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

Cheng Wang and Ruonan Han
Massachusetts Institute of Technology
Cambridge, MA, USA
Outline

• Background
• Dual-Frequency-Comb Spectroscopy
• Architecture and Circuit Design
• Measurement Results
• Conclusions
mm-Wave/THz Rotational Spectroscopy

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

Peak absorption intensity at mmW/sub-THz band

Detection of rotational spectral lines using EM wave

© 2017 IEEE International Solid-State Circuits Conference
Portable Molecular Sensor: Applications

- Human breath analyzer for biomedical diagnosis
- Environment monitoring for toxic gas leakage
  - Sensor network
  - UAV platform

- Human exhaled gases
  - 75% N₂
  - 13% O₂
  - 6% H₂O
  - 5% CO₂
  - 1% VOC
  - 1% volatile organic compounds
  - 3500 chemical species
  - Concentration: ppm-to-ppt level
  - Bio-makers for diseases or metabolic disorders (e.g. acetone → glucose → Type 1 diabetes)
Challenges of Chip-Scale Spectrometer

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

![Spectrum: 210-270GHz](image)

[Source: HITRAN.org]

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Frequency (GHz)</th>
<th>Toxic?</th>
<th>Flammable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>230.538001</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO₂)</td>
<td>251.199668</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen Cyanide (HCN)</td>
<td>265.886441</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Sulfide (H₂S)</td>
<td>300.511959</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Nitric Oxide (NO)</td>
<td>250.436966</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Nitrogen Dioxide (NO₂)</td>
<td>292.987169</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Nitric Acid (HNO₃)</td>
<td>256.657731</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Ammonia (NH₃)</td>
<td>208.145904</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Carbonyl Sulfide (OCS)</td>
<td>231.060989</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Ethylene Oxide (C₂H₄O)</td>
<td>263.292515</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Acrolein (C₃H₆O)</td>
<td>267.279359</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Methyl Mercaptan (CH₃SH)</td>
<td>227.564672</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Methyl Isocyanate (CH₃NCO)</td>
<td>269.788609</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Methyl Chloride (CH₃Cl)</td>
<td>239.187523</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Methanol (CH₃OH)</td>
<td>250.507156</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Acetone (CH₃COCH₃)</td>
<td>259.6184</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Acrylonitrile (C₂H₃CN)</td>
<td>265.935603</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

© 2017 IEEE
International Solid-State Circuits Conference

17.6: 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
Outline

• Background

• Dual-Frequency-Comb Spectroscopy

• Architecture and Circuit Design

• Measurement Results

• Conclusions
**Dual-Frequency-Comb Spectroscopy**

**Conventional single-tone spectroscopy**

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

**Dual-frequency-comb spectroscopy**

- Simultaneous scanning using 20 comb lines (8 minutes for 100GHz bandwidth, $\tau_{int}=1\text{ms}$)
Energy Efficiency Improvement

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

Radiated power of silicon-based sources above 200GHz

Total energy consumption for full-band scanning

Peak RF power (mW) vs. Bandwidth (%)

Consumed energy (a.u.) vs. Bandwidth (%)

- Conventional single-tone spectrometer: $E \propto BW^3$
- DFC spectrometer: $E \propto BW^2$
- Radiated power: $P \propto \frac{1}{BW}$

On-wafer measured with an assumed 50% radiation efficiency

© 2017 IEEE International Solid-State Circuits Conference

17.6: 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
Outline

• Background
• Dual-Frequency-Comb Spectroscopy
• Architecture and Circuit Design
• Measurement Results
• Conclusions
Architecture of A 220-to-320GHz Comb

- Tunable transceiver: 10 active molecular probes (AMP)
  - Seamless coverage of 100GHz bandwidth
  - Simultaneous transmit and receive $\rightarrow$ $\sim$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

![Diagram of AMP module](image-url)
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 $U$

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

$Y_{in}$ $\rightarrow$ Lossless embedding network $\rightarrow$ $Y_{out}$

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

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

Simulation using 65nm bulk CMOS process

[R. Spence, Linear Active Networks 1968]

[O. Momeni, ISSCC 2013]
Conventional YZ Embedding for $G_{\text{max}}$

**Equivalent circuit**

- Y element for shunt feedback
- Z element for series feedback

**Transistor structure**

- DC feed
- Source
- Y element
- Gate
- Drain

[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

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

Equations for feedback parameter calculation:

\[
\begin{align*}
\tan \theta_1 &= \frac{1}{Z_1} \cdot \frac{1}{b_{11} - g_{11}} \cdot \frac{mUb_{12} - b_{21}}{mUg_{12} - g_{21}} \\
\sin \theta_2 &= \frac{1}{Z_2} \cdot \frac{g_{11}Z_1 \sin \theta_1 (mU - 1)}{mUg_{12} - g_{21}}
\end{align*}
\]

where

\[
m = \frac{1 + \sqrt{1 - \frac{1}{U}}}{\sqrt{U^2 - U}} (U + \sqrt{U^2 - U} - 1)
\]

Simulation using 65nm CMOS process:

- $G_{max}$, $K=1$
- 5 dB gain boost
- Original power gain

Gain (dB) vs. Frequency (GHz)
DTL Feedback Based on Slot Line @\(f_0\)

Slot 1: \(\lambda/4\) Resonator

Input+ @\(f_0\)

\[\lambda/4\]

Input- @\(f_0\)

Slot 2: Feedback

Feedback through Slot 2

\[K \geq 1, \text{ with DTL feedback} \]

\[K = 0.9, \text{ w/o feedback} \]

Simulated stability factor, \(K\)

Electrical field

Current

Quasi-TEM Wave (Differential Mode) Supported

TM Wave (Common Mode) Rejected

E-field distribution @ \(f_0\)
Loss Minimization and Radiation @2f₀

Slot 1: Folded Slot Antenna

Slot 2: Leakage Rejection

Harmonic signal isolation

E-field distribution @ 2f₀

Electrical field

Current

Quasi-TEM Wave (Differential Mode) Supported

TM Wave (Common Mode) Rejected

Folded-slot antenna

© 2017 IEEE
International Solid-State Circuits Conference
Simulation Results for Doubler at 275GHz

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

Doubler efficiency $\eta$ (%)
AMP RX Mode: Heterodyne Mixing

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

Simulated SSB noise figure
Slot Balun with Orthogonal Mode Filtering

![Active Molecular Probe (AMP)](image)

- 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: $\lambda/4$ Resonator**

**Electrical field**

**Output**

**Open**

**Input**

**Differential mode (support)**

**Common mode (reject)**
Slot Balun with Orthogonal Mode Filtering

- 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

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

• Background
• Dual-Frequency-Comb Spectroscopy
• Architecture and Circuit Design
• Measurement Results
• Conclusions
Chip Micrograph and Packaging

- TSMC 65nm bulk CMOS process
- Chip area: 2mm × 3mm
- DC power consumption: 1.7W
Measurement Setup of TX Mode

- 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

- 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**

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

= 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)**

\[
\text{NF} = \text{IF noise floor (dBm/Hz)} - (-174 \text{ (dBm/Hz)}) - \text{CG (dB)}
\]
Measurement Results of RX Mode

- Measured SSB noise figure: 14.6~19.5dB
# Performance Comparison Table

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Technology (f\textsubscript{\text{max}})</th>
<th>Topology</th>
<th>Frequency (GHz)</th>
<th>BW (GHz)</th>
<th>Pradiated (mW)</th>
<th>Phase Noise\textsuperscript{1} (dBc/Hz)</th>
<th>Noise Figure (dB)</th>
<th>P\textsubscript{DC} (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>65nm CMOS (250GHz)</td>
<td>Comb (Tx/Rx)</td>
<td>220~320</td>
<td>100</td>
<td>5.2</td>
<td>-102</td>
<td>14.6~19.5</td>
<td>1.7</td>
</tr>
<tr>
<td>TST2016</td>
<td>0.13μm SiGe (500GHz)</td>
<td>Tx+Rx</td>
<td>245</td>
<td>14</td>
<td>4.0</td>
<td>-85</td>
<td>18</td>
<td>1.5+0.6 (Tx+Rx)</td>
</tr>
<tr>
<td>JSSC2014</td>
<td>32nm CMOS (320GHz)</td>
<td>Tx+Rx</td>
<td>210</td>
<td>14</td>
<td>0.7\textsuperscript{2}</td>
<td>-81</td>
<td>11~12\textsuperscript{3}</td>
<td>0.24+0.086 (Tx+Rx)</td>
</tr>
<tr>
<td>VLSI2016</td>
<td>65nm CMOS (N/A)</td>
<td>Tx</td>
<td>208~255</td>
<td>47</td>
<td>0.1\textsuperscript{4}</td>
<td>-80</td>
<td>N/A</td>
<td>1.4</td>
</tr>
<tr>
<td>JSSC2015</td>
<td>0.13μm SiGe (280GHz)</td>
<td>Tx</td>
<td>317</td>
<td>N/A</td>
<td>3.3</td>
<td>-79</td>
<td>N/A</td>
<td>0.61</td>
</tr>
<tr>
<td>ISSCC2016</td>
<td>65nm CMOS (N/A)</td>
<td>Rx</td>
<td>210~305</td>
<td>95</td>
<td>N/A</td>
<td>N/A</td>
<td>18.4<del>23.5\textsuperscript{5} (NF\textsubscript{ISO}=13.9</del>19)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

1. 1 MHz frequency offset.
2. The Pradiated 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\textsubscript{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
  - $\Delta f = 240\text{kHz}$, $f_m = 50\text{kHz}$, $f_{IF} = 950\text{MHz}$

© 2017 IEEE
International Solid-State Circuits Conference
Spectrum of Acetonitrile (CH$_3$CN)

- 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), $1.21 \times 10^{-21}$ cm integrated line intensity (JPL) at 279.685GHz
  - Integration time: 100ms

1st order derivative, SNR=54dB

2nd order derivative, SNR=44dB
Outline

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

• Architecture level: Dual-frequency-comb spectroscopy with >2N× (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 $G_{\text{max}}$

• 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
Acknowledgement

- MIT Center for Integrated Circuits & Systems
- TSMC University Shuttle Program
- Dr. Richard Temkin (MIT Physics), Prof. Tomás Palacios (MIT EECS), Prof. Ehsan Afshari (University of Michigan) and Prof. Anantha Chandrakasan (MIT EECS) for the support of testing instruments
- Dr. Stephen Coy, Prof. Keith Nelson, Prof. Robert Field (MIT Chemistry), Tingting Shi (MIT and Fudan University) and Prof. John S. Muenter (University of Rochester) for technical discussions and assistance