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SESSION 17
TX and RX Building Blocks

Rapid and Energy-Efficient Molecular Sensing Using Dual mm-Wave Combs in 65nm CMOS:

A 220-to-320GHz Spectrometer with 5.2mW Radiated Power and 14.6-to-19.5dB Noise Figure

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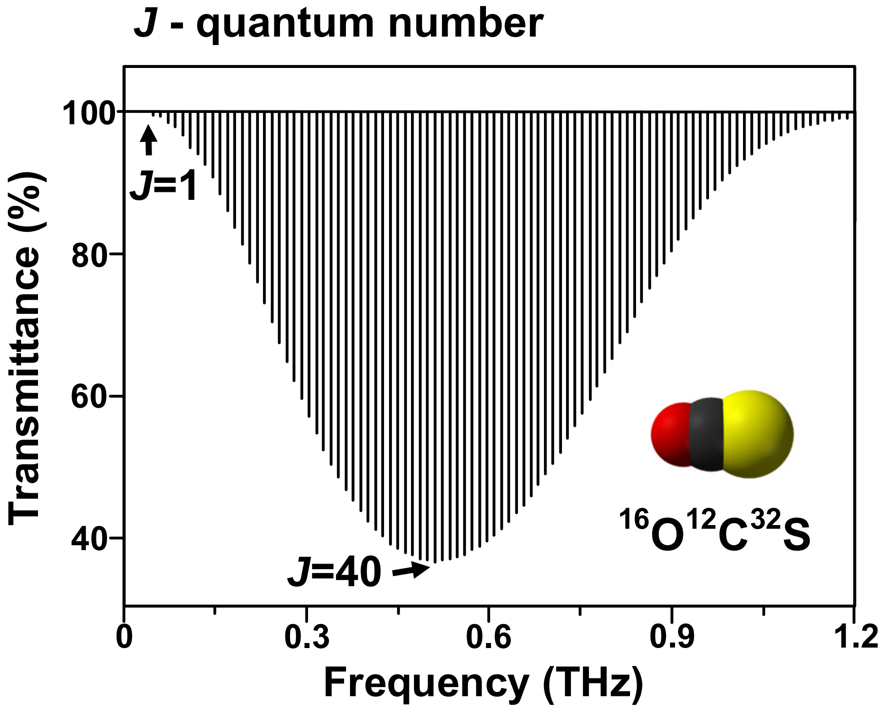
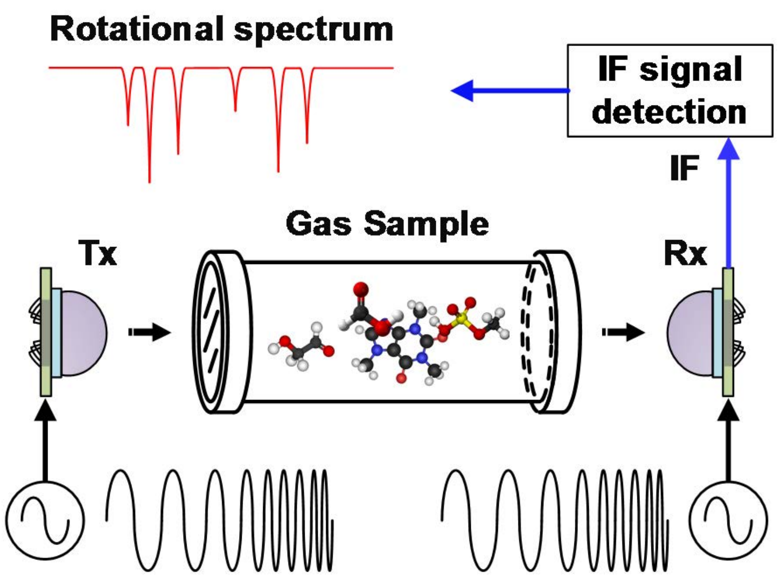
Outline

- Background
- Dual-Frequency-Comb Spectroscopy
- Architecture and Circuit Design
- Measurement Results
- Conclusions

mm-Wave/THz Rotational Spectroscopy





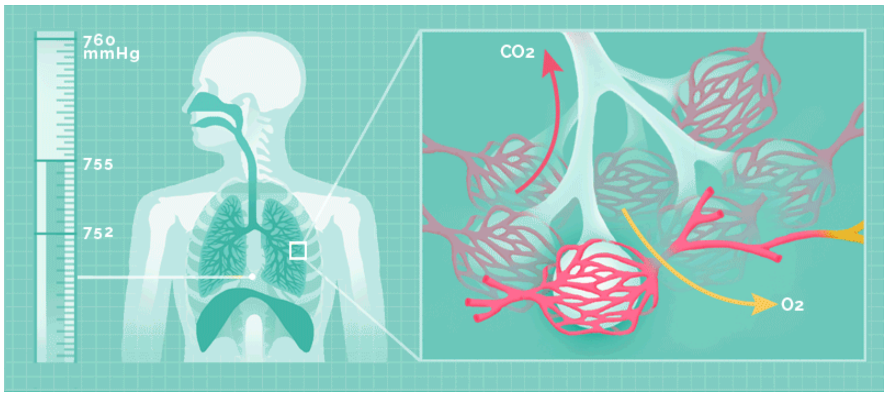
Peak absorption intensity at mmW/sub-THz band

Detection of rotational spectral lines using EM wave

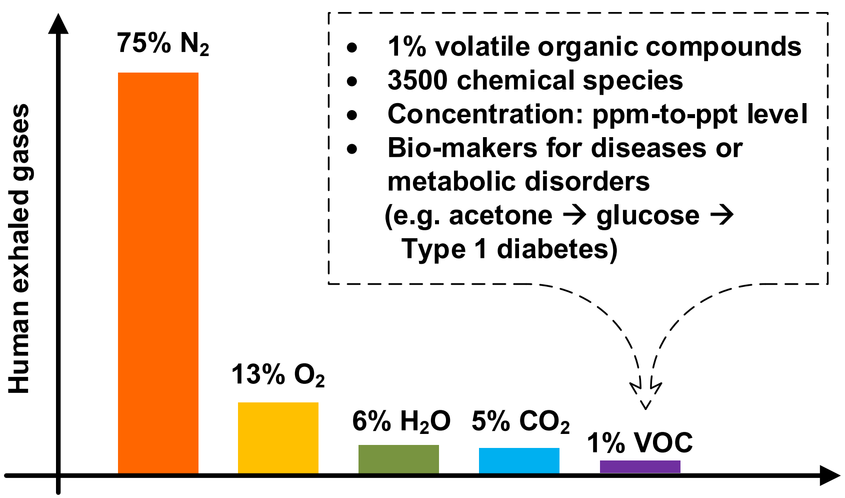
- **Rotation of polar molecules leads to absorption spectrum**
  - Maximum absorption in mmW/lower-THz range
  - Sub-MHz Doppler-limited linewidth → high selectivity

Portable Molecular Sensor: Applications

- **Human breath analyzer for biomedical diagnosis**



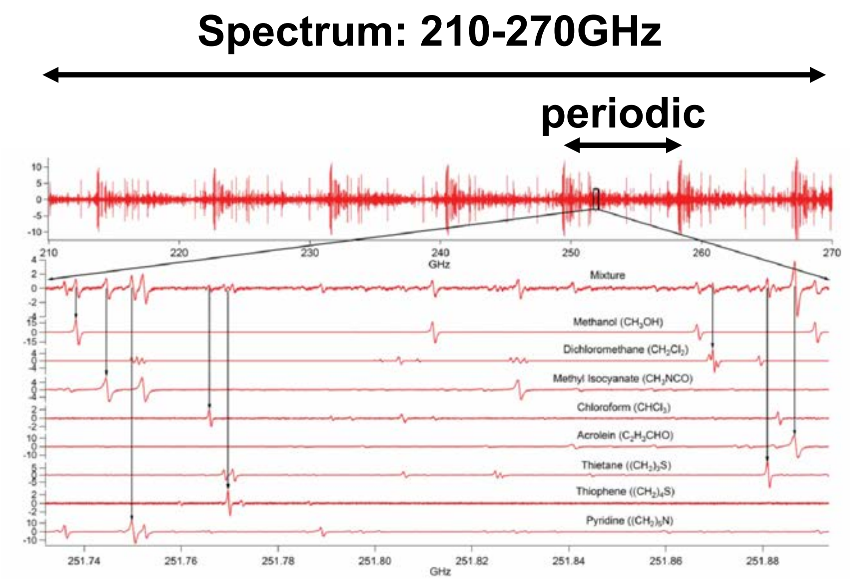
[tabletopwhale.com]



- **Environment monitoring for toxic gas leakage**
  - Sensor network
  - UAV platform

[www.dji.com]

Challenges of Chip-Scale Spectrometer



[C. F. Neese, IEEE Sensors Journal, 2012]

Molecule	Frequency (GHz)	Toxic?	Flammable ?
Carbon Monoxide (CO)	230.538001	Y	Y
Sulfur Dioxide (SO_2)	251.199668		
Hydrogen Cyanide (HCN)	265.886441		Y
Hydrogen Sulfide (H_2S)	300.511959		Y
Nitric Oxide (NO)	250.436966	Y	
Nitrogen Dioxide (NO_2)	292.987169	Y	
Nitric Acid (HNO_3)	256.657731	Y	
Ammonia (NH3)	208.145904	Y	
Carbonyl Sulfide (OCS)	231.060989	Y	Y
Ethylene Oxide (C_2H_4O)	263.292515	Y	
Acrolein (C_3H_4O)	267.279359	Y	
Methyl Mercaptan (CH_3SH)	227.564672	Y	
Methyl Isocyanate (CH_3NCO)	269.788609	Y	
Methyl Chloride (CH_3Cl)	239.187523	Y	Y
Methanol (CH_3OH)	250.507156	Y	Y
Acetone (CH_3COCH_3)	259.6184	Y	Y
Acrylonitrile (C_2H_3CN)	265.935603	Y	Y

[Source: HITRAN.org]

- **High selectivity**
  - Wideband(100GHz), high resolution(10kHz) spectrometer
- **High sensitivity, fast scanning**
  - High radiated power (below saturation), low noise detection
- **High energy efficiency**

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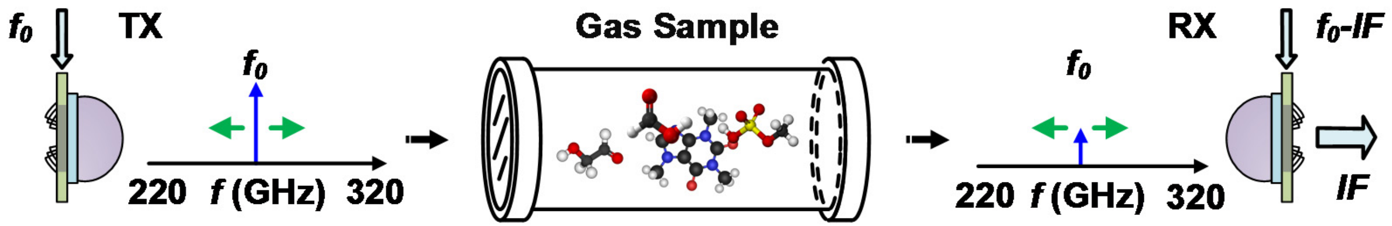
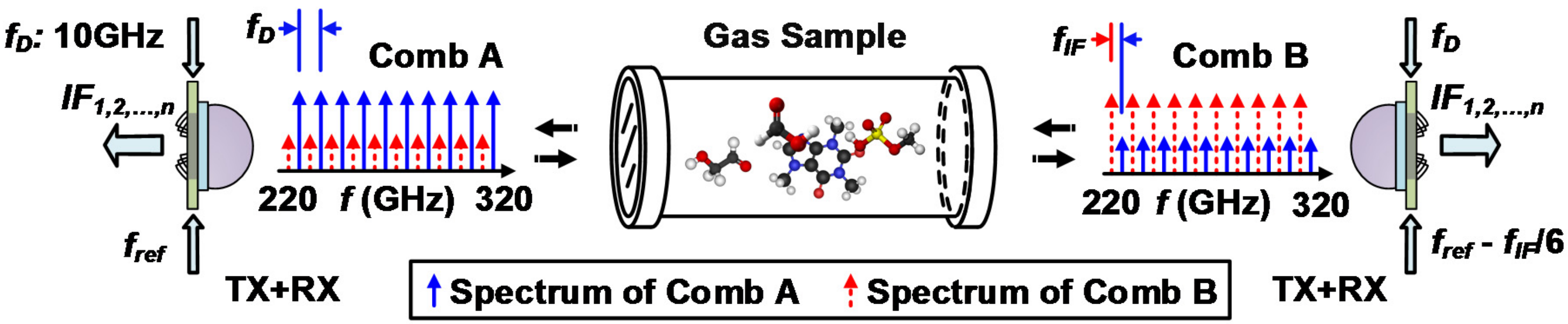
Dual-Frequency-Comb Spectroscopy

Conventional single-tone spectroscopy



- Single frequency sweep (e.g. ~3 hours for 100GHz bandwidth, τ_{int}=1ms)

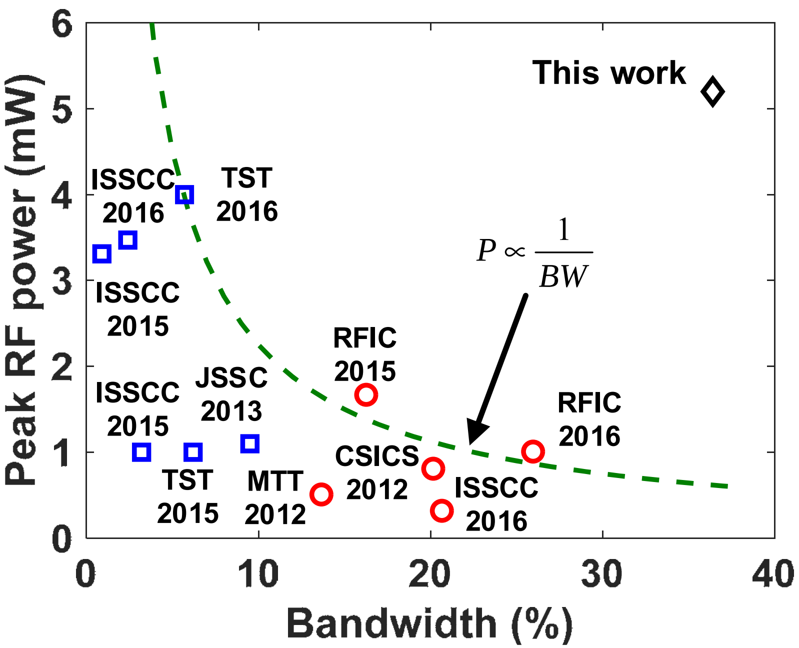
Dual-frequency-comb spectroscopy



- Simultaneous scanning using 20 comb lines (8 minutes for 100GHz bandwidth, τ_{int}=1ms)

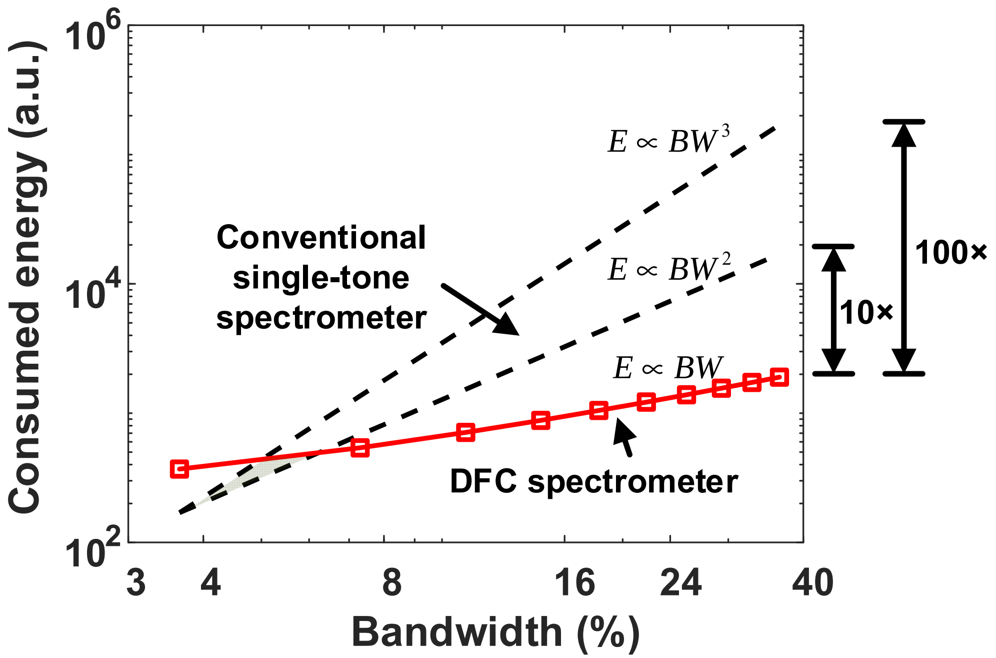
Energy Efficiency Improvement

Radiated power of silicon-based sources above 200GHz



Radiated — On-wafer measured with an assumed 50% radiation efficiency

Total energy consumption for full-band scanning



- **Dual frequency combs (DFC) scheme breaks the conventional efficiency-bandwidth tradeoff using parallelism**
- **Linear scalability between bandwidth and energy consumption**

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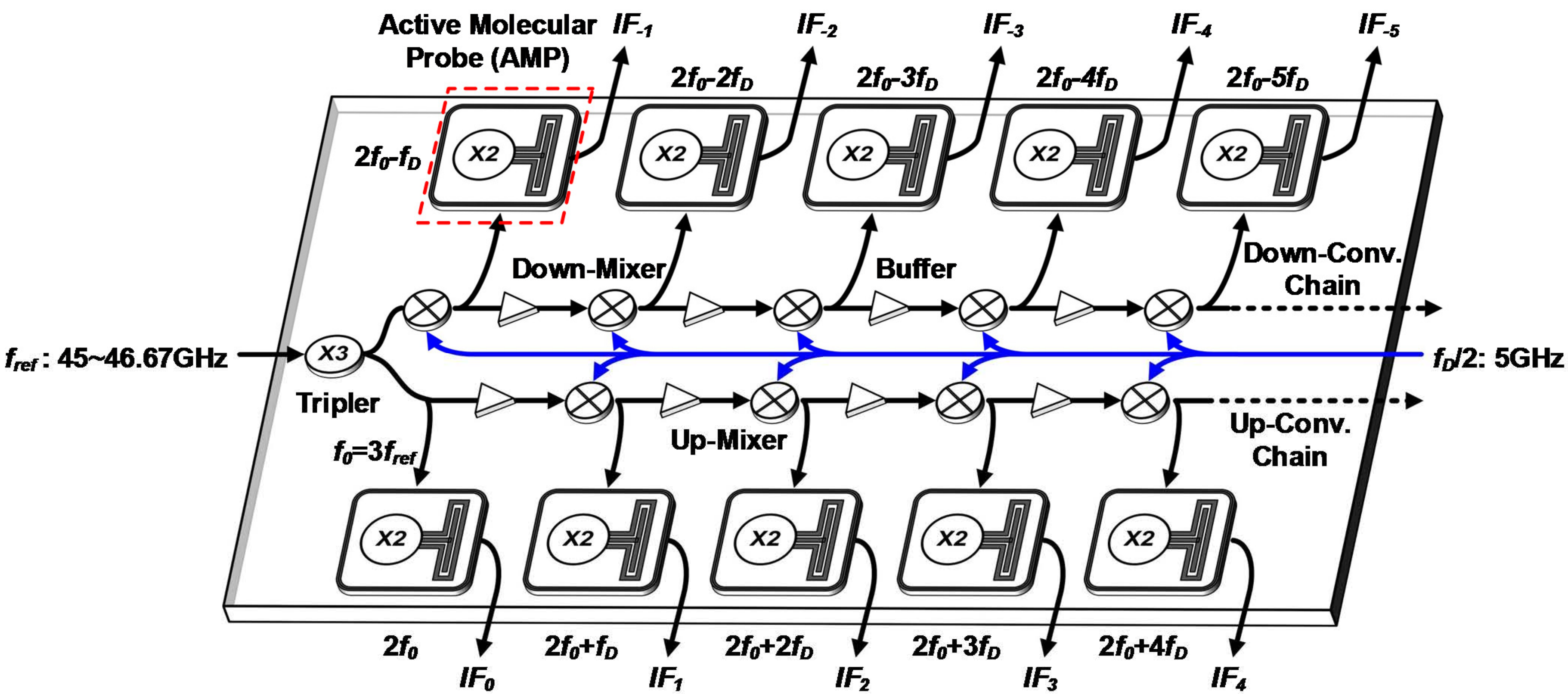
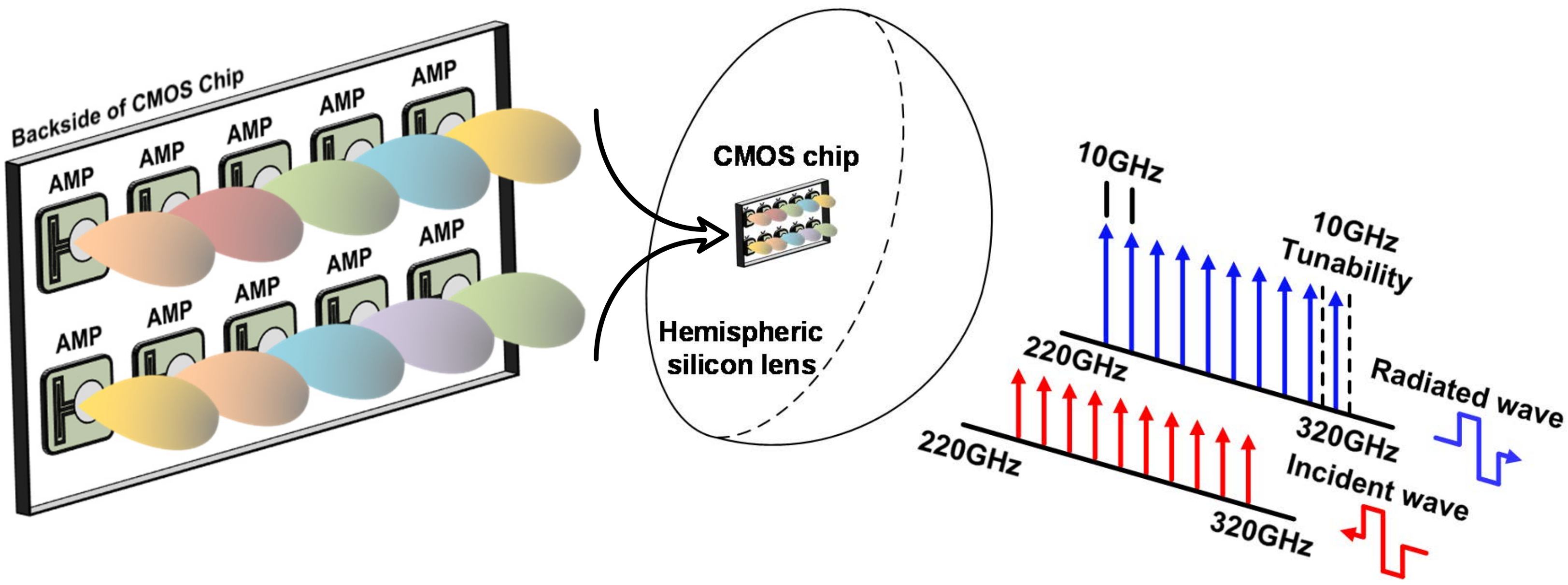
Architecture of A 220-to-320GHz Comb



- **Tunable transceiver: 10 active molecular probes (AMP)**
  - Seamless coverage of 100GHz bandwidth
  - Simultaneous transmit and receive → ~2x higher efficiency

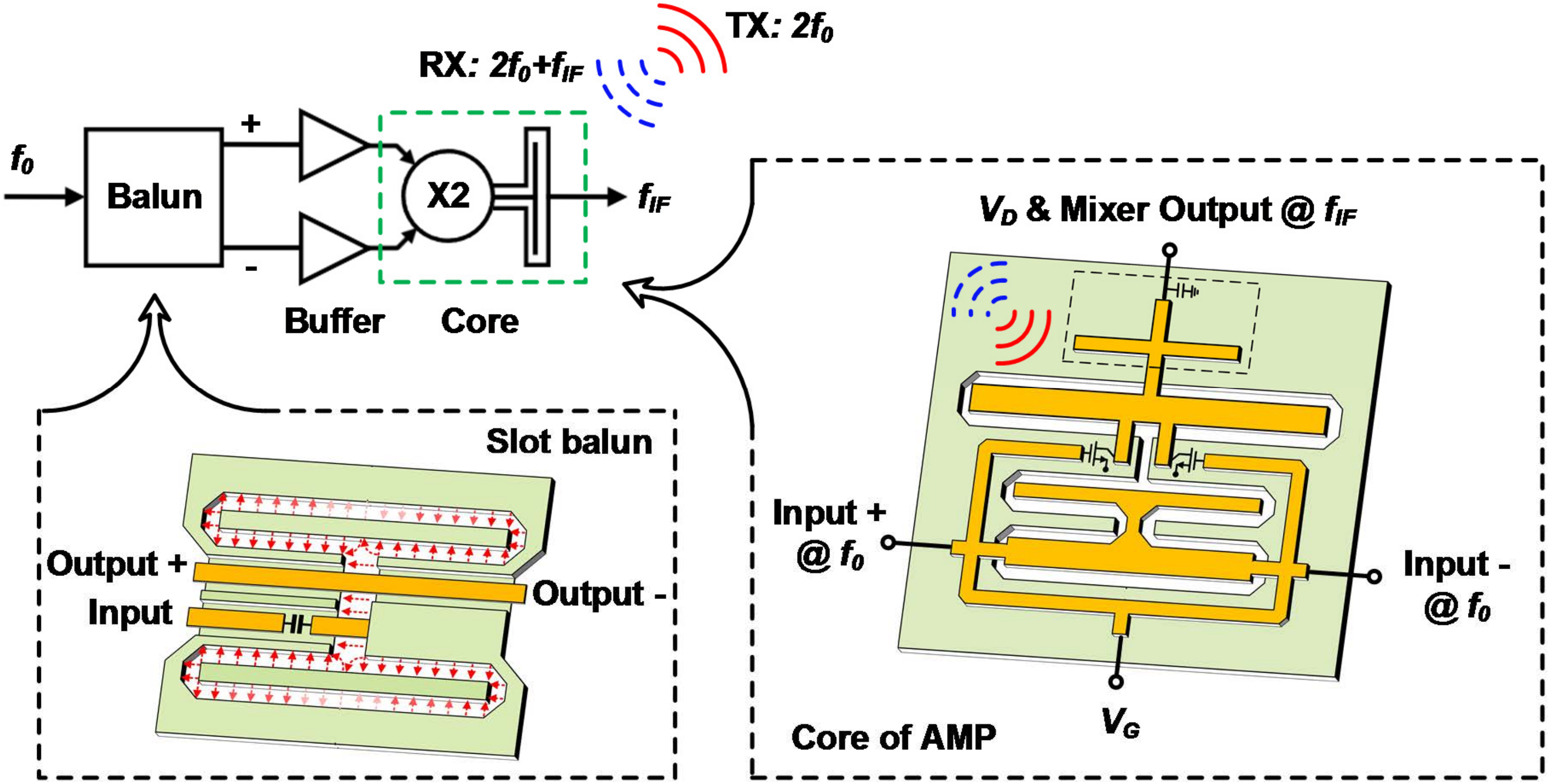
Distributed Comb-Spectral Radiation

- **On-chip backside radiation through 10 radiators**
  - Improved antenna efficiency by narrowband operation
- **High-resistivity hemispheric silicon lens is used**
  - Lower sensitivity to the radiator offset from the center (compared to hyper-hemispheric lens)
  - No additional beam collimation



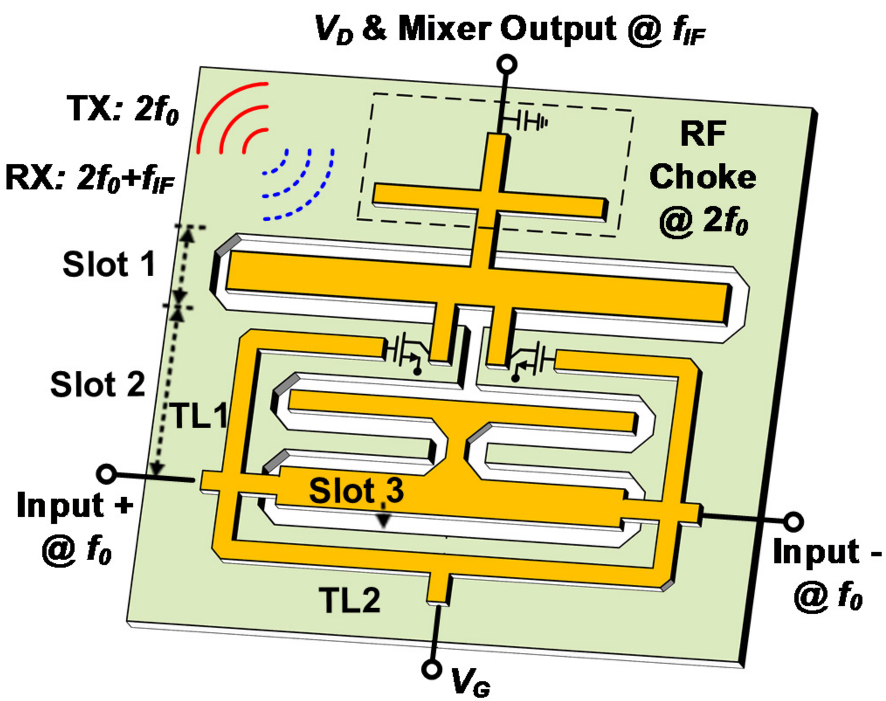
Active Molecular Probe (AMP)

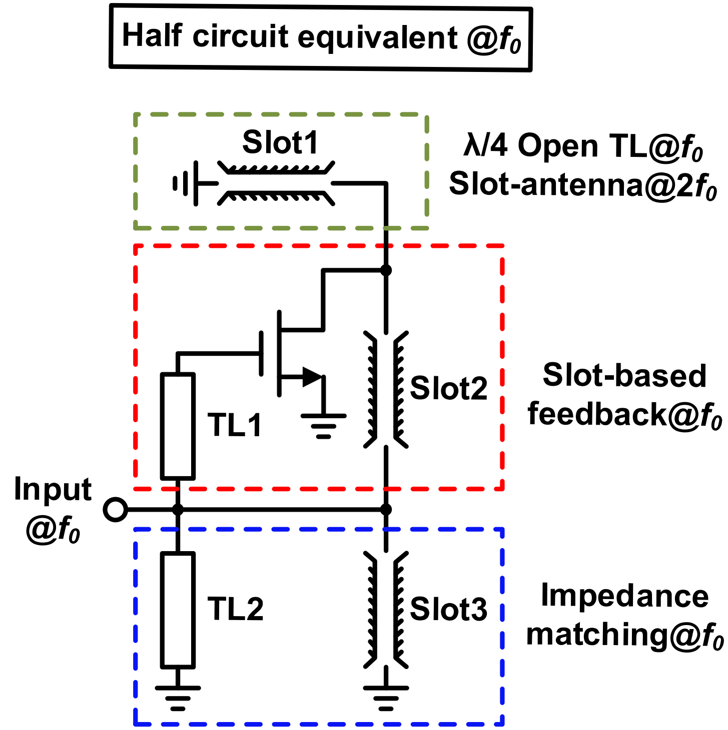
- **Multi-functional module simultaneously performs**
  - Highly-efficient frequency doubling
  - Low-noise heterodyne sub-harmonic down mixing
  - Efficient antenna for input/output radiation waves



AMP TX Mode: Frequency Doubling

- **Conditions for high conversion efficiency**
  - Maximum device power gain at fundamental frequency (f_0)
  - Minimum loss at $2f_0$ (e.g. harmonic feedback to the lossy gates)
  - Instantaneous signal radiation at $2f_0$

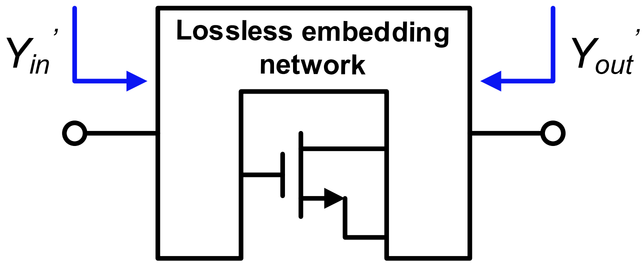




Maximum Device Power Gain G_{max}

- **Upper limit of matched power gain G_{max} depends on the unilateral gain U**

$$G_{max} = \left(1+\sqrt{1-\frac{1}{U}}\right)^2$$

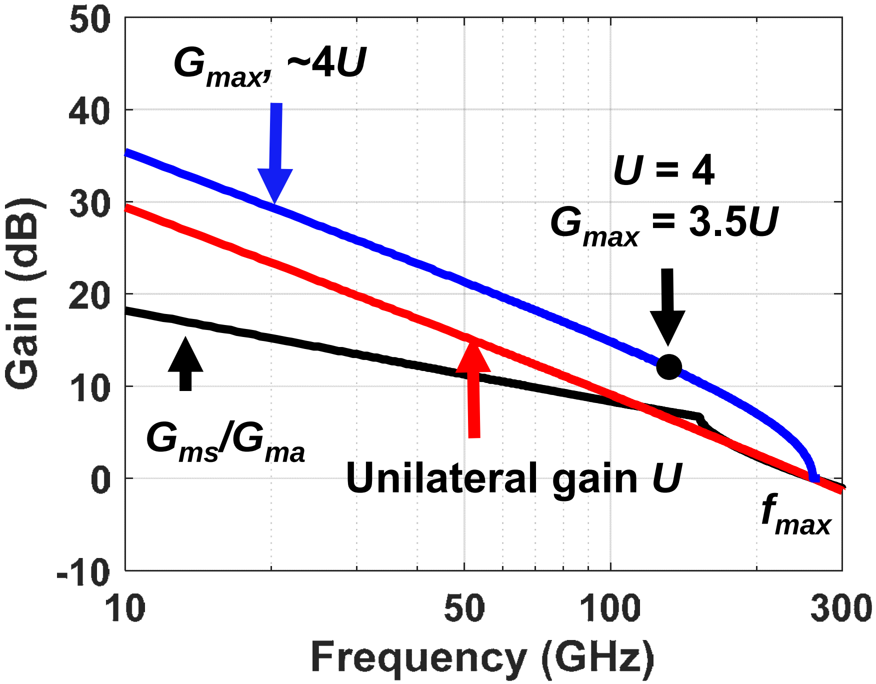


$$[Y] = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}$$

$$Y_{ij} = g_{ij} + j \cdot b_{ij}$$

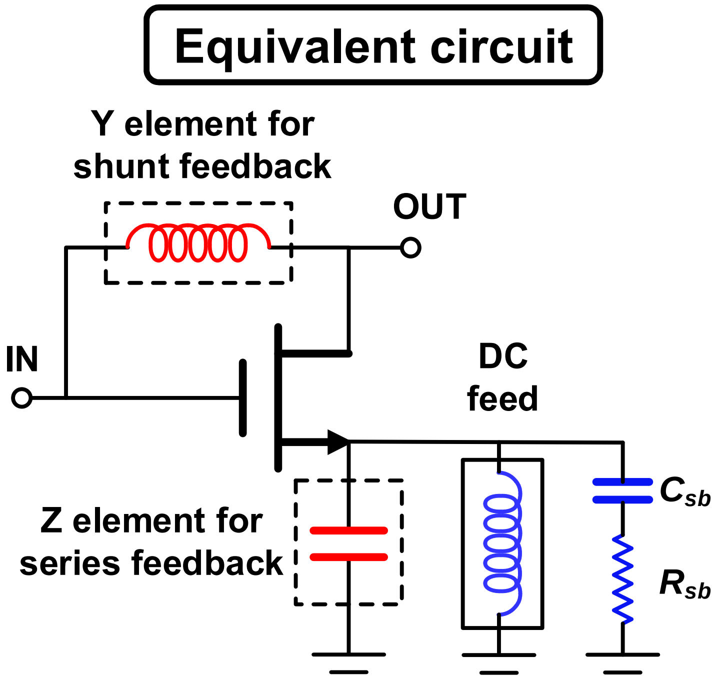
[R. Spence, Linear Active Networks 1968]

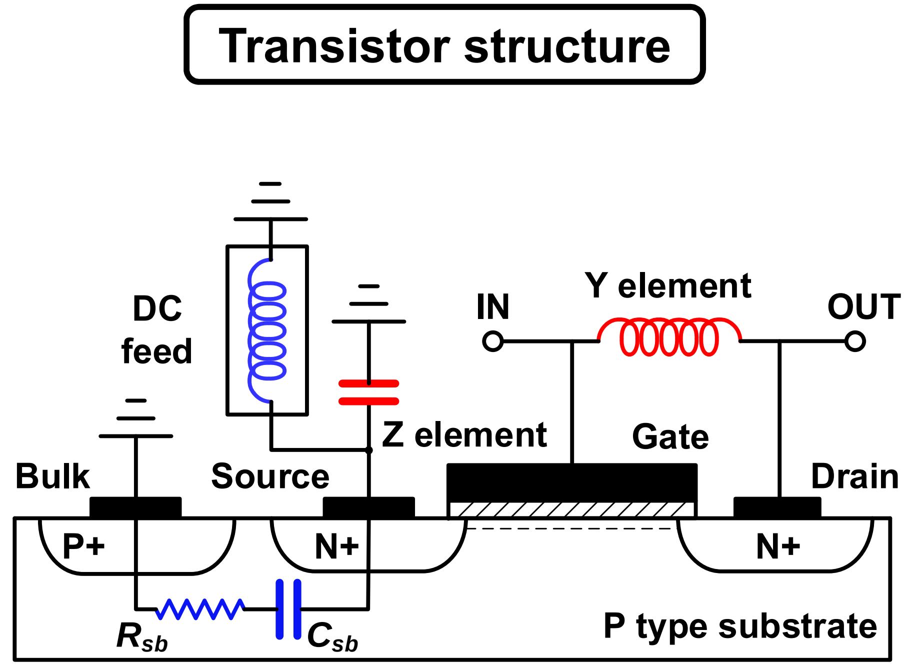
[O. Momeni, ISSCC 2013]



Simulation using 65nm bulk CMOS process

Conventional YZ Embedding for G_{max}

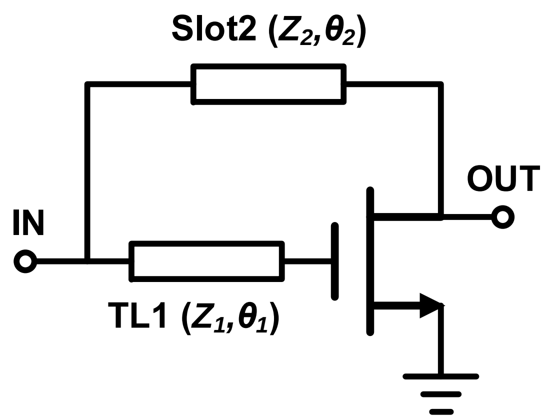




[R. Spence, Linear Active Networks 1968]

- **Issues of YZ embedding with lumped elements**
  - Loss from DC feed to bypass source current
  - Loss from parasitic resistor associated with the source
  - Impractical large inductor for Y element due to distributed effect in high frequency

Dual-transmission-line (DTL) Feedback



Equations for feedback parameter calculation:

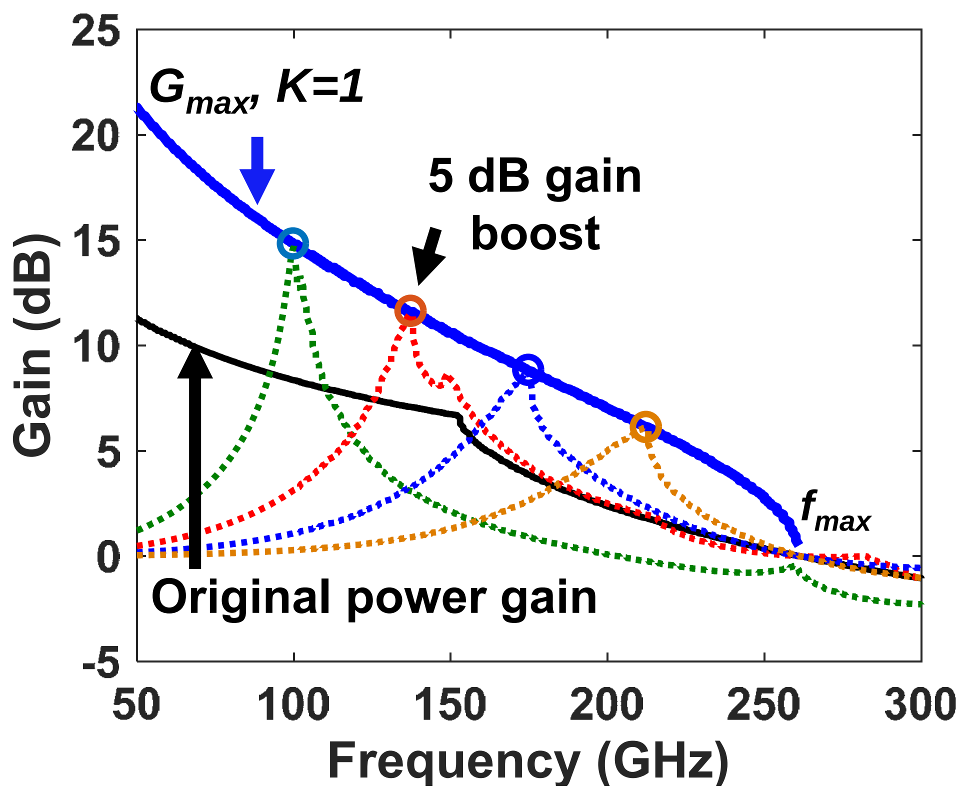
$$\begin{cases} \tan\theta_1 = \dfrac{1}{Z_1} \cdot \dfrac{1}{b_{11} - g_{11} \dfrac{mUb_{12} - b_{21}}{mUg_{12} - g_{21}}} \\ \sin\theta_2 = \dfrac{1}{Z_2} \cdot \dfrac{g_{11} Z_1 \sin\theta_1 (mU - 1)}{mUg_{12} - g_{21}} \end{cases}$$

where

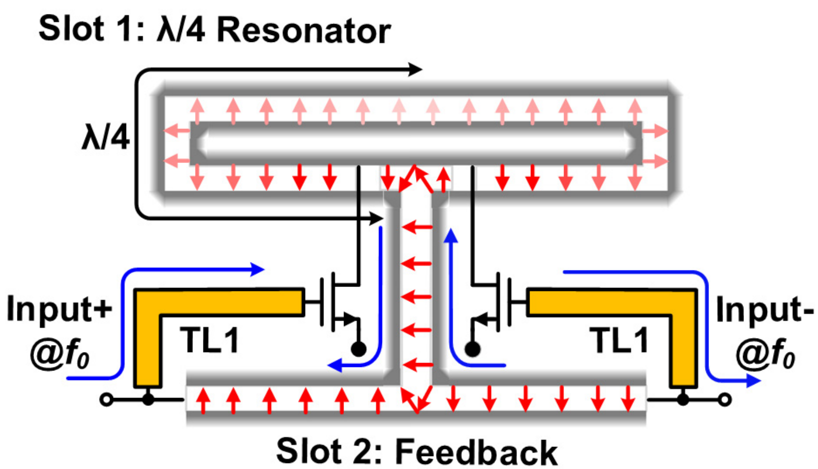
$$m = \frac{\left(1+\sqrt{1-\frac{1}{U}}\right)\left(U+\sqrt{U^2-U}-1\right)}{-\sqrt{U^2-U}}$$

- **Adopt distributed feedback elements**
- **Ground the source of transistor**
- **Achieve G_{max} accurately**

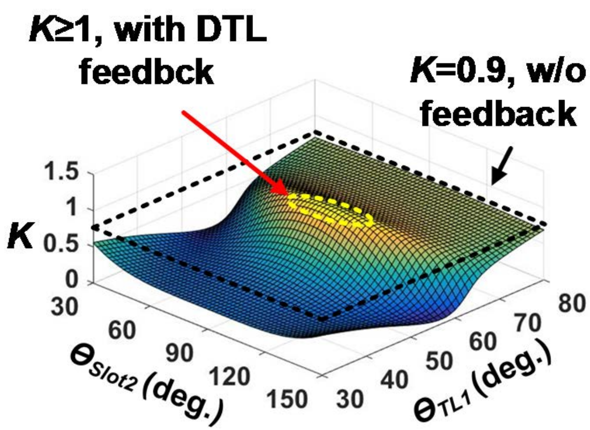
Simulation using 65nm CMOS process



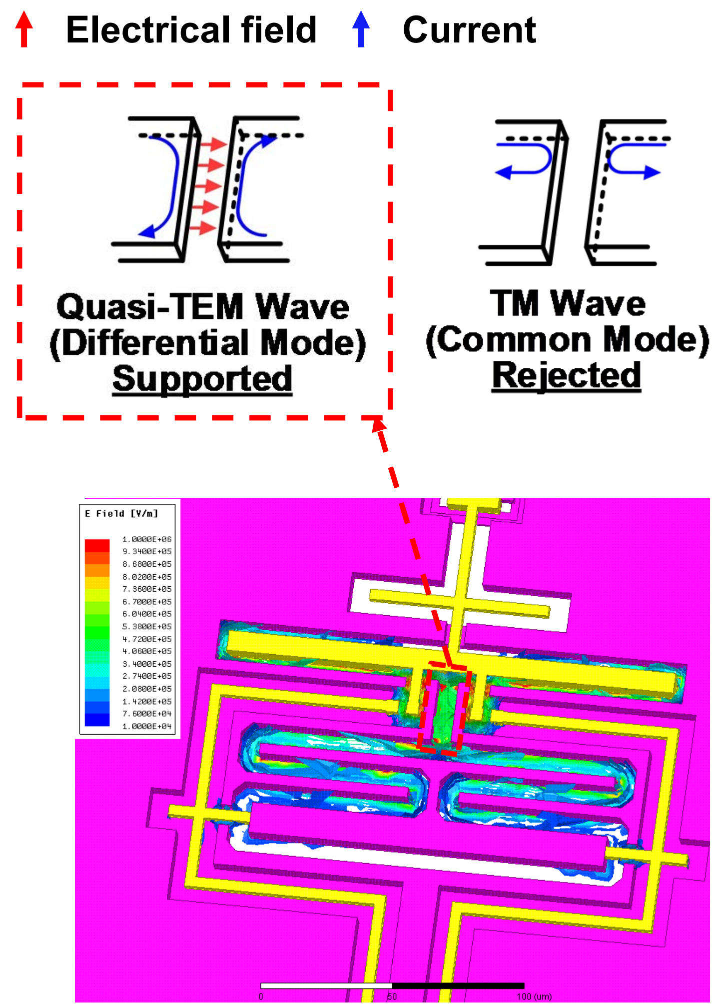
DTL Feedback Based on Slot Line @f_0



Feedback through Slot 2

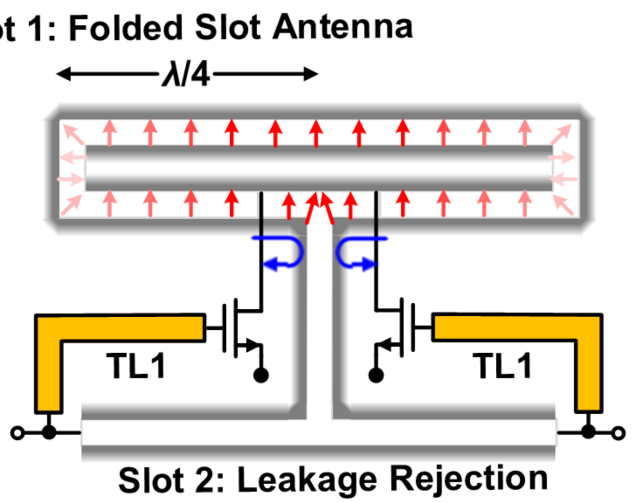


Simulated stability factor, *K*

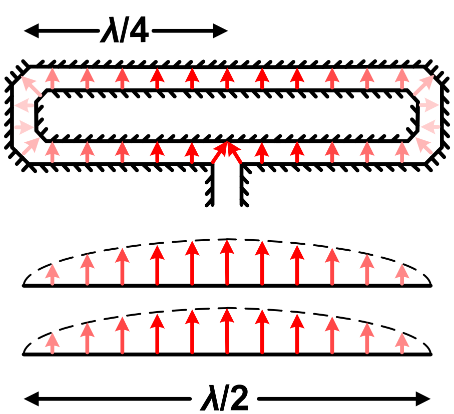


E-field distribution @ f_0

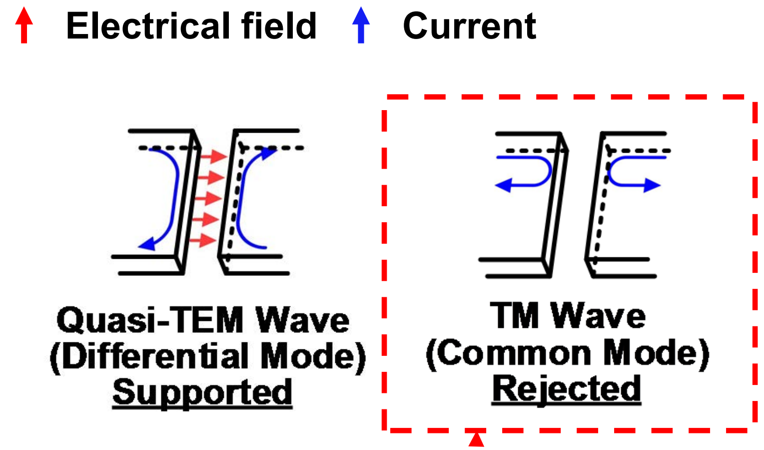
Loss Minimization and Radiation @$2f_0$

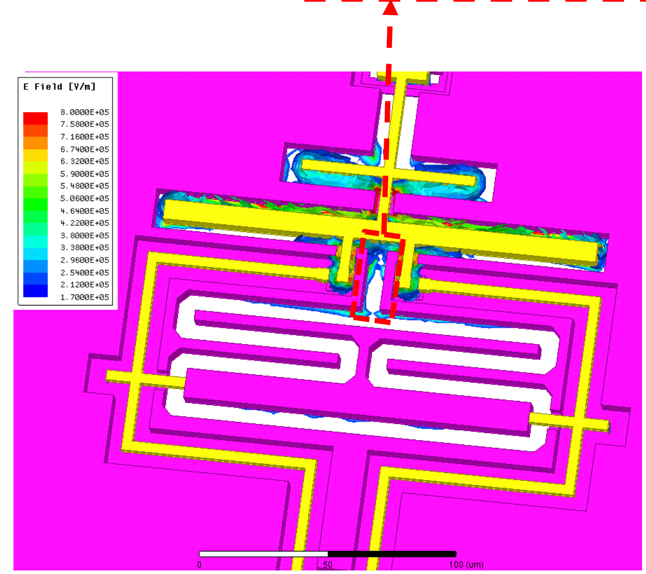


Harmonic signal isolation



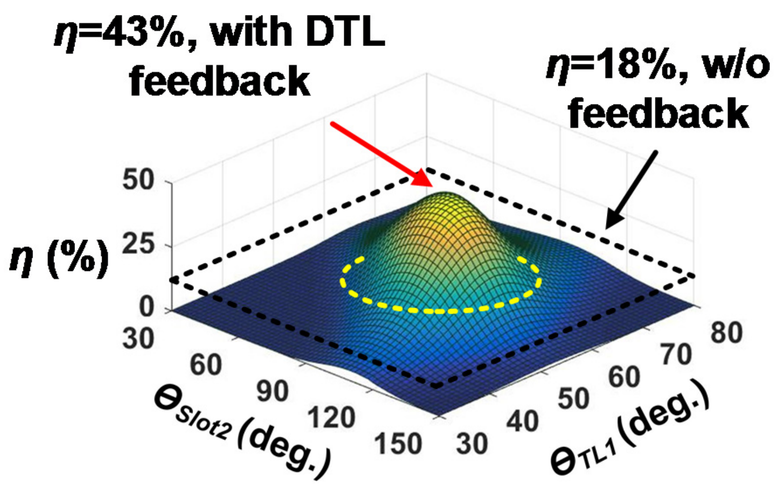
Folded-slot antenna

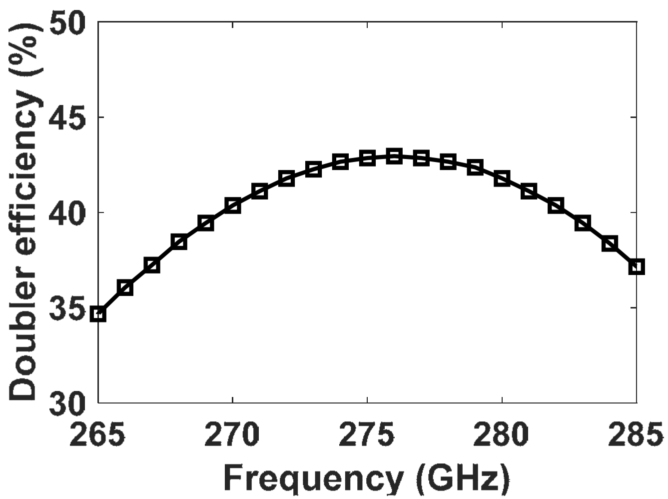




E-field distribution @ $2f_0$

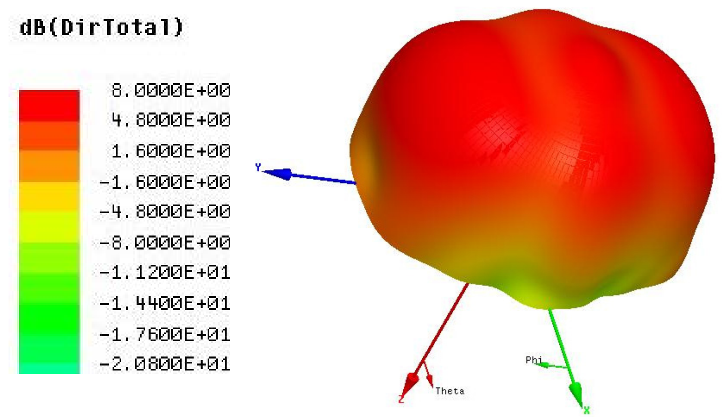
Simulation Results for Doubler at 275GHz





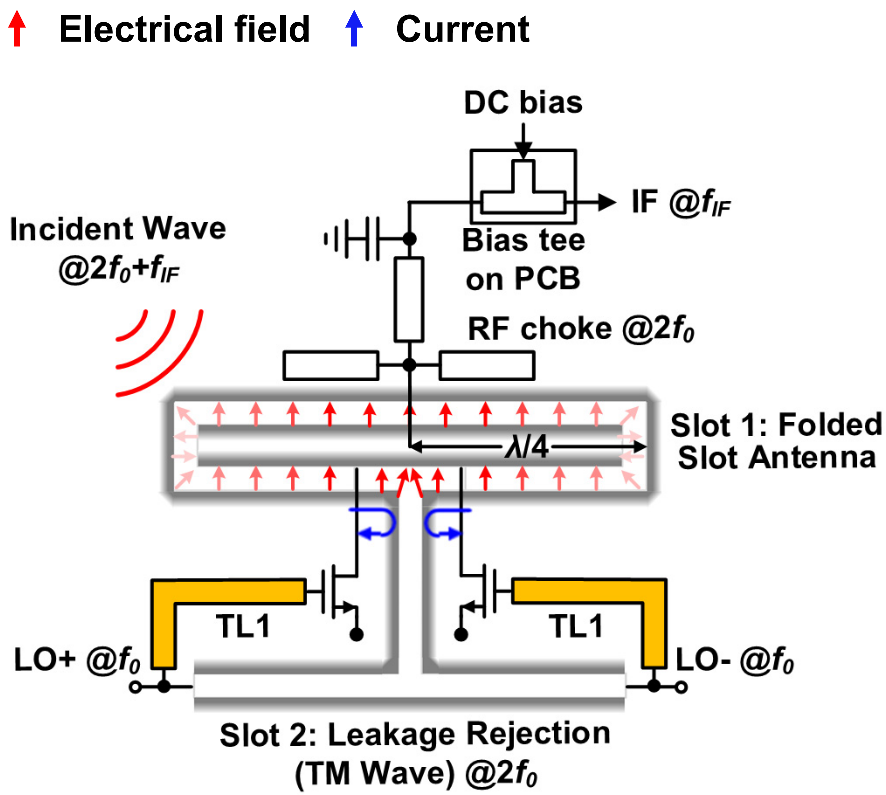
Doubler efficiency η (%)

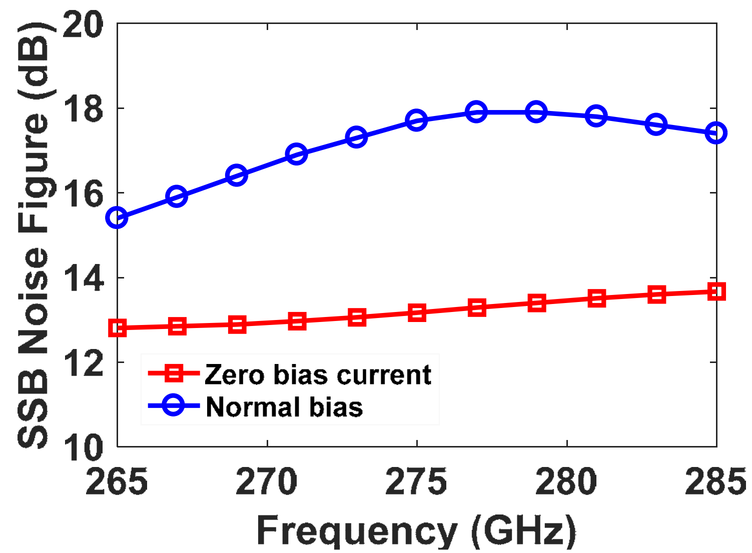
- 65nm bulk CMOS
- NMOS W/L=24µm/60nm
- Output power: 1.6mW
- Doubler efficiency: 43%
- Antenna efficiency: 45%



Antenna directivity

AMP RX Mode: Heterodyne Mixing



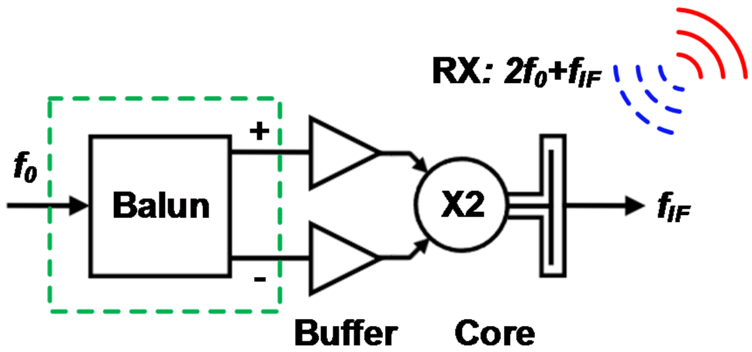


Simulated SSB noise figure

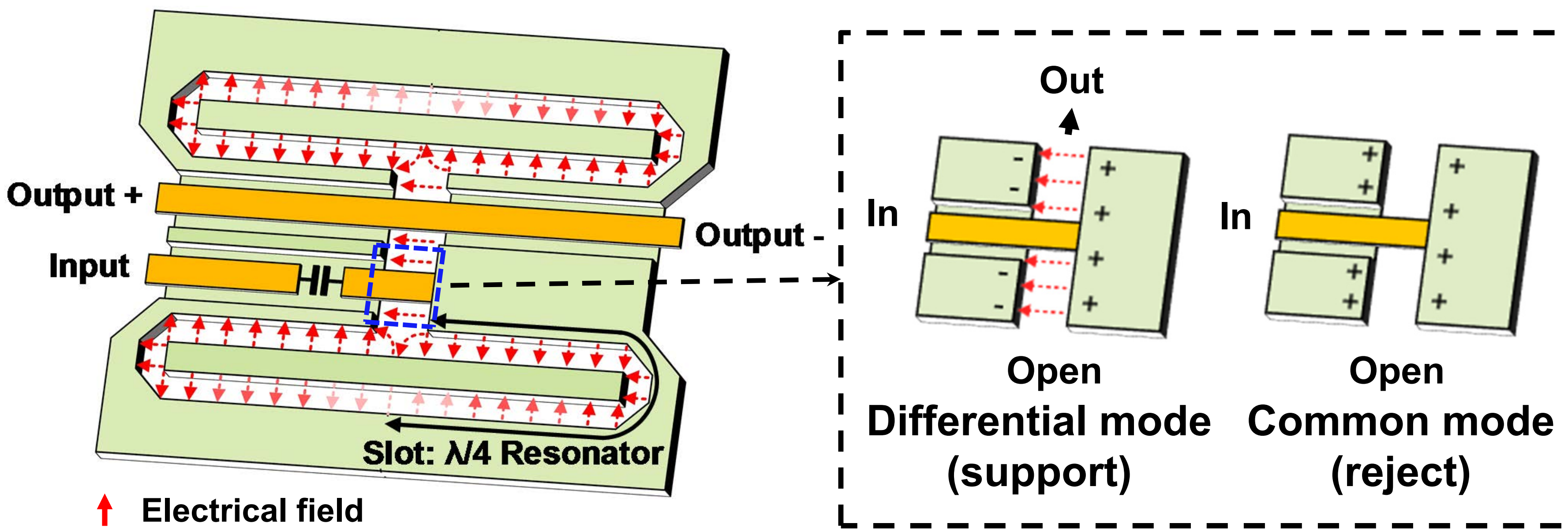
- Mixer LO signal is the same as the doubler input signal @f_0
- Further noise reduction: zero drain bias current
  → varistor mode mixing with reduced channel noise

Slot Balun with Orthogonal Mode Filtering

Active Molecular Probe (AMP)

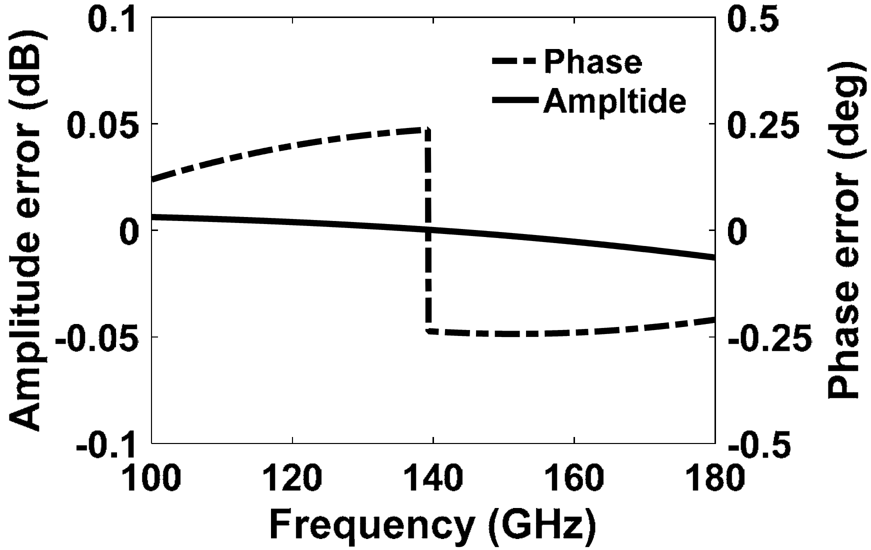


- **Amplitude and phase imbalance in conventional baluns causes**
  - Lower doubler efficiency
  - Higher LO signal radiation at f_0
- **Proposed slot balun**
  - Orthogonal mode filtering
  - Symmetric output coupling

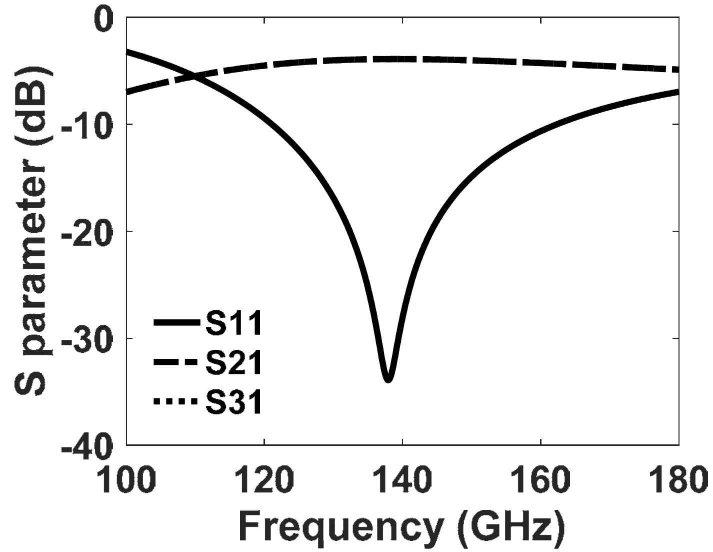


Slot Balun with Orthogonal Mode Filtering

Simulated amp. and phase error

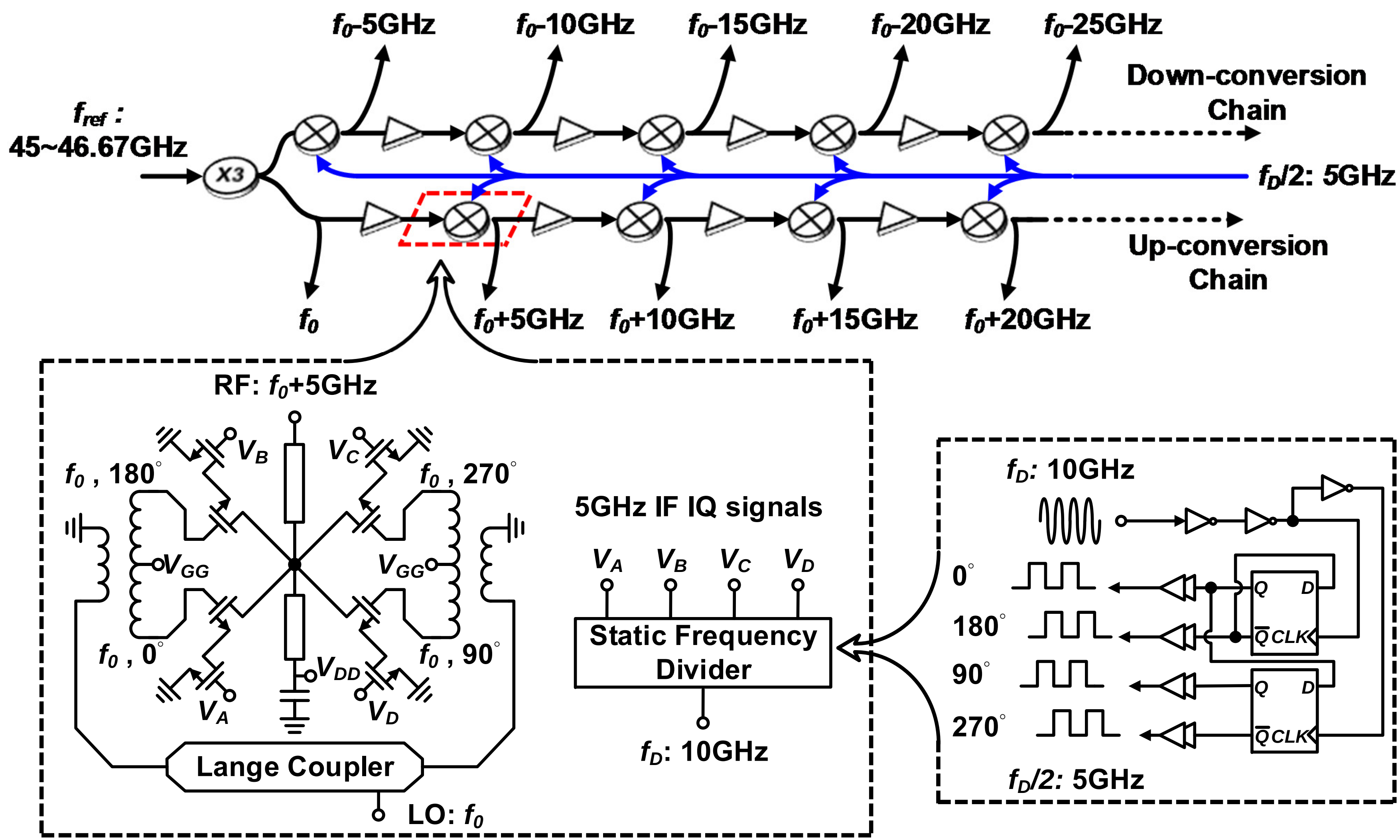


Simulated S-parameter



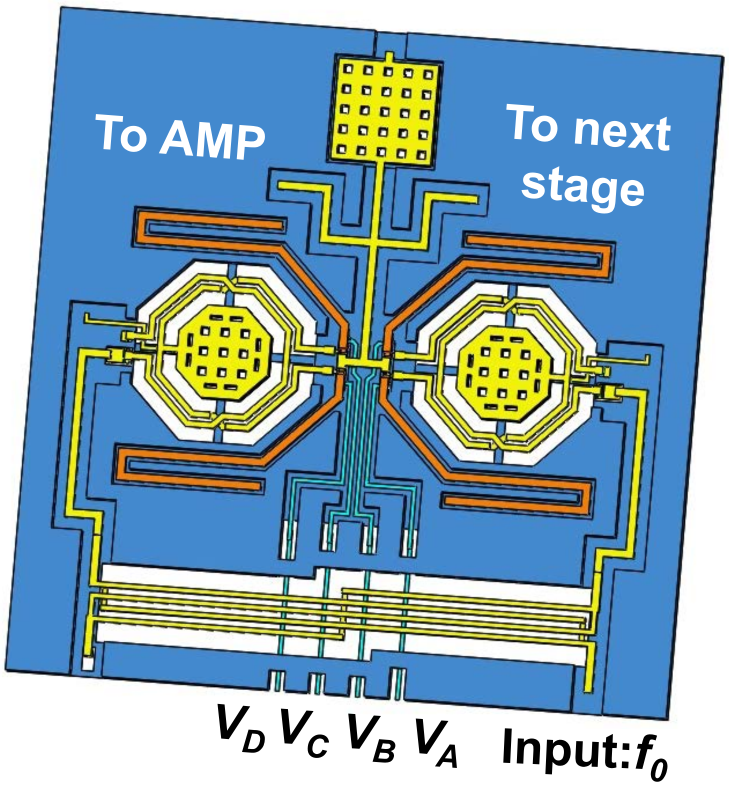
- Nearly perfect single-ended signal to differential signal conversion without errors
- Minimum insertion loss: 0.9 dB
- -10dB return loss bandwidth: 30%

Up/Down-Conversion Mixer

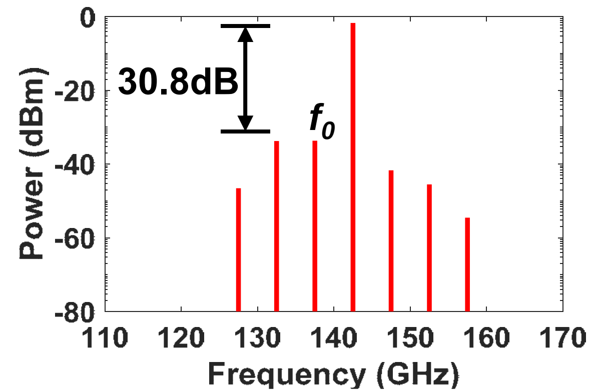


- **SSB mixers configured for up/down conversion chains**

Up/Down-Conversion Mixer

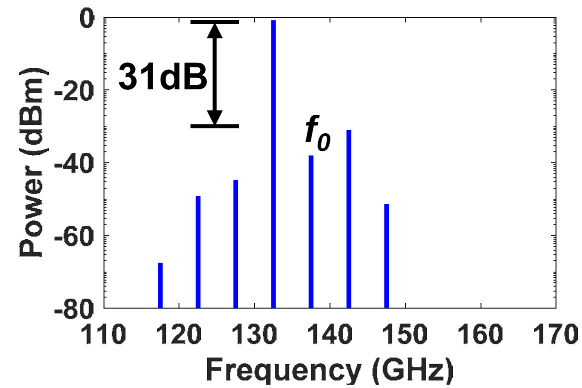


Phase(V_A,V_B,V_C,V_D)
=(0°,180°,90°,270°)



Up sideband conv.

Phase(V_A,V_B,V_C,V_D)
=(0°,180°,270°,90°)



Down sideband conv.

- IF phase configuration → up or down sideband selection
- Low conversion loss: 2.3 dB
- Rejection of image, LO and inter-modulation signals: >30dB

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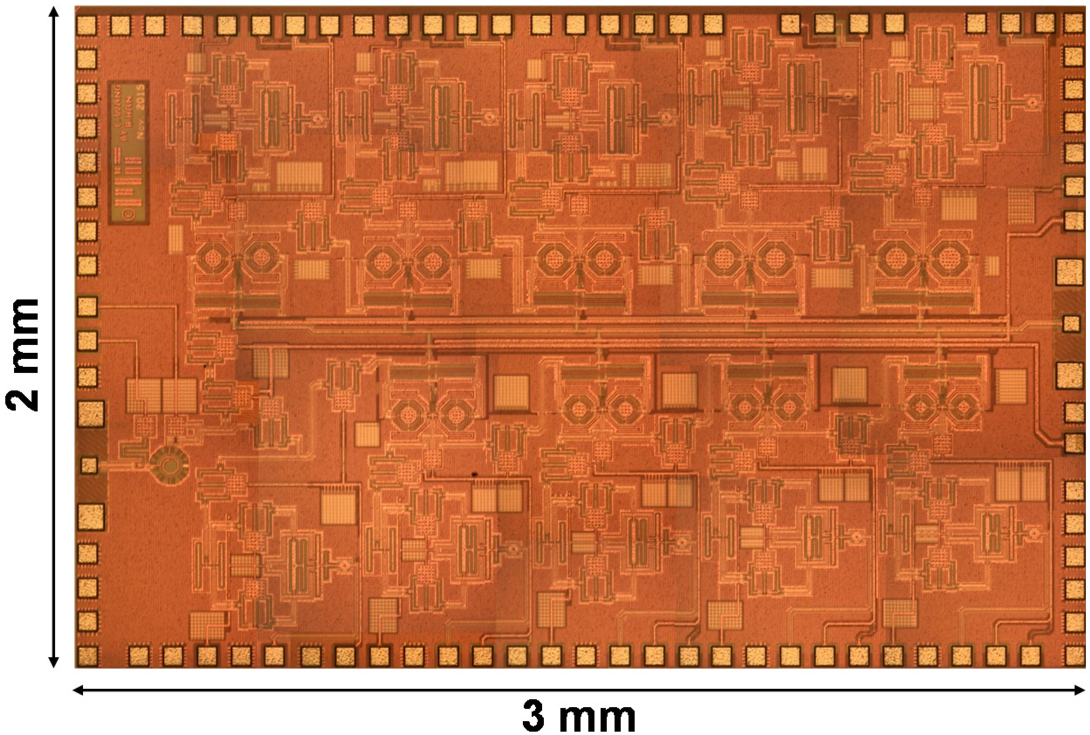
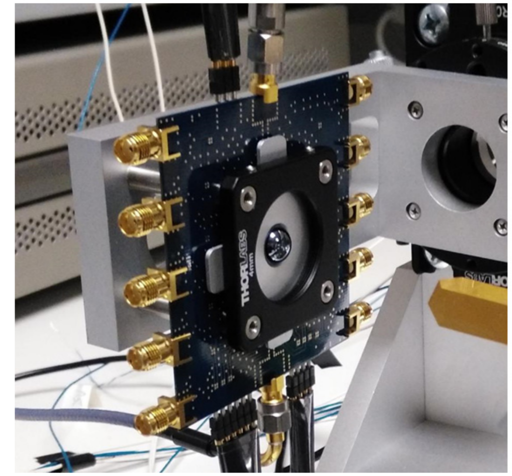
Chip Micrograph and Packaging

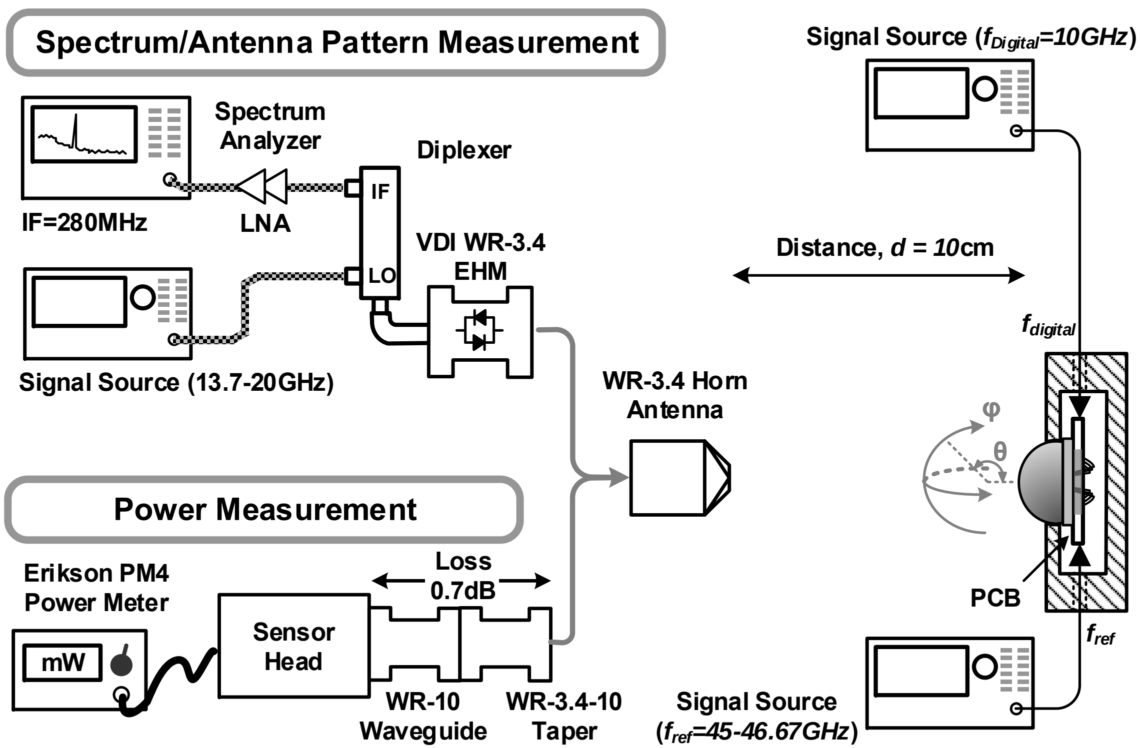


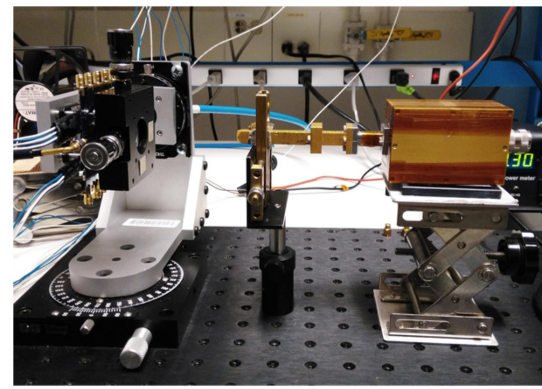


Chip bonded on PCB with hemispheric silicon lens

- **TSMC 65nm bulk CMOS process**
- **Chip area: 2mm × 3mm**
- **DC power consumption: 1.7W**

Measurement Setup of TX Mode

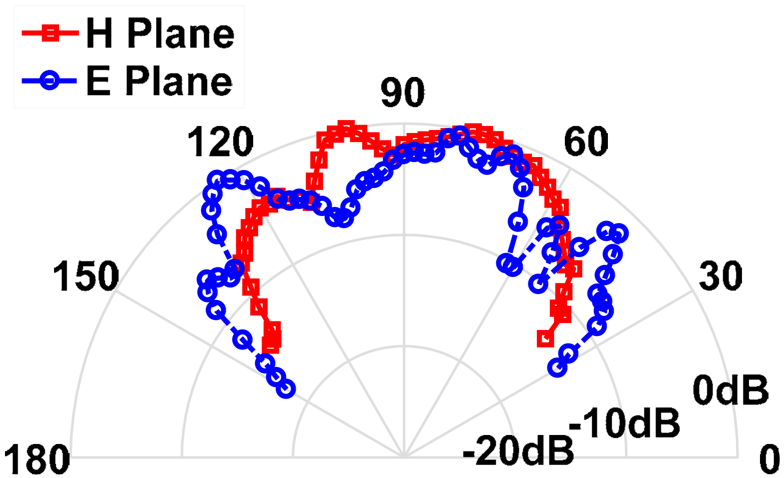




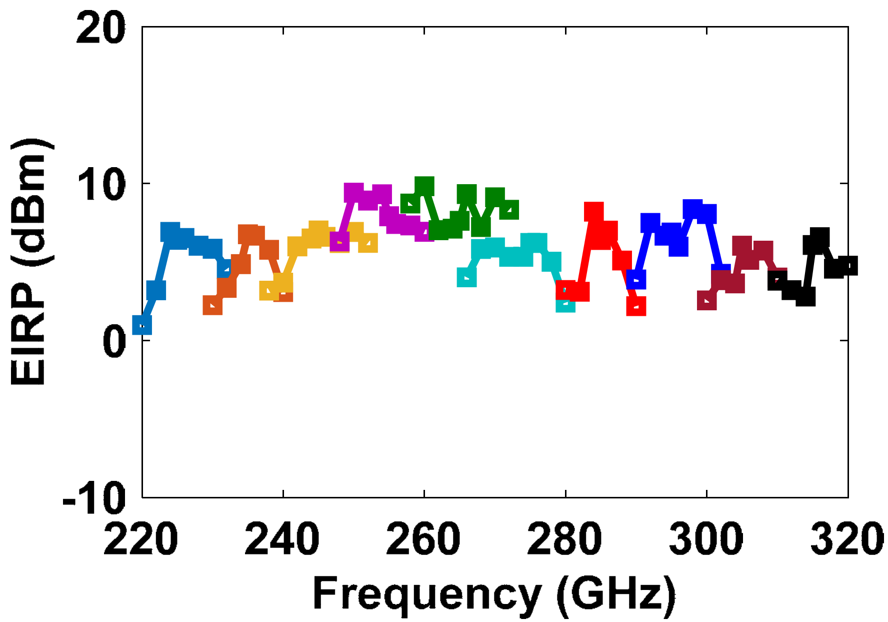
Power measurement using VDI Erickson PM-4 power meter

- For power measurement, only one AMP is turned on at each time

Measurement Results of TX Mode



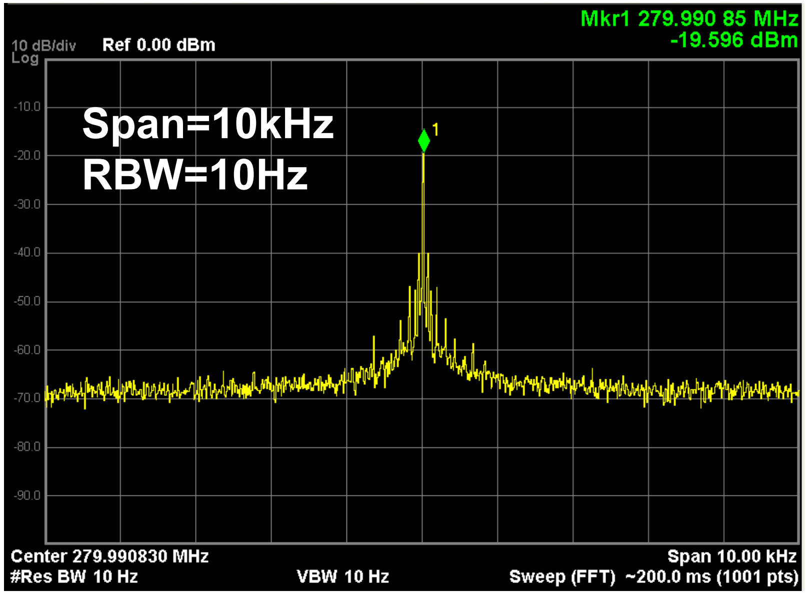
Antenna pattern of a comb line at 265GHz

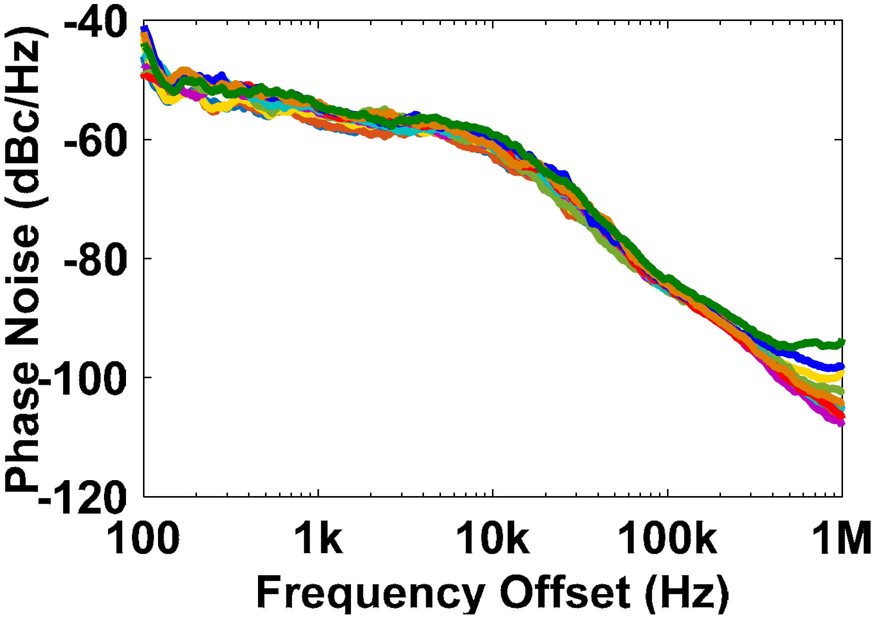


Equivalent isotropic radiated power (EIRP)

- Total radiated power of 10 comb lines: 5.2mW

Measurement Results of TX Mode



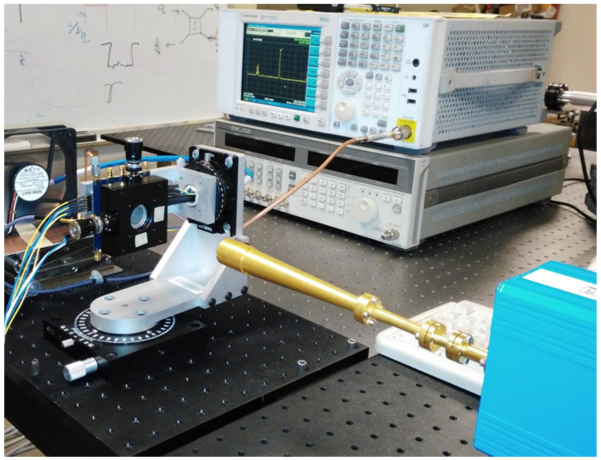


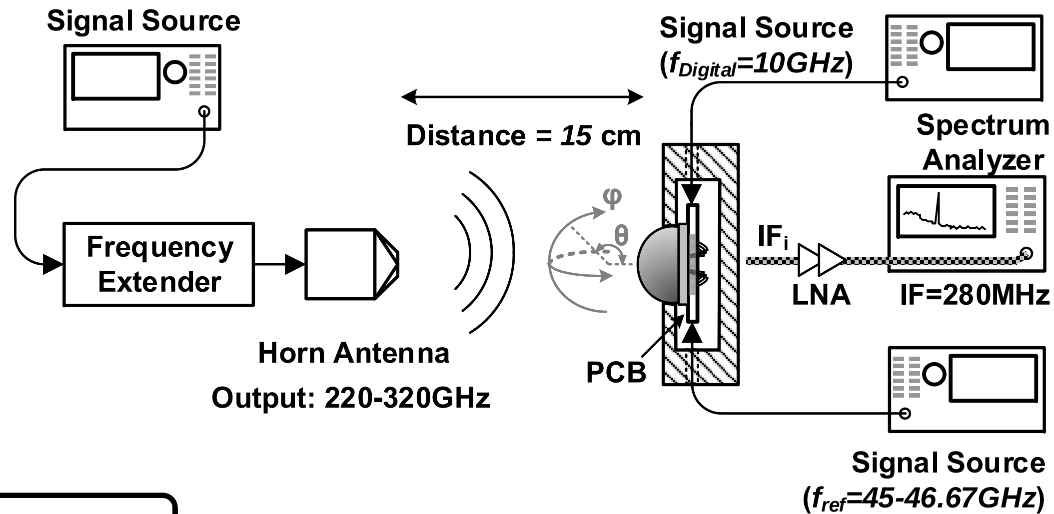
Spectrum of a comb line at 265GHz

Phase noise of 10 comb lines

- Average measured phase noise for 10 comb lines at 1MHz offset: -102dBc/Hz

Measurement Setup of RX Mode





Single-sideband conversion gain

$$CG = \frac{\text{IF output power}}{\text{Power received by RX antenna aperture}}$$

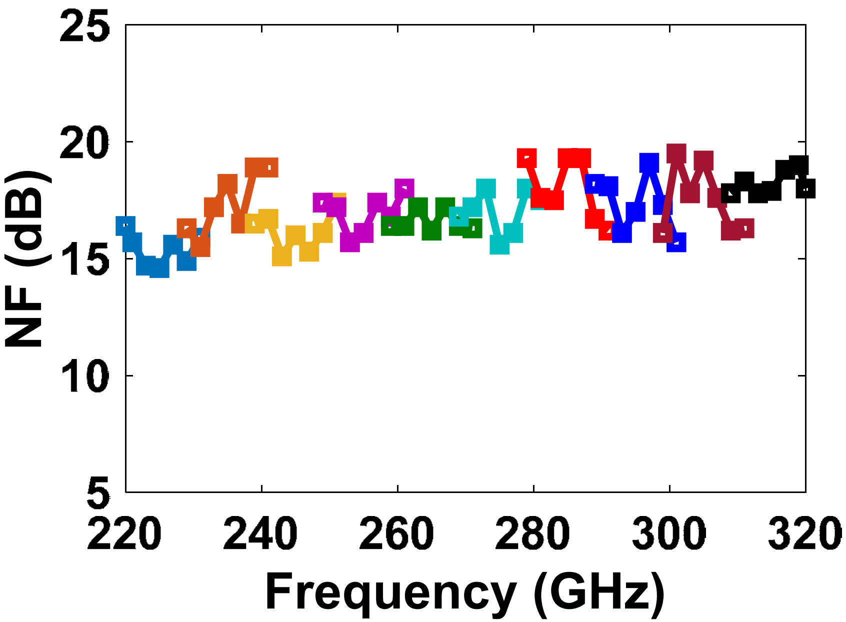
= IF output power (dBm) – (TX power (dBm) +TX antenna gain (dB)

– Path loss (dB) + RX antenna directivity (dB))

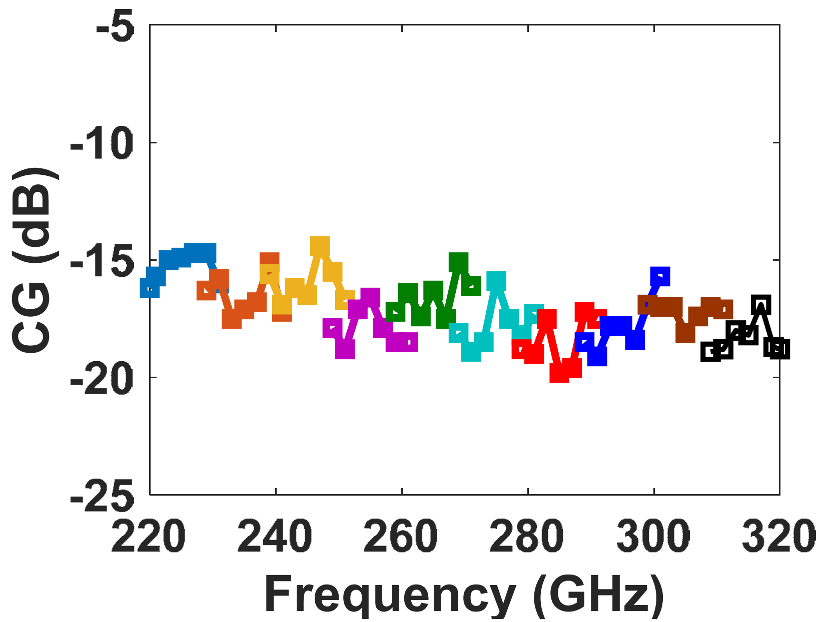
Single-sideband noise figure (antenna loss incorporated)

NF = IF noise floor (dBm/Hz) – (-174 (dBm/Hz)) – CG (dB)

Measurement Results of RX Mode



Single-sideband noise figure



Single-sideband conversion gain

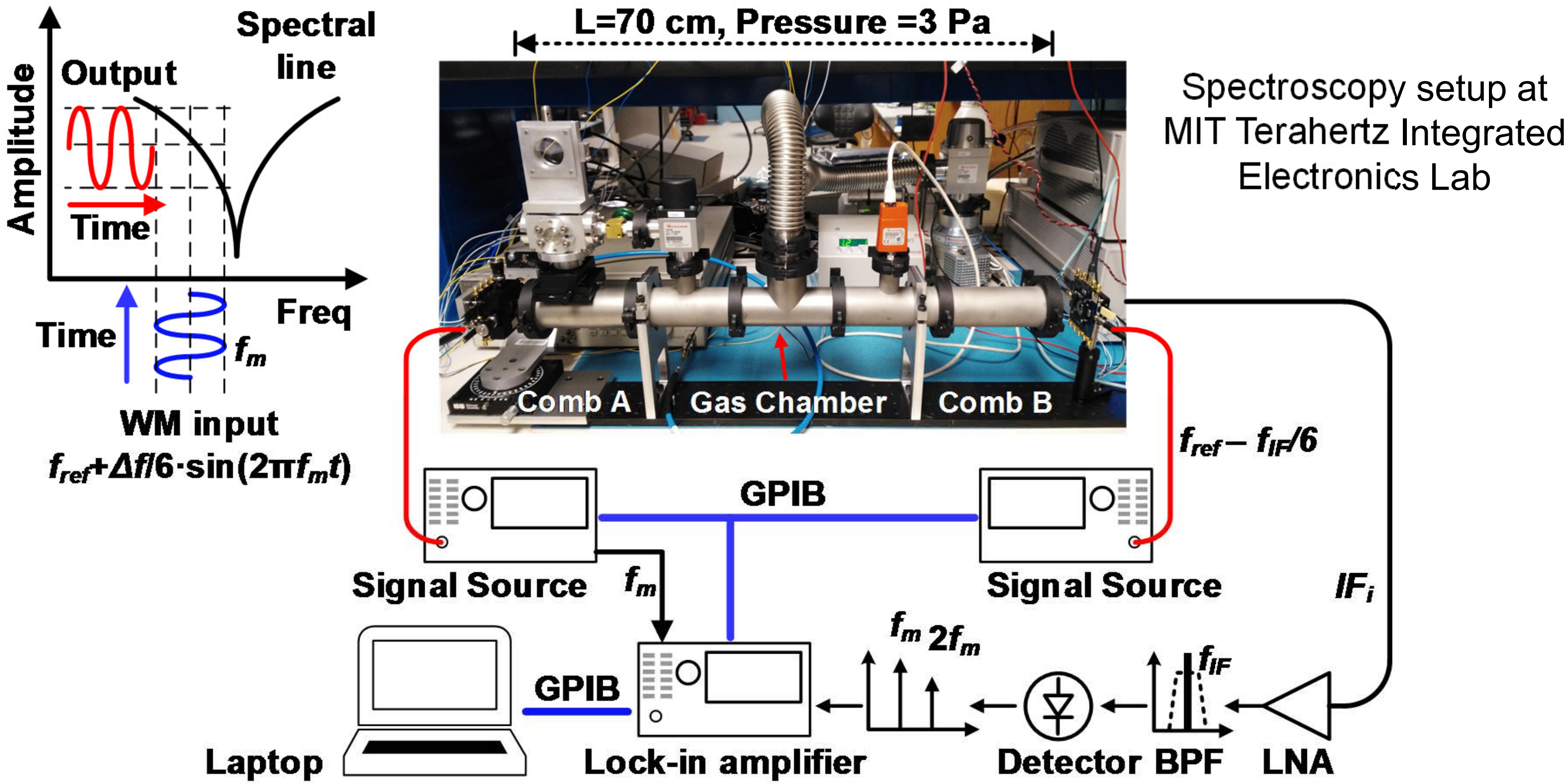
- **Measured SSB noise figure: 14.6~19.5dB**

Performance Comparison Table

Ref.	Technology (f_{max})	Topology	Frequency (GHz)	BW (GHz)	$P_{radiated}$ (mW)	Phase Noise[1] (dBc/Hz)	Noise Figure (dB)	P_{DC} (W)
This work	65nm CMOS (250GHz)	Comb (Tx/Rx)	220~320	100	5.2	-102	14.6~19.5	1.7
TST2016	0.13μm SiGe (500GHz)	Tx+Rx	245	14	4.0	-85	18	1.5+0.6 (Tx+Rx)
JSSC2014	32nm CMOS (320GHz)	Tx+Rx	210	14	0.7[2]	-81	11~12[3]	0.24+0.086 (Tx+Rx)
VLSI2016	65nm CMOS (N/A)	Tx	208~255	47	0.1[4]	-80	N/A	1.4
JSSC2015	0.13μm SiGe (280GHz)	Tx	317	N/A	3.3	-79	N/A	0.61
ISSCC2016	65nm CMOS (N/A)	Rx	210~305	95	N/A	N/A	18.4~23.5[5] (NF_{ISO}=13.9~19)	N/A

1. 1 MHz frequency offset.
2. The $P_{radiated}$ is estimated from the PA output power of 2.9 mW, and the antenna loss of 6 dB.
3. The NF of low noise amplifier in the receiver, excluding on-chip antenna loss.
4. The reported power in [3] is EIRP, not the total radiated power.
5. The overall NF (18.4~23.5 dB) =NF_{ISO}(13.9~19 dB, Isotropic Noise Figure)- (Antenna Loss (~4 dB) + Antenna Gain (-1~2 dBi)) .

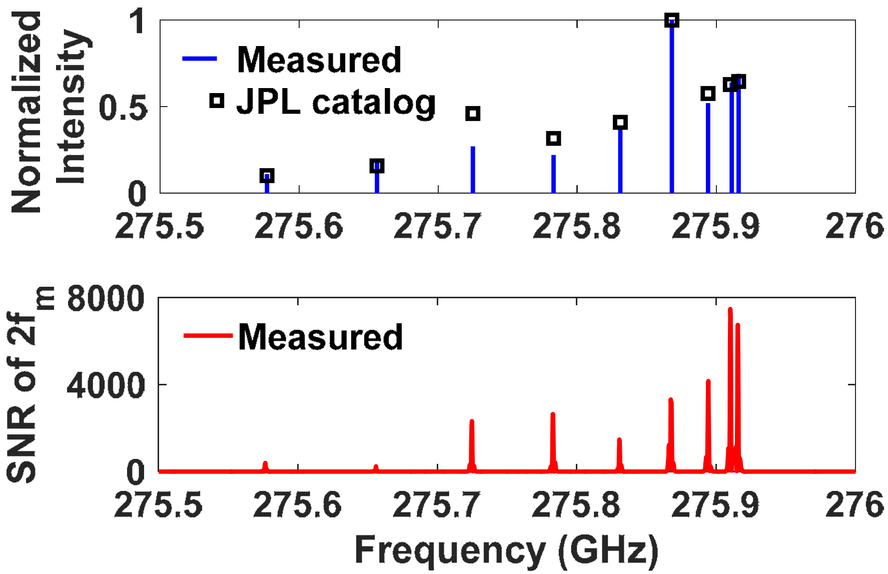
Spectroscopy Demonstration Setup



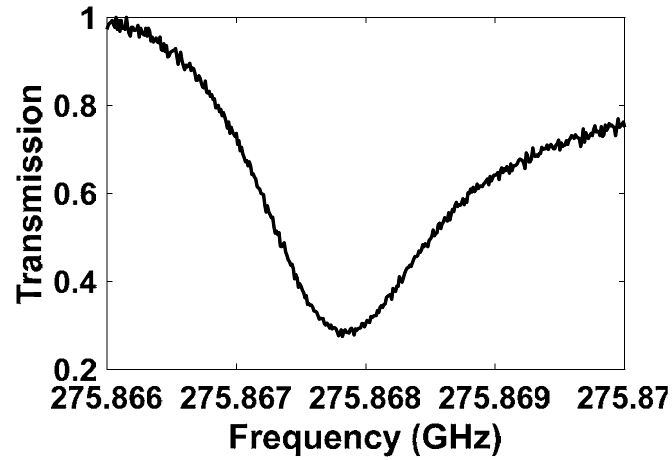
- **Wavelength modulation (WM) is applied for reduced impacts due to standing-wave formation**
  - Δf=240kHz, f_m=50kHz, f_{IF}=950MHz

Spectrum of Acetonitrile (CH_3CN)

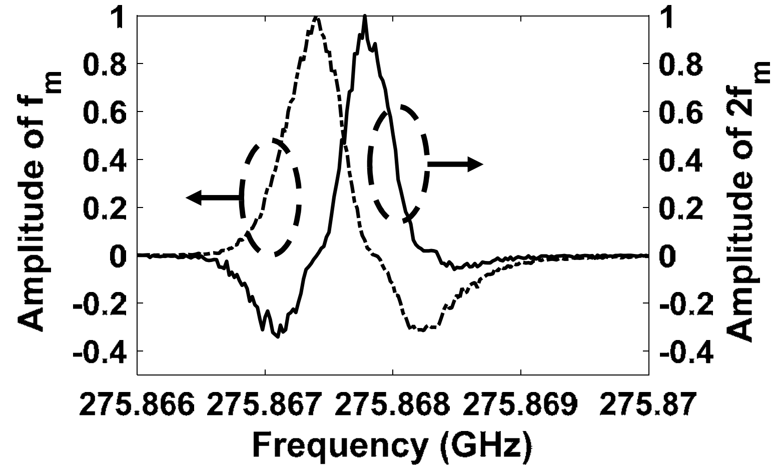
Measured spectrum of CH_3CN



Spectral line w/o WM



Spectral line with WM



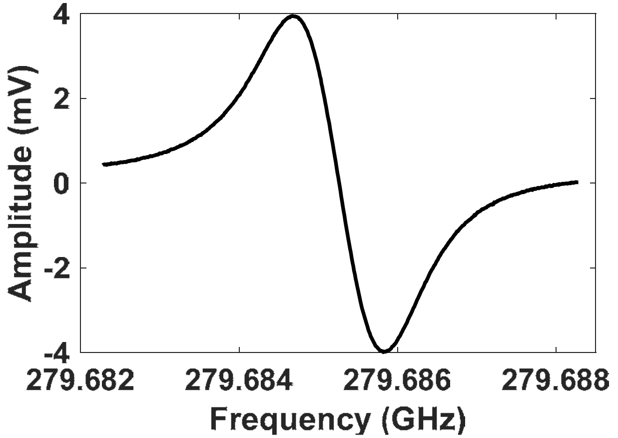
- **Measurement matches the JPL molecular database**
- **Spectral linewidth of 380kHz is obtained**
  - Absolute specificity (Q=7×10^5)

[JPL Molecular Spectroscopy, spec.jpl.nasa.gov.]

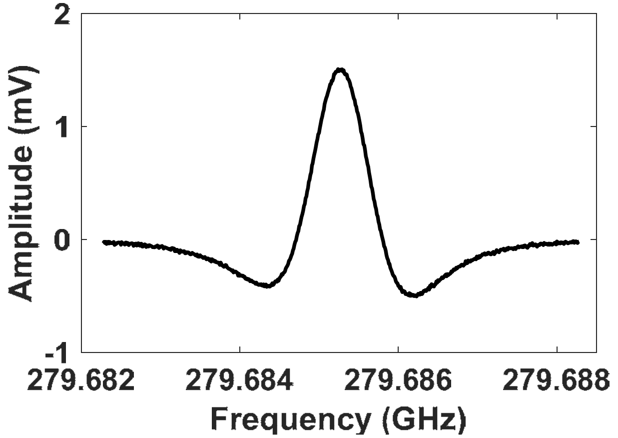
Spectrometer Miniaturization

- **54dB SNR has been achieved with reduced gas cell size**
  - Compact 3cm-long gas cell
  - Sample: carbonyl sulfide (OCS), 1.21×10^{-21} cm integrated line intensity (JPL) at 279.685GHz
  - Integration time: 100ms

1st order derivative, SNR=54dB

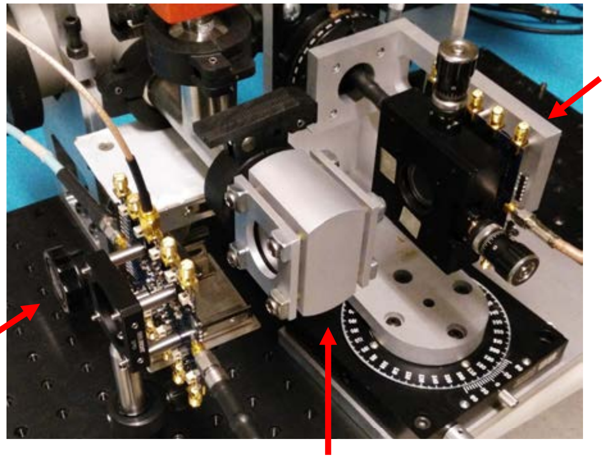


2nd order derivative, SNR=44dB



Comb B

Comb A



3cm-long gas cell

Outline

- Background
- Dual-Frequency-Comb Spectroscopy
- Architecture and Circuit Design
- Measurement Results
- **Conclusions**

Conclusions

- **Architecture level: Dual-frequency-comb spectroscopy with >2*N*× (*N*=10) faster frequency scanning and lower total energy consumption**
  - Simultaneous bilateral transmit/receive
- **Circuit level: multi-functional active molecule probe (AMP), performing frequency doubler, sub-harmonic mixer and on-chip antenna simultaneously**
  - Proposed dual-transmission-line (DTL) feedback accurately achieves G_{max}
- **Prototype: 220-to-320GHz comb spectrometer with state-of-the-art 5.2mW radiated power and 14.6-to-19.5dB NF**
  - Spectroscopy demonstration with 3-cm gas cell and a SNR of 54dB

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