^2 RG(\kappa_p A)^2} \right\}}$$

This interesting expression will be addressed further in the laboratory write-up

Best THz Pyroelectric to Date