A 410-GHz CMOS Push-push Oscillator with a Patch Antenna

Eunyoung Seok[1], Changhua Cao[1,2], Dongha Shim[1],
Daniel J. Arenas[1], David B. Tanner[1],
Chih-Ming Hung[3], and Kenneth K. O[1]

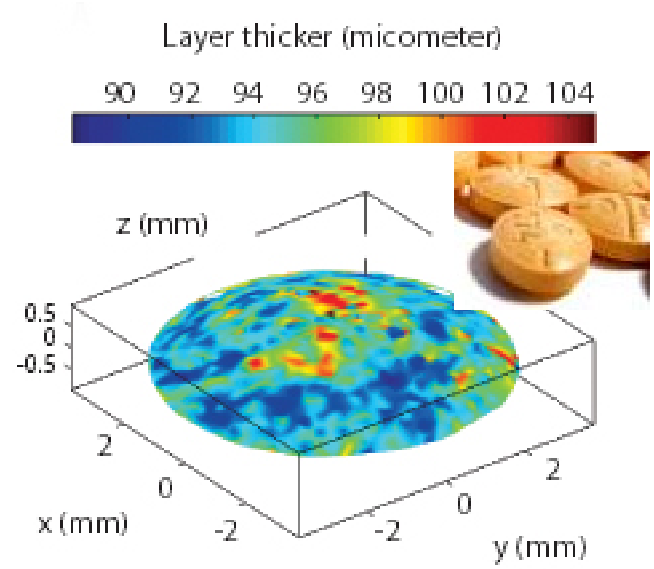
[1]University of Florida, Gainesville, FL
[2]NXP Semiconductors, Austin, TX
[3]Texas Instruments Inc., Dallas, TX

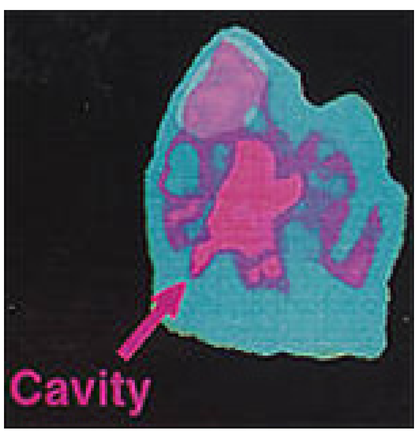
Outline

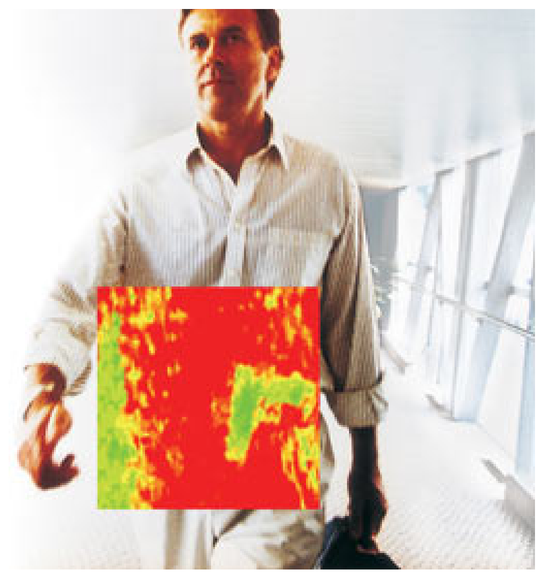
- Introduction
- Push-push oscillator design
- On-chip patch antenna design
- Measurements of submillimeter-wave/THz
- Conclusions

Submillimeter-wave/THz

- 300GHz-3THz
- The radio astronomy
- Advanced imaging, detection of concealed weapons, chemicals, bio-agents and cancers
- Non-ionizing radiation: less risk for human body





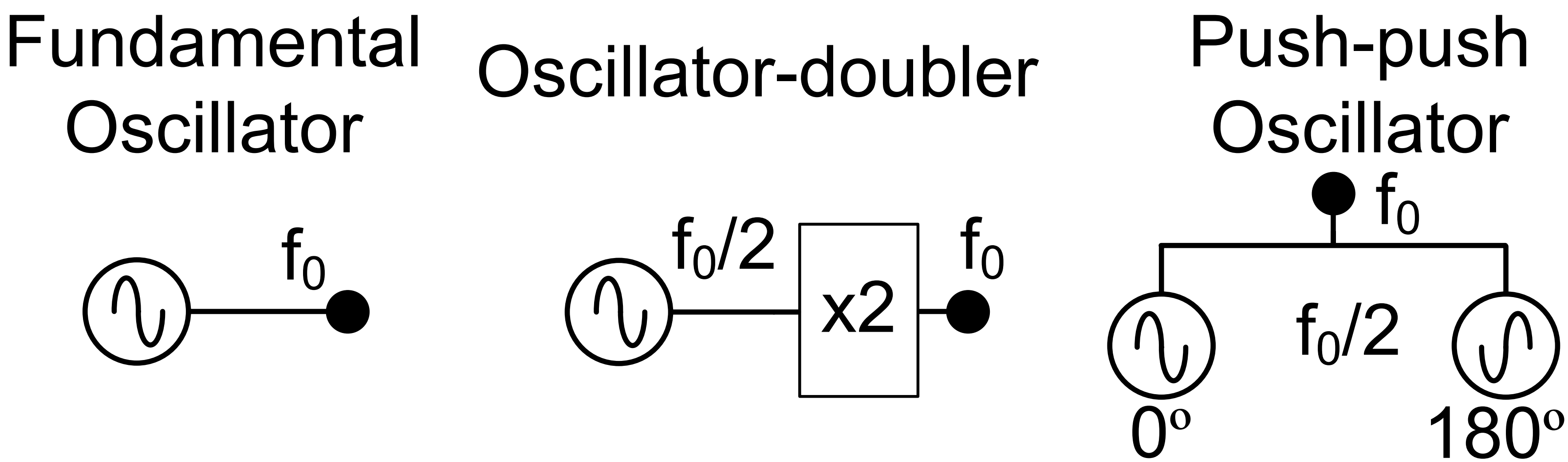


Submillimeter-wave/THz

- Compound semiconductor devices are employed.
- Industrial and commercial applications of submillimeter-wave require low cost, compact and portable systems.
  - ✓ Higher levels of integration
  - ✓ Higher yield
  - ✓ Lower manufacturing cost
  - ✓ Larger die size
- Correct imperfections of submillimeter-wave circuits using digital CMOS circuits

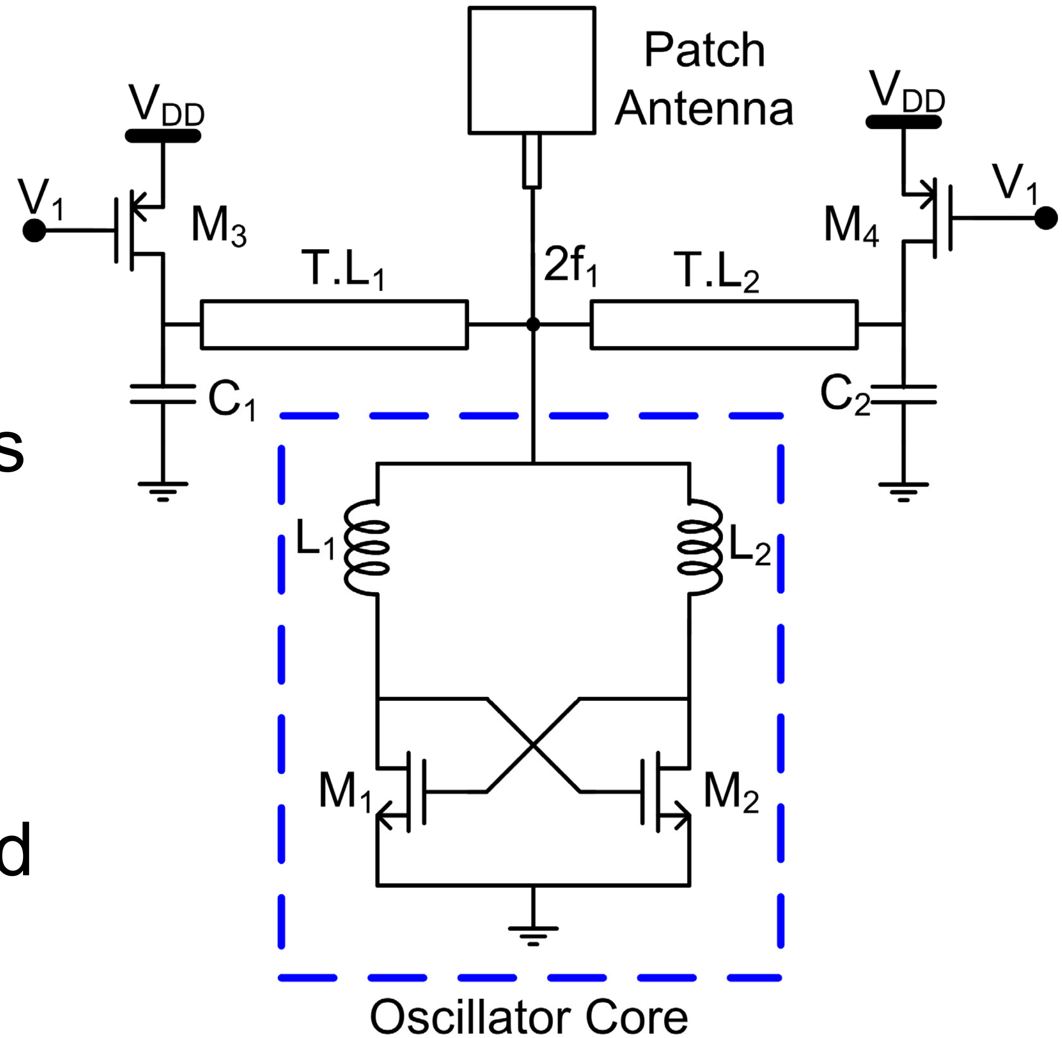
Push-push VCO

- Fundament oscillator: limited by f_{max}
- Oscillator-doubler: larger and more complex
- Push-push oscillator: compact and overcome f_{max}



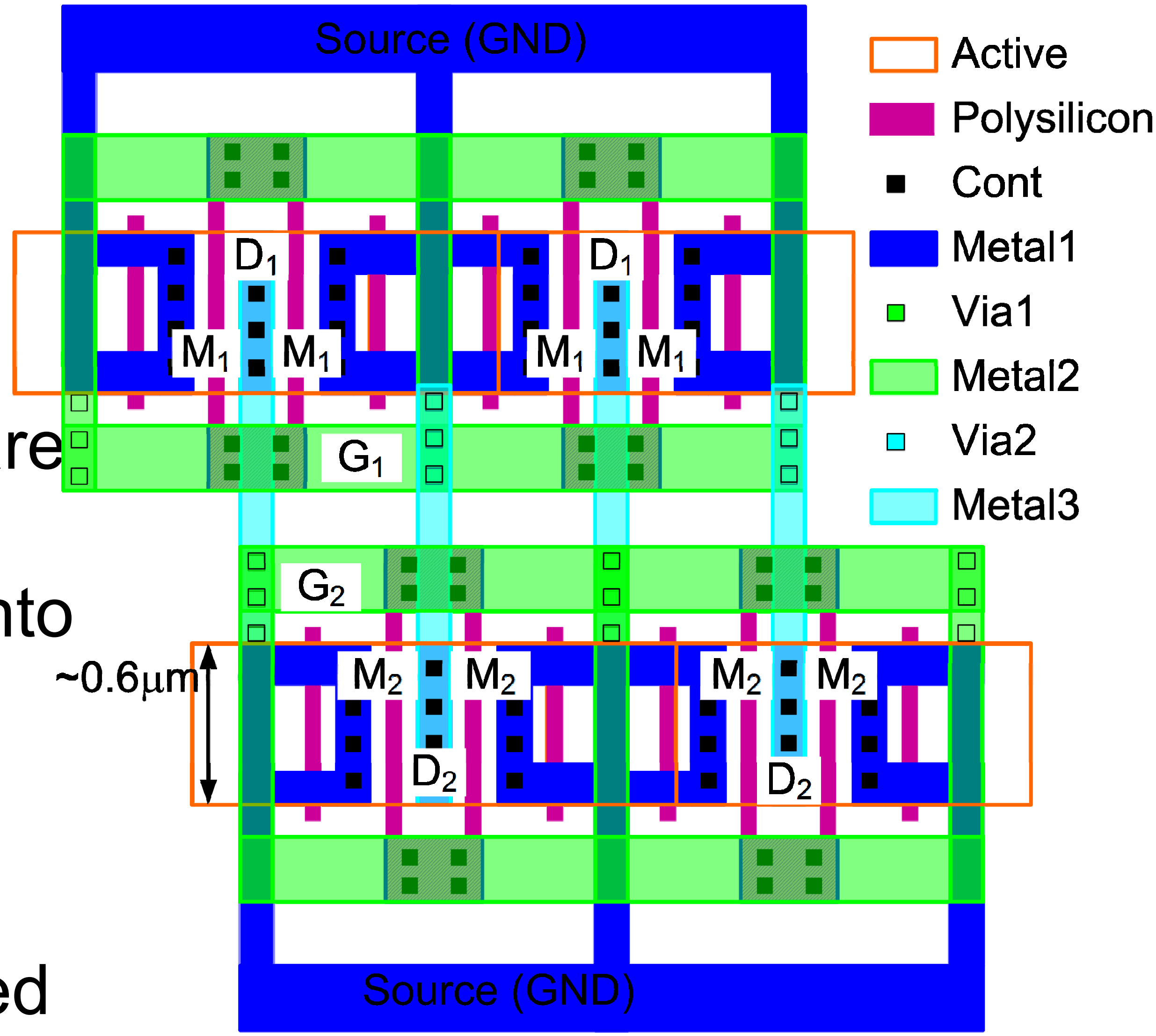
Push-push Oscillator

- ❑ Generate differential signals and eliminates the concern for even-mode oscillation.
- ❑ 2nd harmonic is extracted and radiated through the on-chip patch antenna.

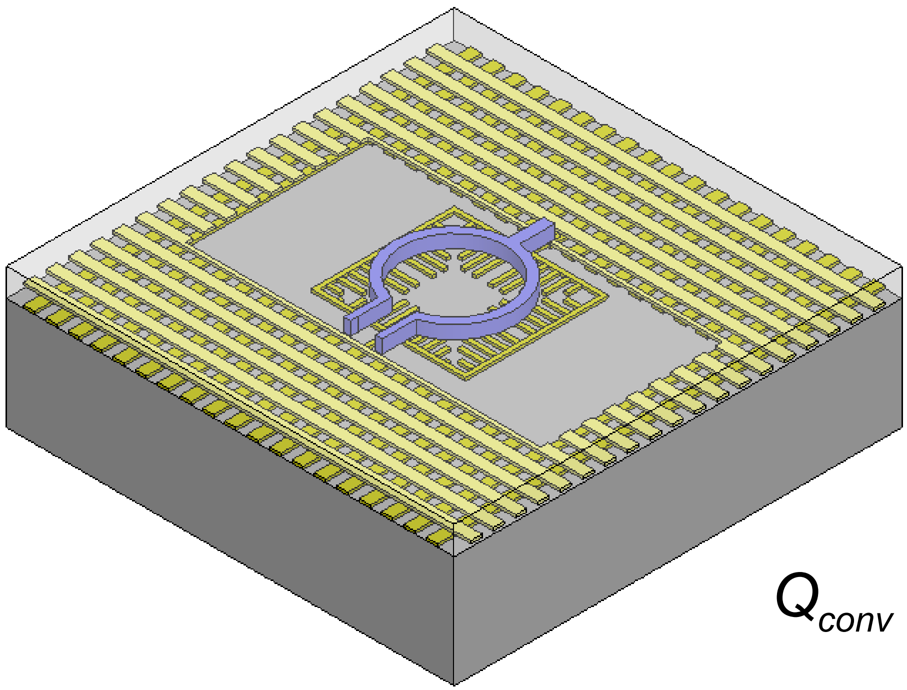


Push-push Oscillator

- The width of the cross-coupled transistor is about 10μm.
- Transistor gates are contacted on both ends and folded into multiple fingers.
- Each finger has 2 contacts on each side and connected using metal2.



Passive Device Modeling



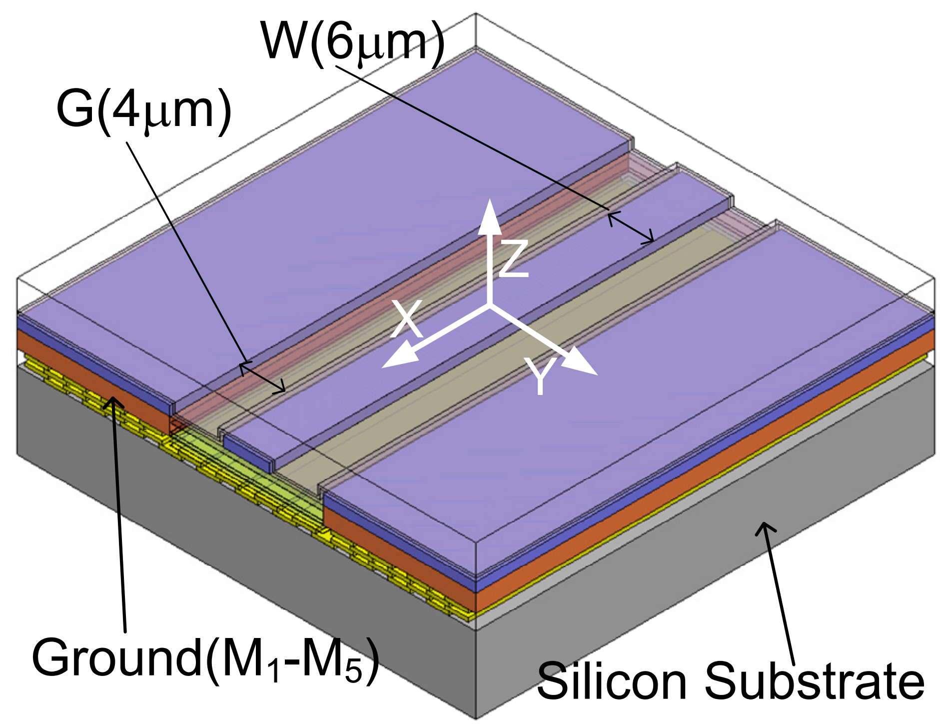
$$L_{eff} = \frac{\mathrm{Im}(Z_{11})}{\omega} \approx 40pH$$

$$Q_{conv} = -\frac{\mathrm{Im}(Y_{11})}{\mathrm{Re}(Y_{11})} \approx 8 \quad @ \ 200\mathrm{GHz}$$

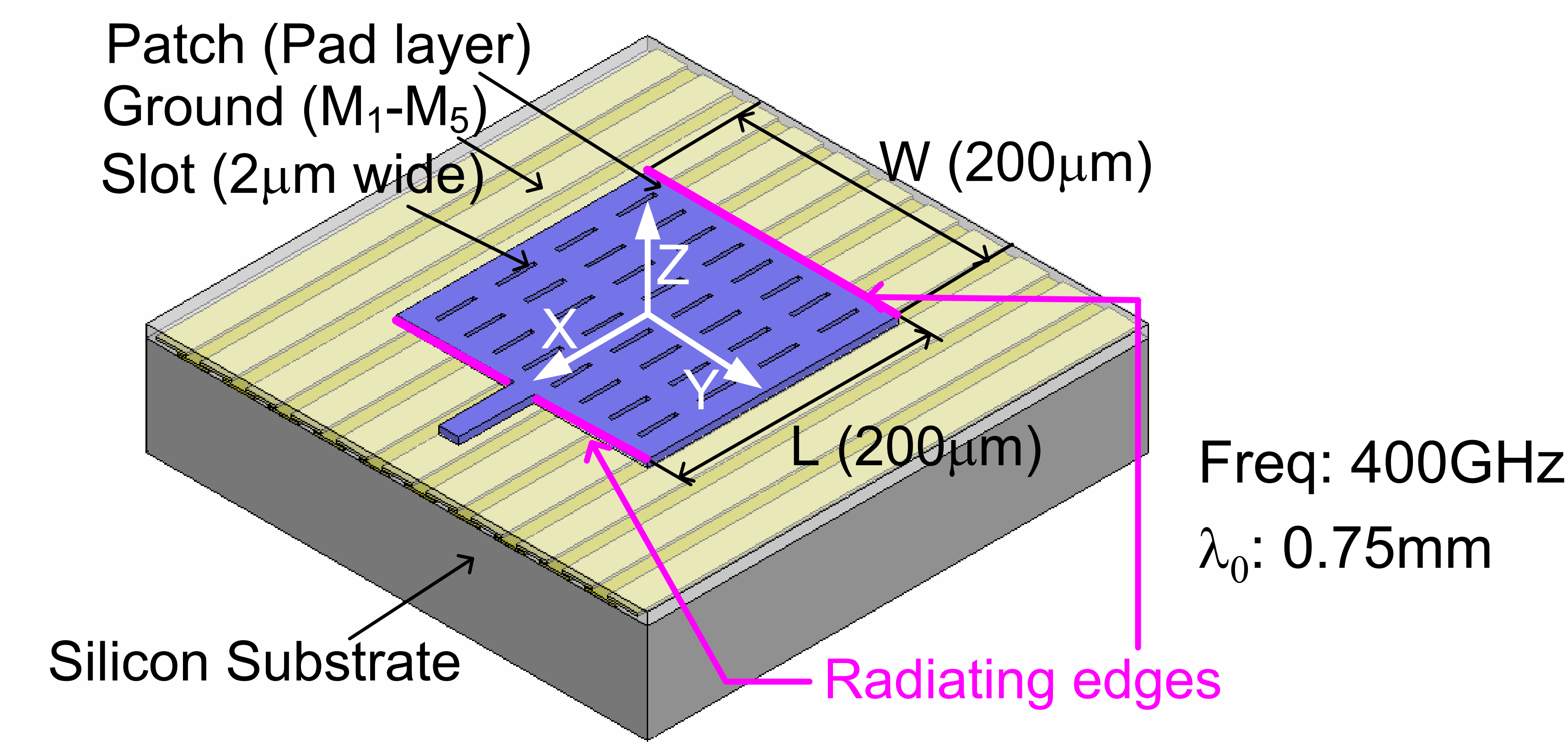
- Design and optimization of inductors solely rely on the 3D EM simulator (Ansoft HFSS).
- Diameter ~ 20μm, Width ~ 1.6μm
- Inductors are 3-port devices in the simulation.

Passive Device Modeling

- Grounded Coplanar Wave guide (GCPW)
- Confine fields relatively small area
- Reduce loss caused by substrate & interference with nearby circuits
- Loss ~ 2.5 dB/mm @400GHz
- W=6μm, G=4μm for Z_0= 50Ω

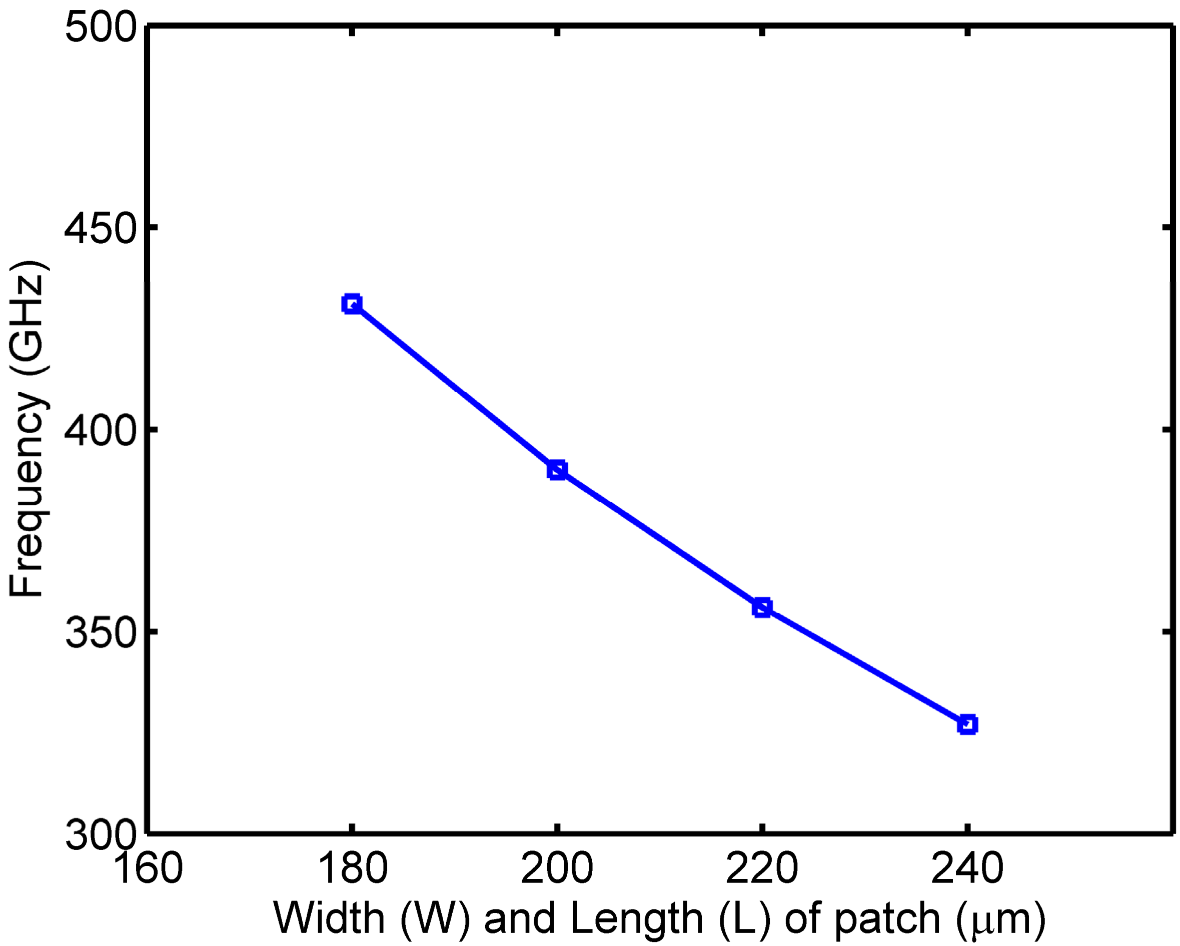


On-chip Antenna



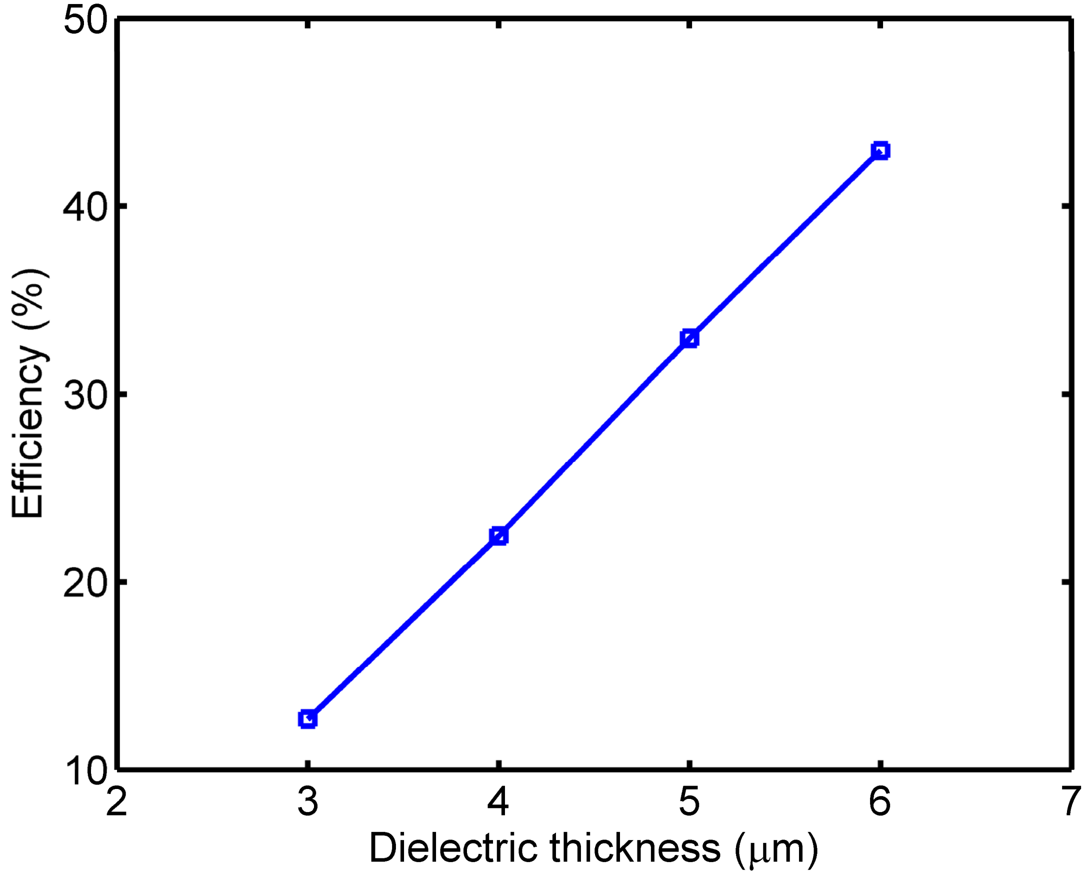
- The fringing fields at the edges are responsible for the radiation.
- The dielectric thickness between the patch and ground plane is ~4μm.

Antenna Size



- The patch length (L) is about half wavelength.
- L is a dominant factor for the resonant frequency.

Antenna Efficiency

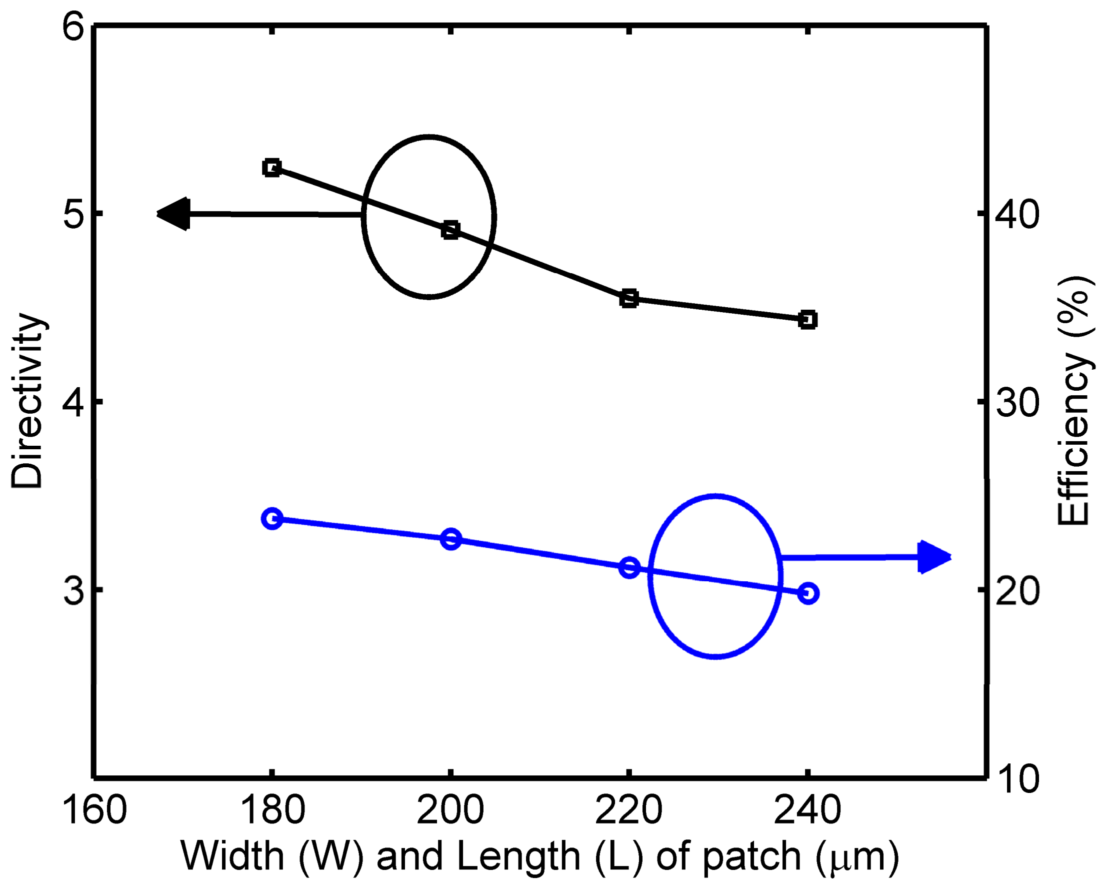


$$\text{Efficiency } (\varepsilon) = \frac{\text{Radiated Power}}{\text{Total Applied Power}}$$

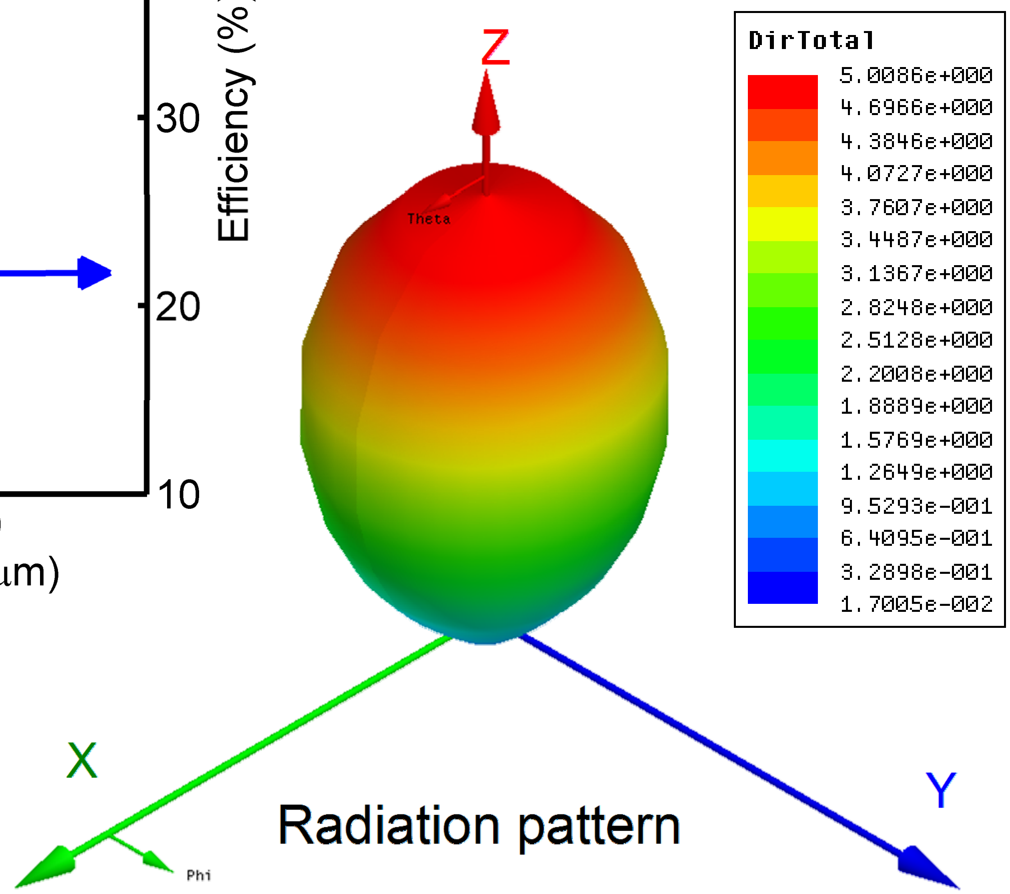
Frequency ~ 390GHz

- The thickness of the dielectric layer between the patch and ground is a dominant factor for the radiation efficiency.

Radiation Pattern



$$\text{Directivity(D)} = \frac{\text{Power Density}(\theta,\phi)}{\text{Average Power Density}}$$

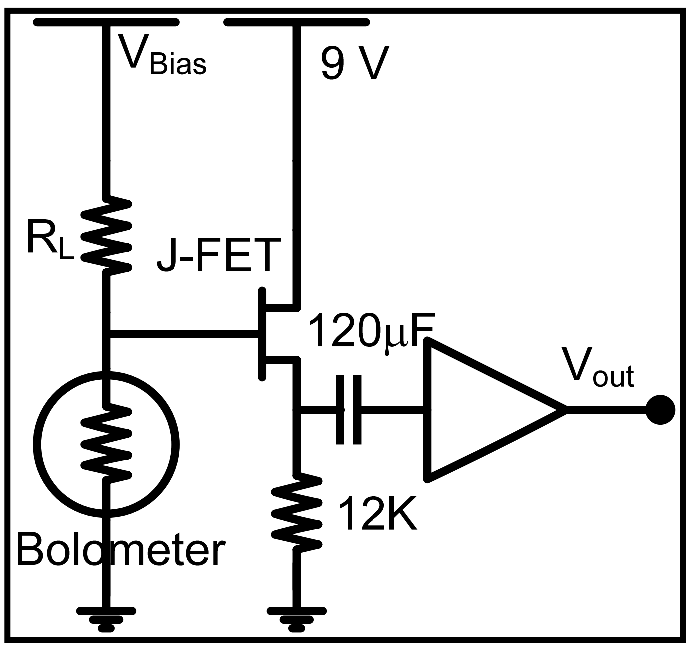


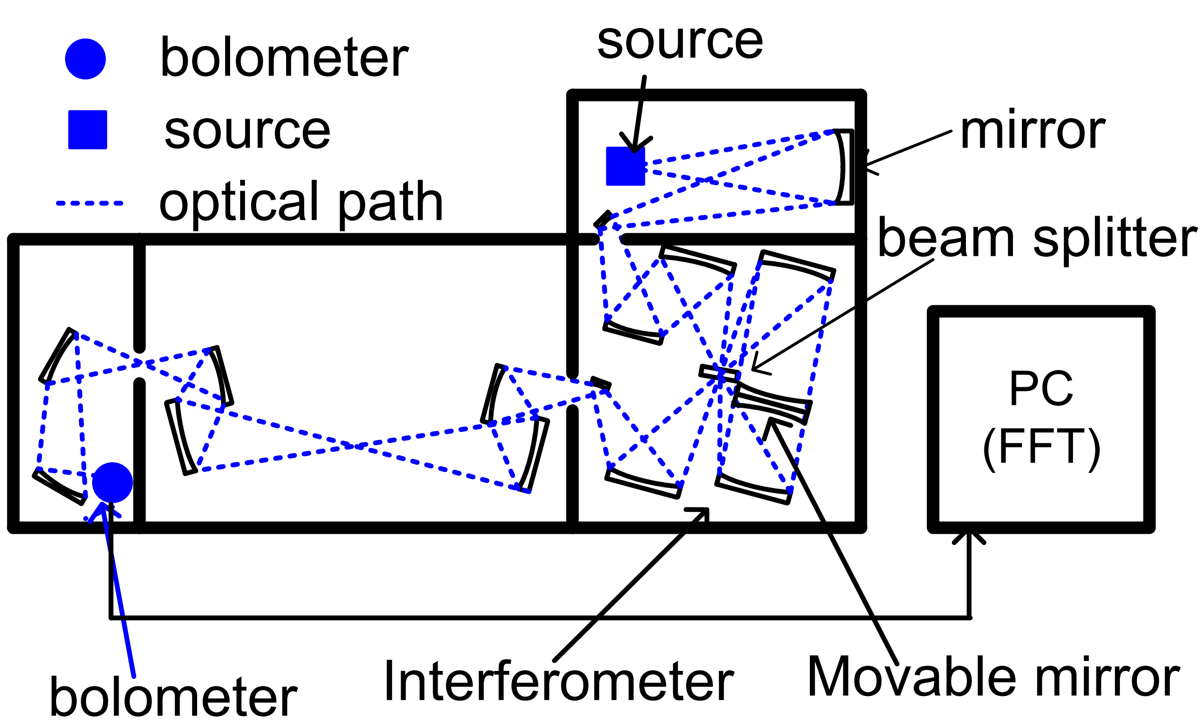
Radiation pattern

Dielectric thickness ~4μm

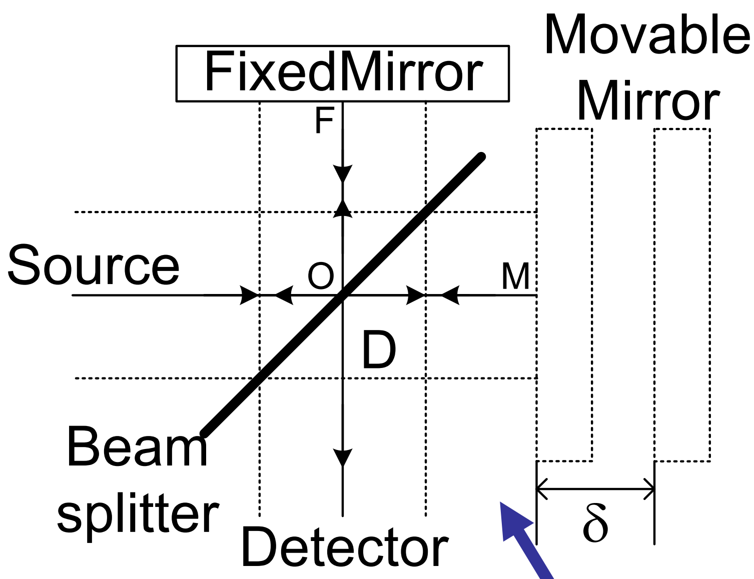
FTIR

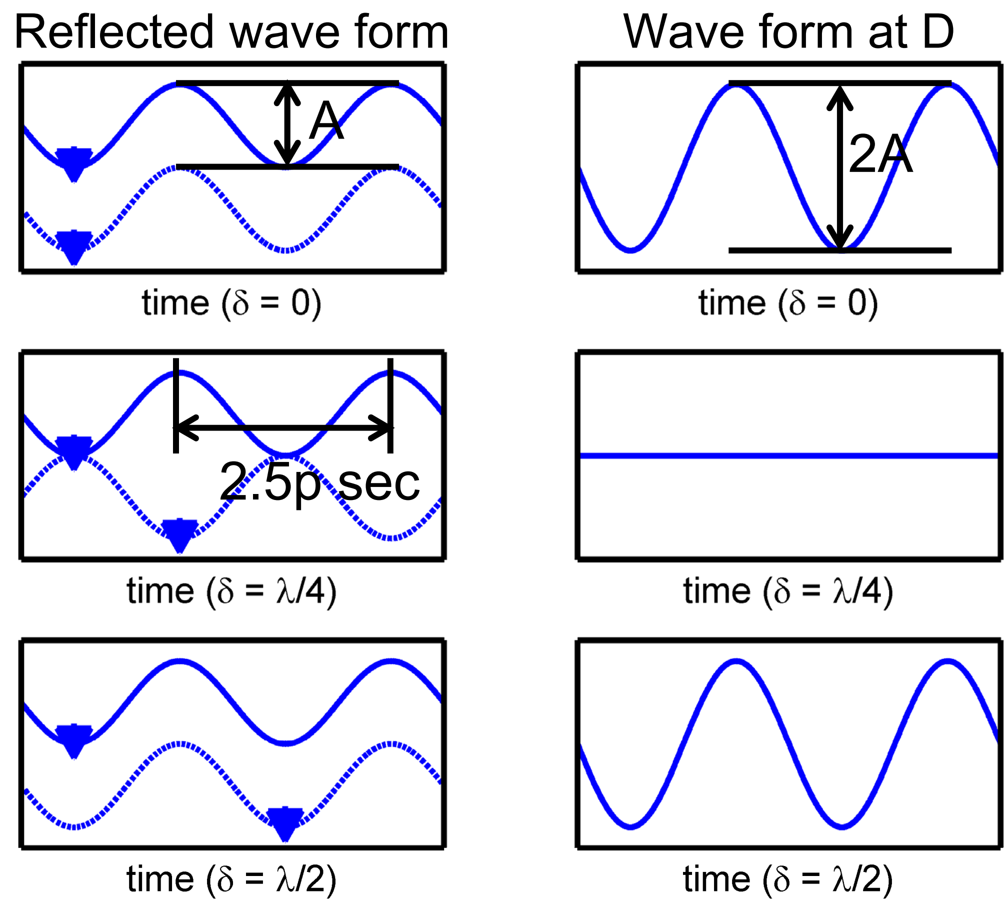
- Off the shelf electrical probes go up to 325GHz.
- Fourier transform infrared spectroscopy (FTIR) consists of a bolometer, an interferometer and sources.
- Silicon bolometer (HD-3,IR Lab), 5-mil beam splitter





Interferometer

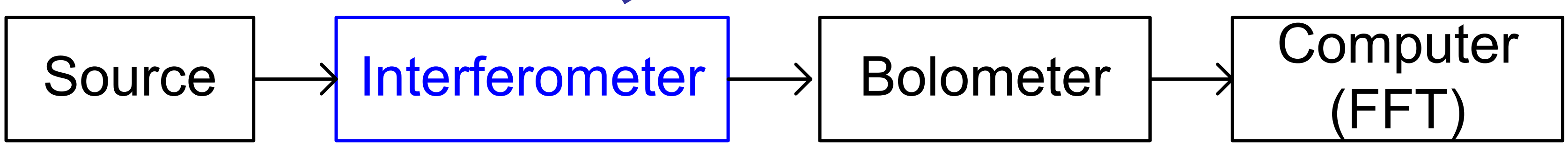




Freq:400GHz

Period: 2.5p sec

λ_0: 0.75mm



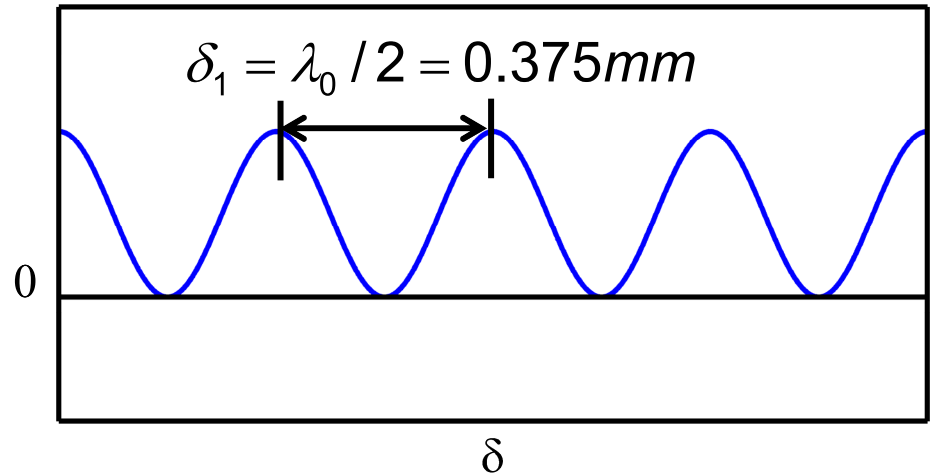
Interferogram

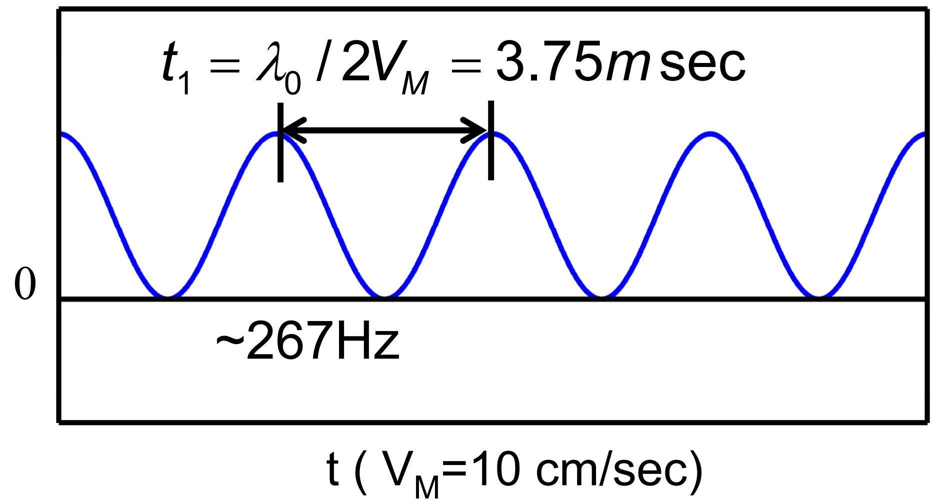
Interferogram

$$= (1 + \cos 2\pi \frac{2\delta}{\lambda_0})$$

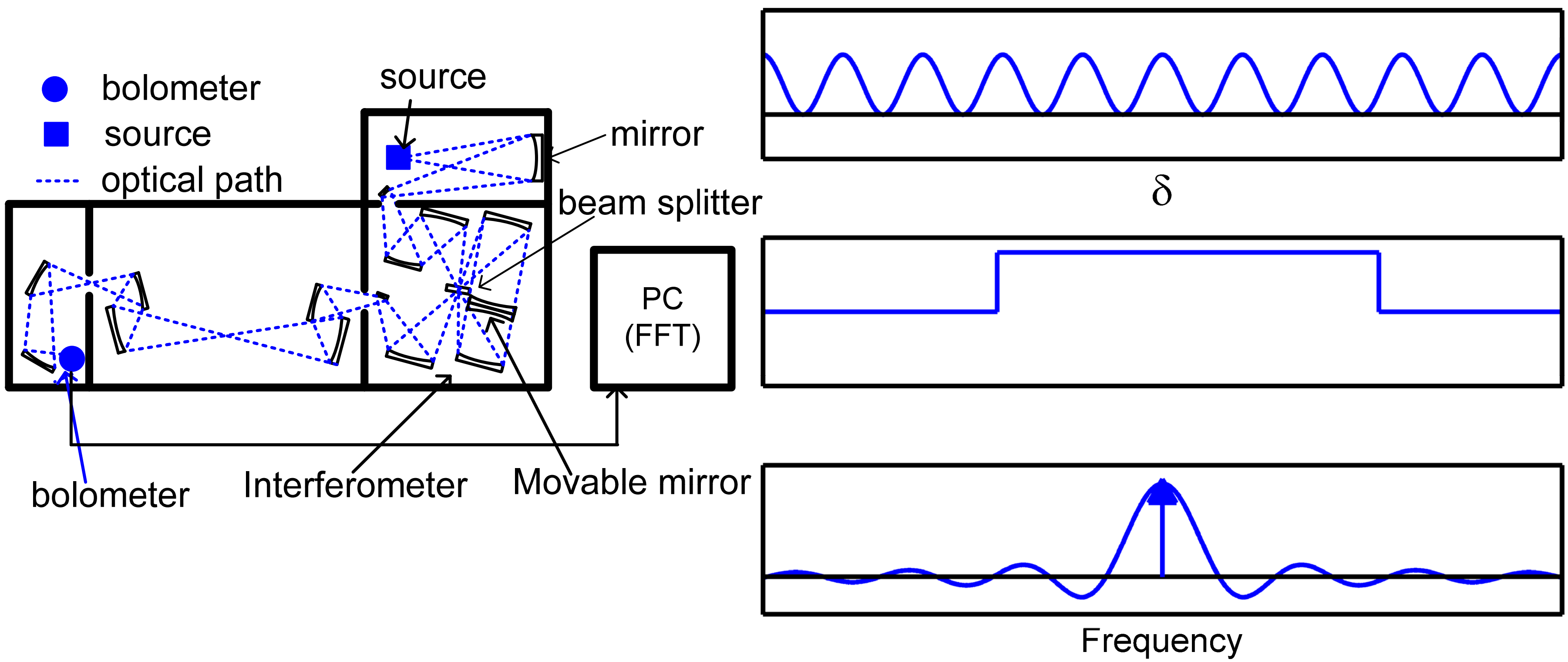
$$= (1 + \cos 2\pi \boxed{\frac{2V_M}{\lambda_0}} \times t)$$

- ❑ $\delta = V_M \times t$
  (V_M : mirror velocity)
- ❑ Freq= $c / (2V_M \times t_1)$
  ($c = 3 \times 10^8$ m/sec)



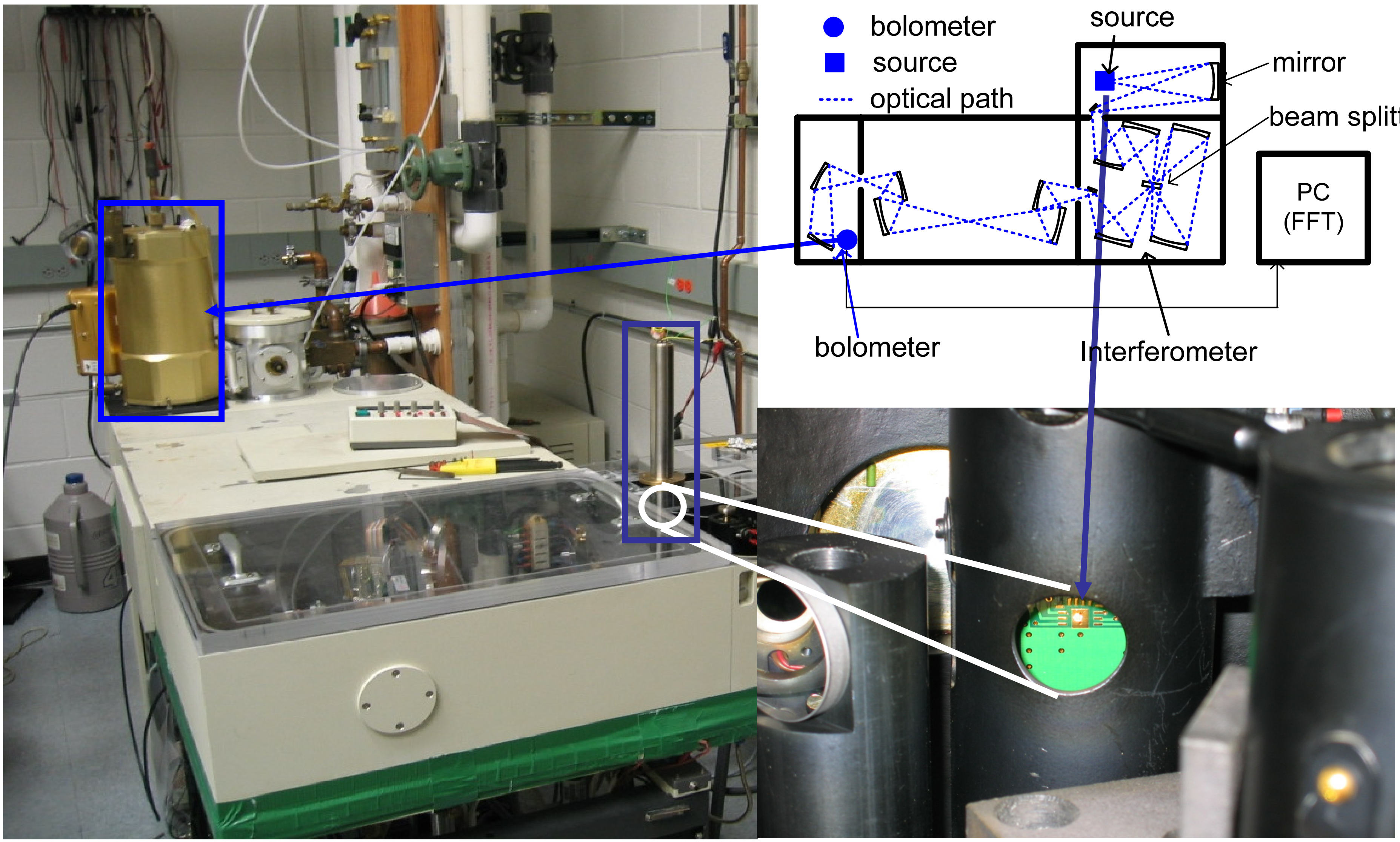


Interferometer

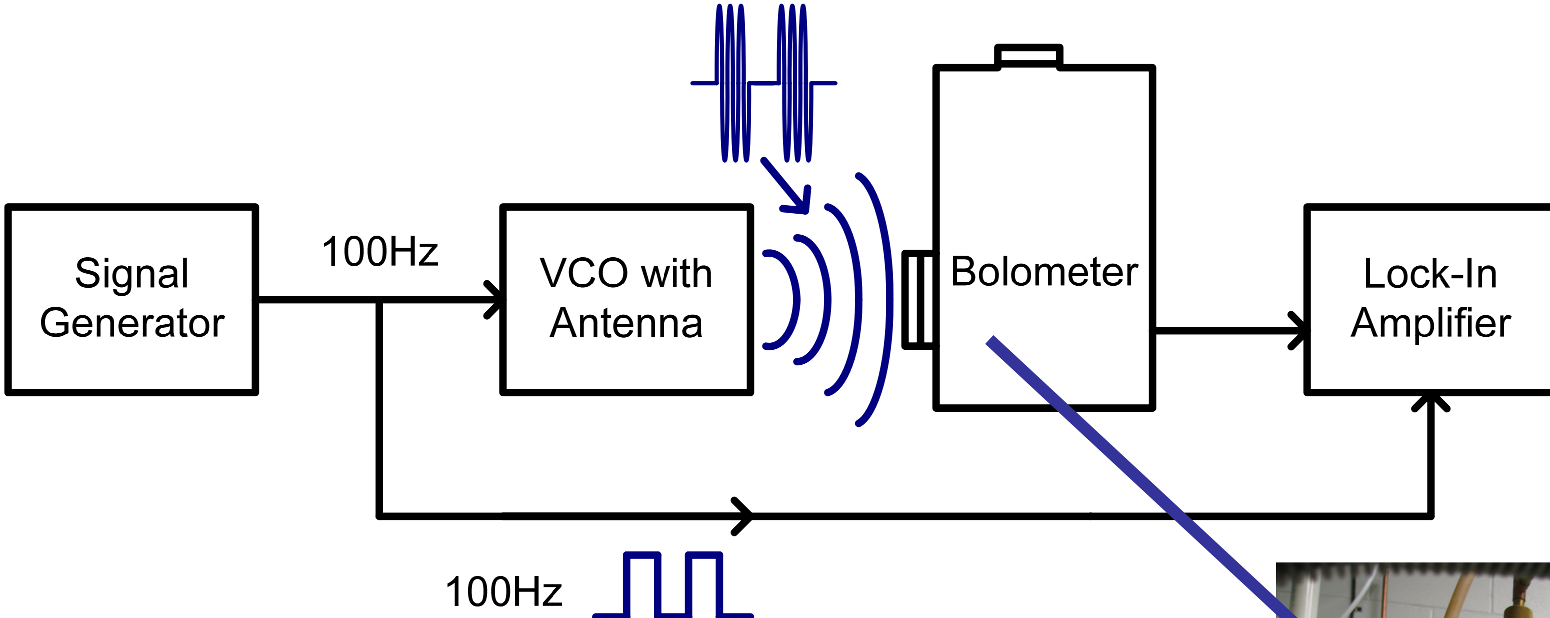


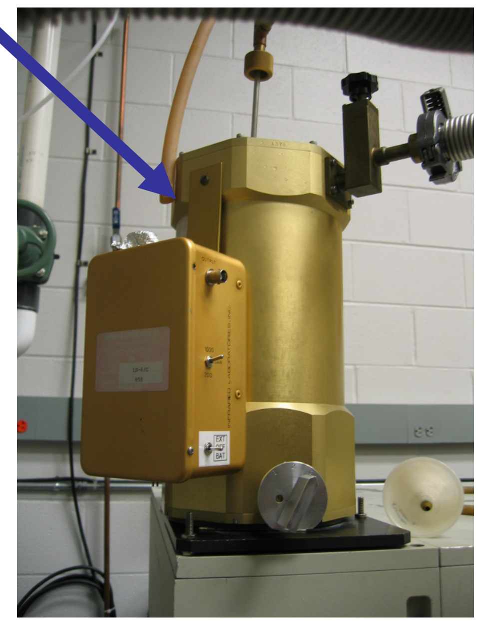
- The mirror movement is limited and the recovered spectrum is convolved with a sinc function in the frequency domain.

THz Measurements



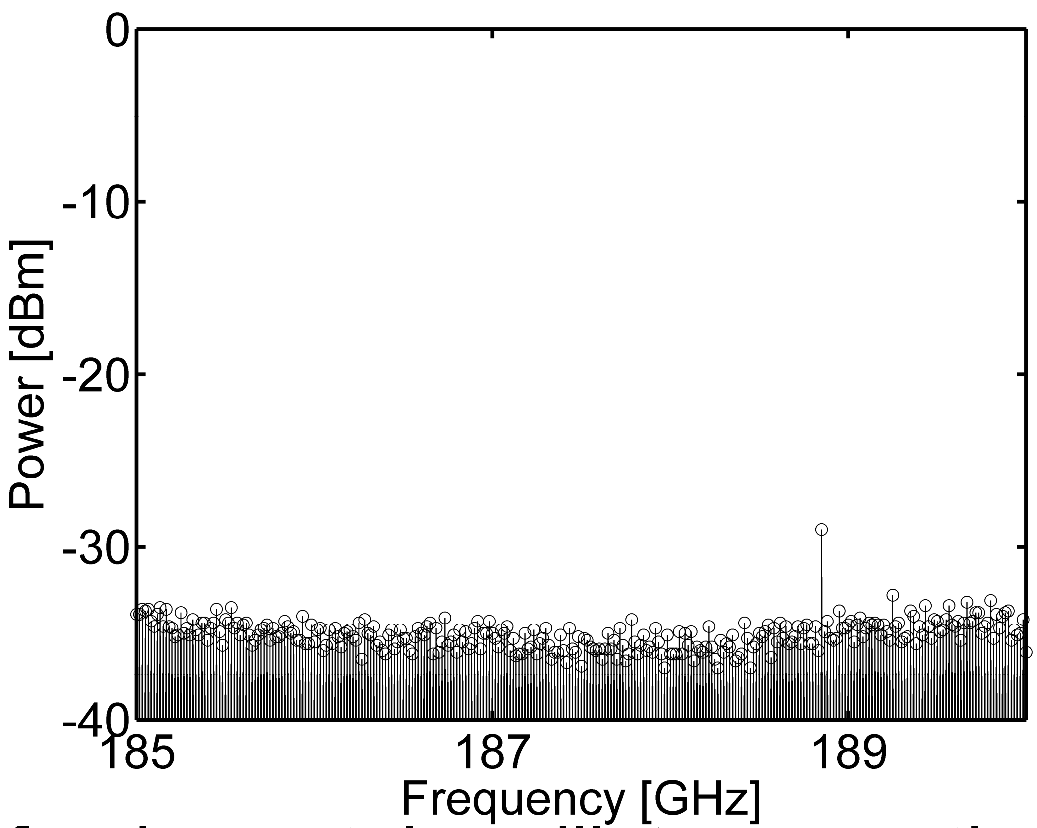
Power Measurement

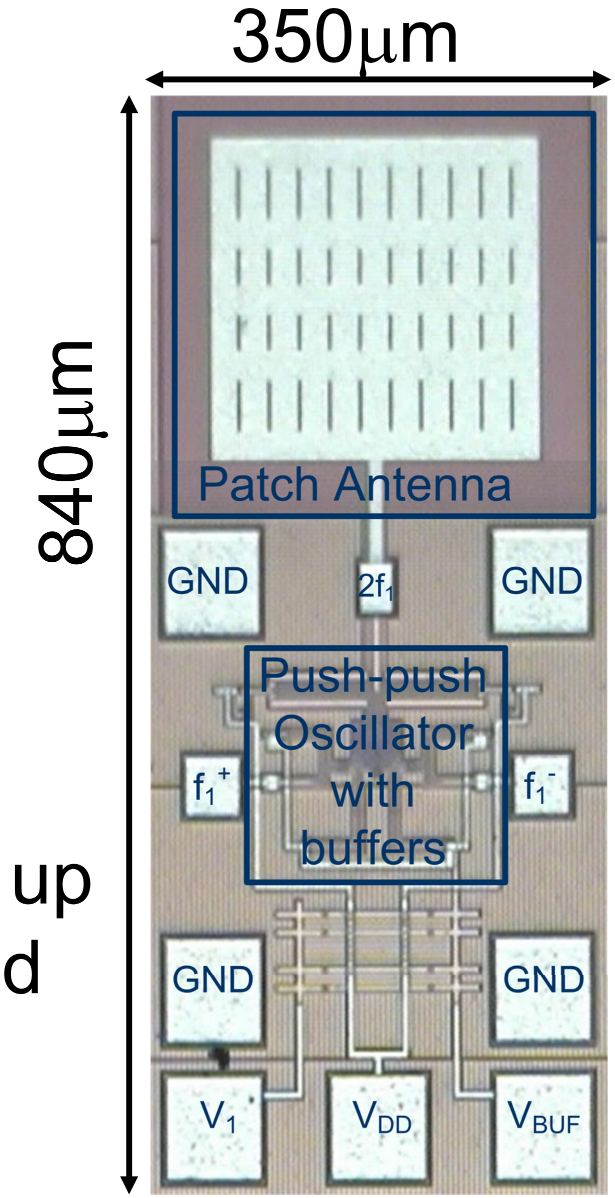




- 100Hz modulation on V_{DD} of Oscillator
- A lock-in amplifier detects signals in noisy environments.
- Measures power radiated through the on-chip patch antenna

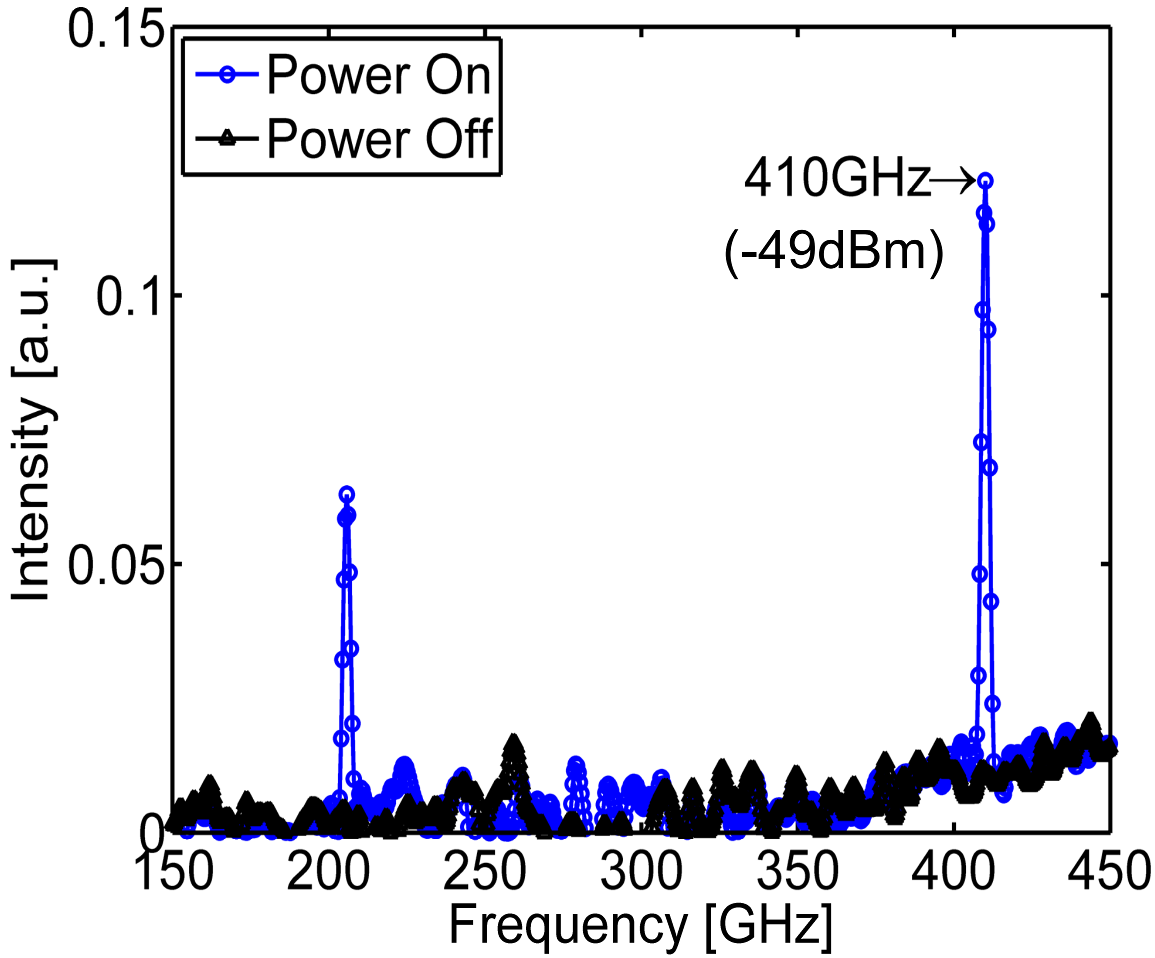
Fundamental Oscillator Measurement



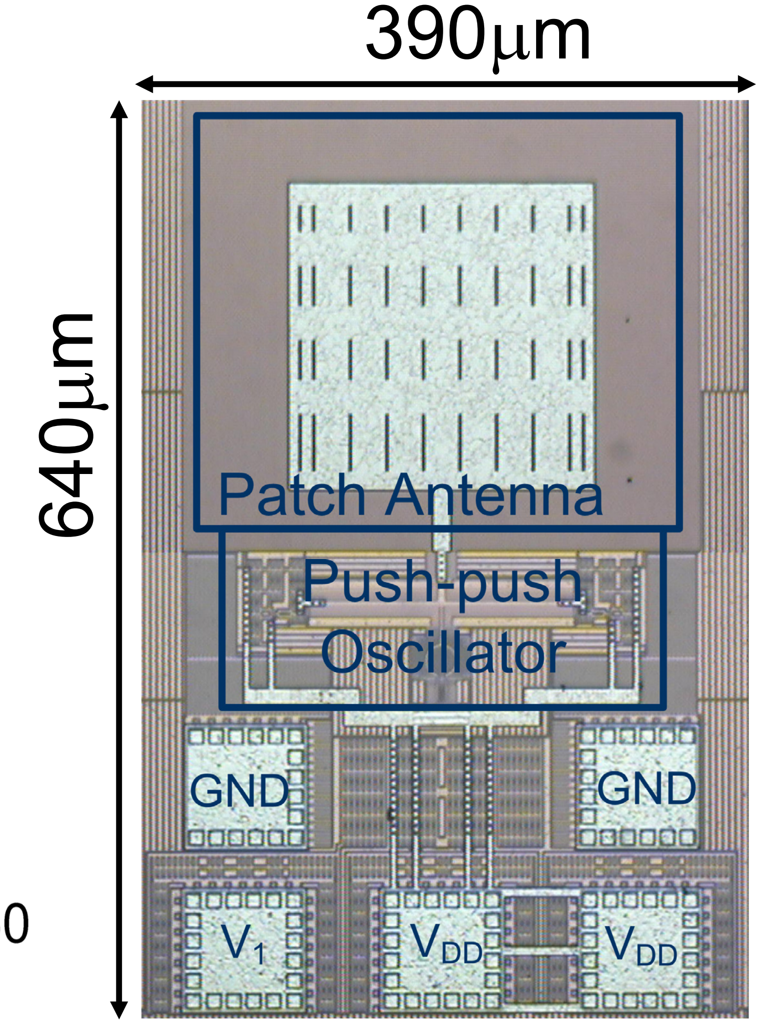


- A fundamental oscillator operating up to 189 GHz has been demonstrated using low leakage transistors in 45nm CMOS.

THz VCO

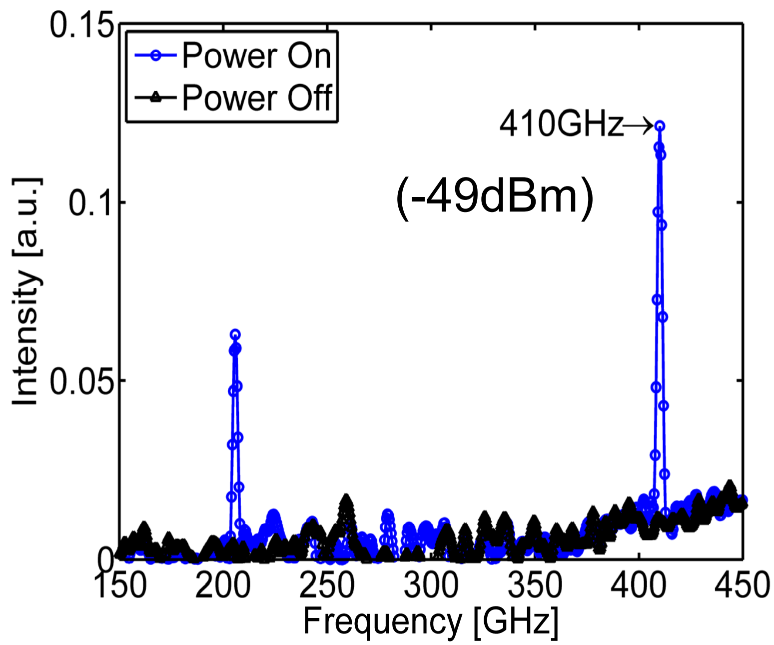


Power On
Power Off
410GHz→
(-49dBm)
Intensity [a.u.]
0.15
0.1
0.05
0
150
200
250
300
350
400
450
Frequency [GHz]



390μm
640μm
Patch Antenna
Push-push
Oscillator
GND
GND
V_1
V_{DD}
V_{DD}

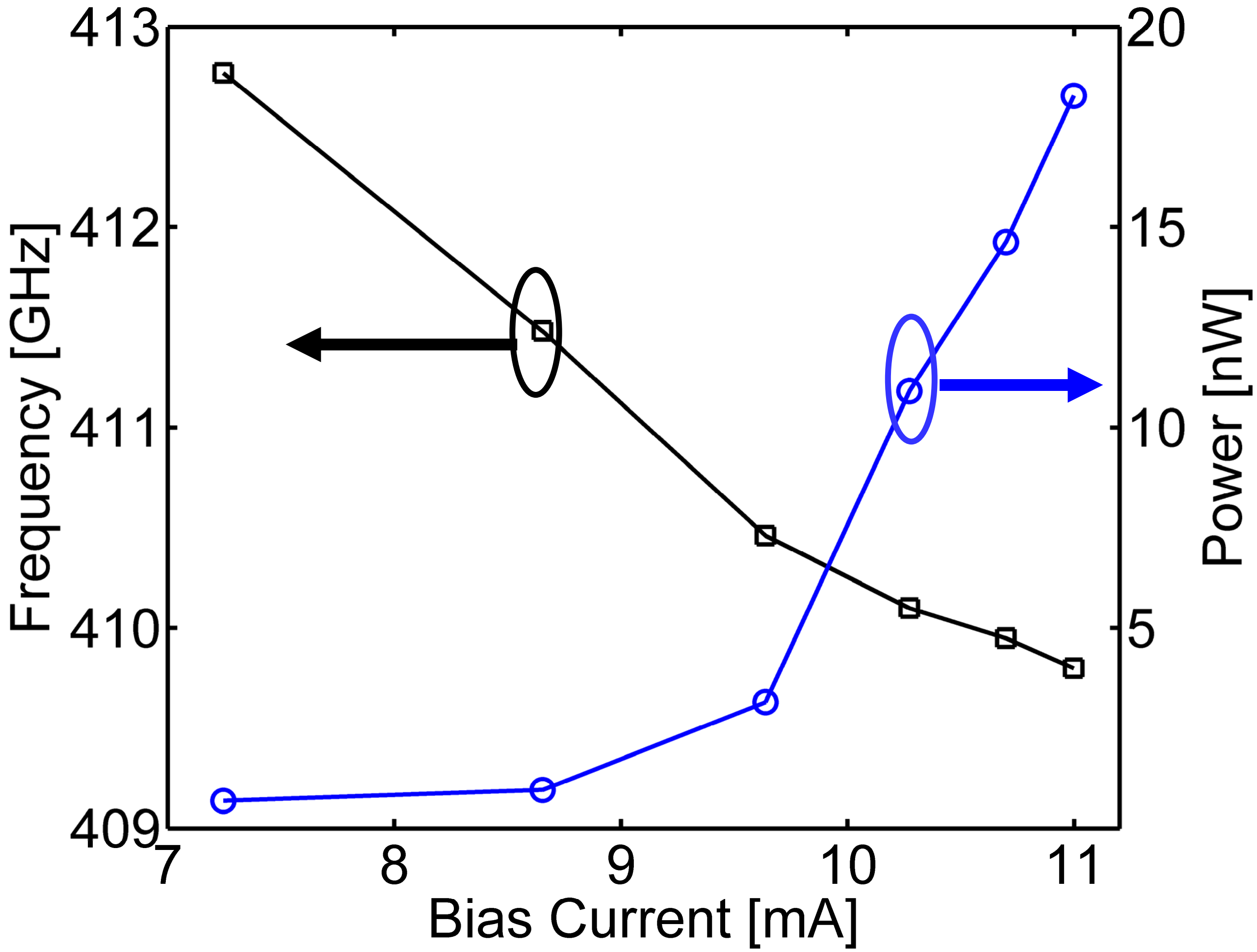
THz Measurements



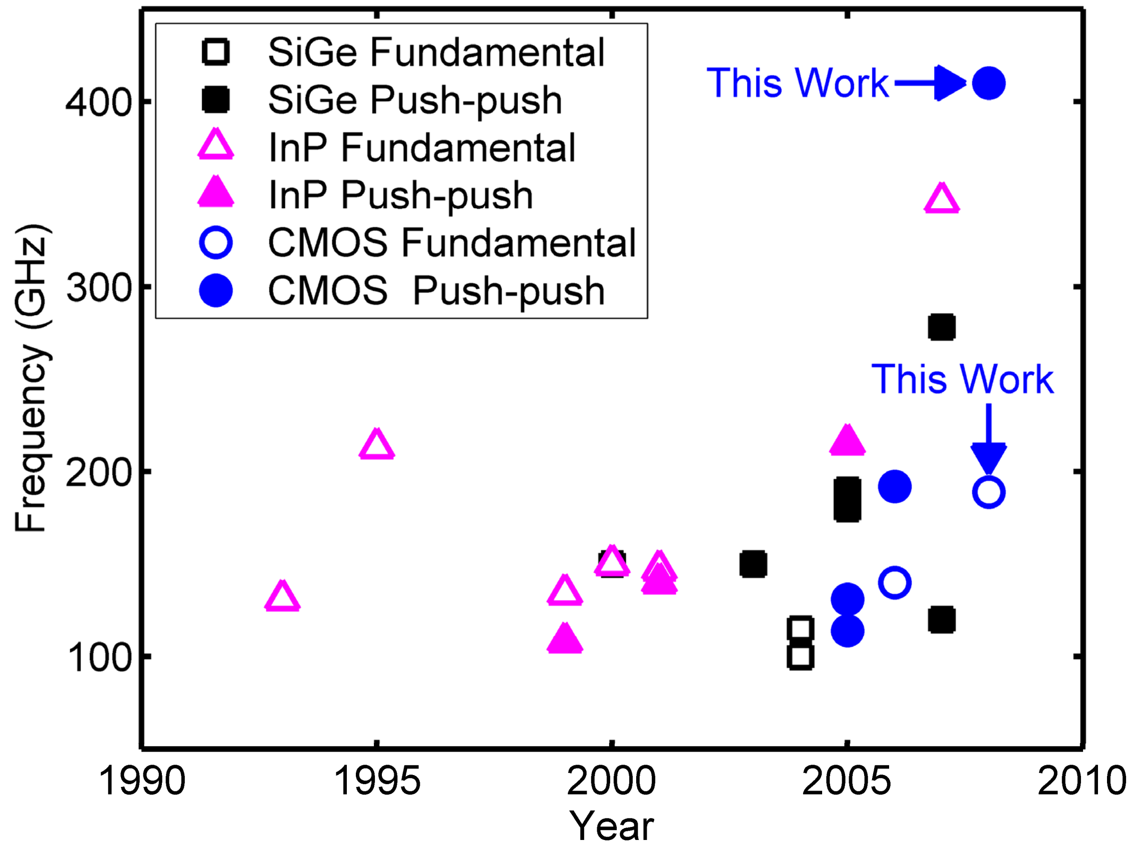
- When the inductor Q increased to 8 and bypass cap Q increased to 5 and R_{sub} = 1kΩ then P_{out} is -18 dBm.

Measured Power	-47 dBm
2nd Harmonic Power	-49 dBm
Antenna loss	7 dB
Mismatch loss	2 dB
Calculated Push-push P_{out}	-40 dBm
Simulated P_{out} with inductor Q of 6 @200GHz, bypass cap Q of 1 @400GHz and R_{sub} of 200Ω	-39dBm

THz Measurements

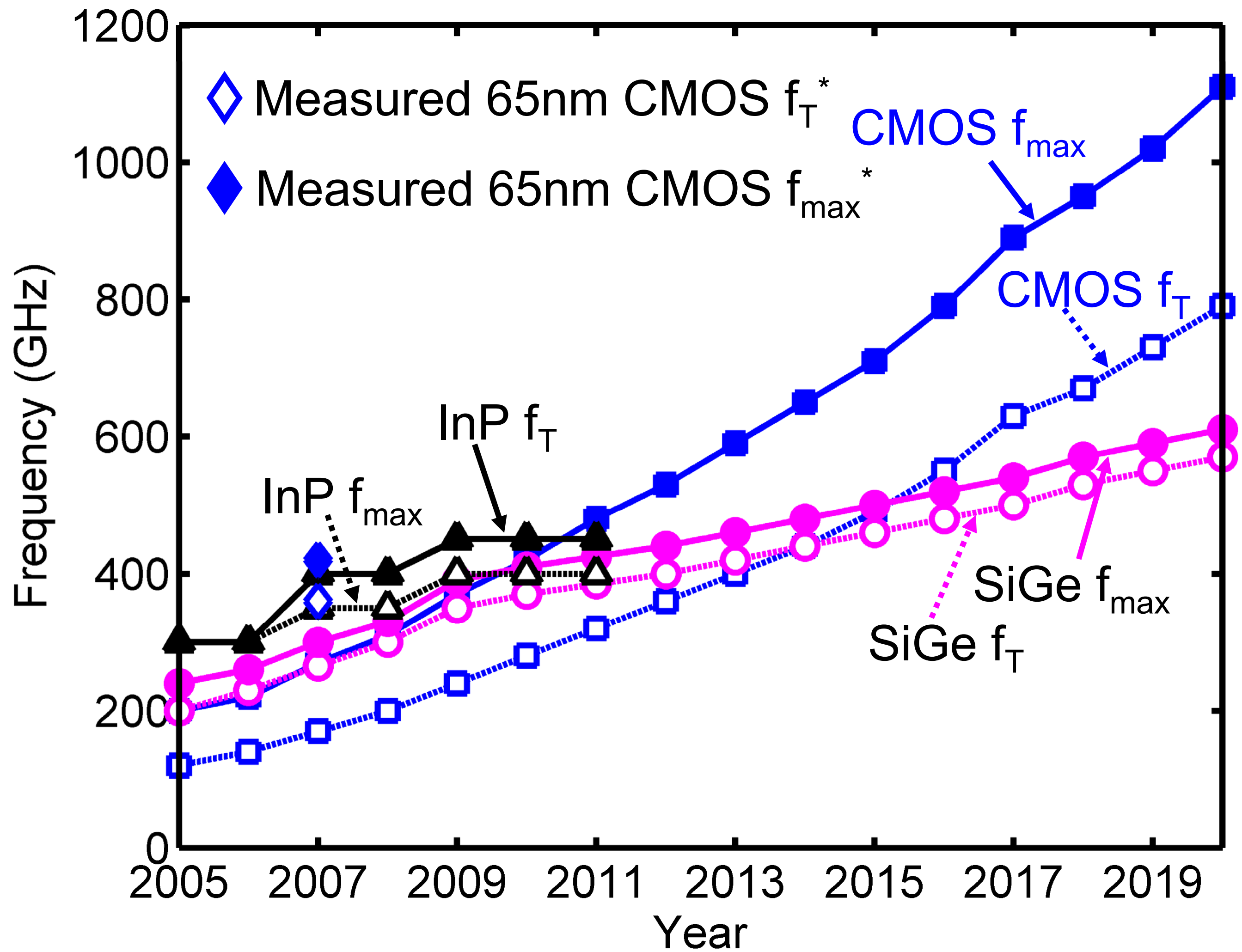


Summary



Process	Freq (GHz)	P_{out} (dBm)	VCO	Ref
SiGe HBT	278	-20	Push-push	IMS 2007
35-nm InP HEMT	346	-16	Fundamental	MWC 2007
45-nm CMOS	**410**	**-49**	**Push-push**	**This Work**

Summary



2006 ITRS roadmap & IEDM 2006*

Conclusions

- A 410-GHz push–push oscillator with an on-chip patch antenna fabricated using low leakage transistors of a 45-nm CMOS process with 6 metal layers is demonstrated.
- Using an FTIR system, the spectrum and power of the 410-GHz signals are measured.
- Presently output power is low.
- This work suggests the possibility of CMOS THz circuits.