Fully-Scalable 2D THz Radiating Array: A 42-Element Source in 130-nm SiGe with 80-μW Total Radiated Power at 1.01THz

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Outline

• Motivation and Challenges
• Design of Oscillator
• Formation of 1-THz Oscillating-Radiating Array
• Measurement Results
• Conclusions
Pushing Frequency and Power Limit of THz Radiator

Applications of high-power high-frequency THz source

High-Resolution Imaging
[F. Schuster et al., ISSCC, 2011.]

Bio-Molecule Spectroscopy
[T. Globus et al., Convergent Science Physical Oncology, 2016.]

High-Precision Vibrometry
[G. Bissinger, D. Oliver, Sound & Vibration, 2007.]

Path to high-power 1-THz radiator

- Building coherent radiating array at higher frequency is more challenging
Why Building 1-THz Radiating Array Is Difficult?

1 THz > $f_{\text{max}}$ of all silicon-based transistors (fastest: 450 GHz in IHP S13G2)

Efficient high-order harmonic generation and radiation

Antenna array requires $\lambda/2$ spacing

$\sim 70\mu$m x $70\mu$m for each radiating unit

Very limited area to fit in all necessary components

Array scale can be very large

Accumulation of phase error between units due to inter-unit injection can cause severe beam tilting
Call for Compact Multi-Functional Array Unit

Array Unit

- Harmonic Filter
- Oscillator
- 1-THz Antenna
- Phase-Synchronizing Coupler
Our Slotline-Bound-Array Solution

- Differential oscillators plus slotlines accomplish all tasks
  - Each unit oscillates at $f_0 = 250$ GHz and radiates $4f_0 = 1$ THz
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Multi-Functional Array Unit

- Harmonic Filter
- Phase-Synchronizing Coupler
- Oscillator
- 1-THz Antenna

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RTU2B-2
At $f_0$ (250 GHz), two oscillators are forced to oscillate differentially.

For even-order harmonics from two oscillators, including $4f_0 = 1$ THz:

- They are in-phase, hence repelled from slotline (feedback loop).
- No dissipation at base, more power is delivered outwards.
Maximize Oscillation at $f_0$ in Single Oscillator

- Phase delay of $V_2$ should be compensated
  - Intrinsic delay of $I_C$
  - Undesired feed-forward current $I_{feed}$
- Use self-feeding topology to adjust phase

$$\angle A_{opt} = \angle V_2 / V_1 = -\left(y_{21} + y_{12}^*\right),$$

$$\varphi_{TL} = \arcsin\left(Z_{TL} \cdot \left( g_{11} + \text{Re}\left(A_{opt} \cdot y_{12} / \text{Im}(A)\right)\right)\right)^{-1}$$

[R. Spence, Linear Active Networks, 1970.]
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Expose Oscillation Using Branched Resonator

- Two $\lambda/4 @ f_0$ transmission lines (short $\rightarrow$ open)
- E-shaped pattern composes the boundary of oscillating unit
- Resonator is implemented by slotlines
Structure of a Complete Oscillating Unit

- Oscillators sealed by three resonators
  - Two branched resonators
  - One broadband open
- In-shunt resonators present $Q = 18$
Interface Adjacent Units Using Branched Resonator

- Horizontal slotlines on the border (2x1 case) are merged
- Vertical slotlines on the border (1x2 case) run parallel
Multi-Functional Array Unit

- Harmonic Filter
- Oscillator
- 1-THz Antenna
- Phase-Synchronizing Coupler
Coupling (at $f_0$) between Horizontally Adjacent Units

Single-Node Injection vs. Distributed Phase Synchronization

\[
\frac{d\theta}{dt} = \omega_0 - \omega_{\text{inj}} - \frac{\omega_0}{2Q} \cdot \frac{V_{\text{inj,p}}}{V_{\text{osc,p}}} \sin \theta \\
= \omega_0 - \omega_{\text{inj}} - \omega_L \sin \theta.
\]

Phase at every point is synced, even if there is mismatch of $\omega_0$.

[B. Razavi, JSSC, 2004.]

RTU2B-2
Coupling (at $f_0$) between Vertically Adjacent Units

- Branched resonator shared $\rightarrow$ phase relationship determined
- Use slotline for the purpose of array-wide in-phase radiation (discuss later)
Multi-Functional Array Unit

- Harmonic Filter
- Phase-Synchronizing Coupler
- Oscillator
- 1-THz Antenna

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Radiation Cancellation at $f_0$ (250 GHz): Vertical

- Vertical slotlines pairs do not radiate
  - E-field in left and right slotlines balance out
Radiation Cancellation at $f_0$ (250 GHz): Horizontal

- Horizontal slotlines pairs do not radiate
  - E-field in left and right slotlines balance out

Antenna Gain at $f_0$:

- $-66$ dBi
Radiation Cancellation at $2f_0$ (500 GHz): Horizontal

- Horizontal slotlines do not radiate
  - E-field in central slotlines balance out with top/bottom slotlines
Radiation Cancellation at $2f_0$ (500 GHz): Vertical

- Vertical slotlines pairs do not radiate
  - E-field in left and right slotlines balance out
Radiation Cancellation at $3f_0$ (750 GHz)

- Horizontal slotlines pairs do not radiate
  - E-field in left and right slotlines balance out
Radiation Cancellation at $3f_0$ (750 GHz)

- Vertical slotlines pairs do not radiate
  - E-field in left and right slotlines balance out

Antenna Gain at $3f_0$
Multi-Functional Array Unit

Array Unit

- Harmonic Filter
- Oscillator
- 1-THz Antenna
- Phase-Synchronizing Coupler
Radiation at $4f_0$ (1 THz) from Single Unit

- All horizontal slotlines pairs radiate in-phase
- Vertical slotlines do not radiate

Antenna Gain at $4f_0$
1-THz Radiating Array

- In-phase radiation from all units is achieved by CPW and slotline coupling

- 1-THz antennas are spaced by $\lambda/2$ in both horizontal and vertical directions

- Equivalently, the array is like an “active planar wave front” with big aperture underpinned by transistors
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SiGe Chip Prototype

• **Technology:** IHP S13G2 SiGe BiCMOS
  – $f_{\text{max}} = 450$ GHz

• **Area:** 1 mm$^2$

• **Array scale**
  – 42 units
  – 91 antennas

• **DC Power:** 1.1 W
Chip is attached to a half-ball silicon lens and radiates into backside.

Due to device mismatch, there will be little of $f_0$ wave leaking out, with which we can confirm $f_0$ and hence $4f_0$. 

$f_0 = 16f_{LO} + f_{offset}$
Measurement of Total Radiated Power

- Total radiated power of 1 THz (from ZBD): 80μW (-11dBm)
Measurement of Total Radiated Power

- Total radiated power of 1 THz (from ZBD): 80μW (-11dBm)
- Total radiated power of all harmonics (from TK): 100μW
Measurement of Radiation Pattern

- Measured using zero-bias diode detector
- Peak directivity: 24dBi
- EIRP: 13dBm
### Performance Comparison

<table>
<thead>
<tr>
<th>Reference</th>
<th>This Work</th>
<th>MTT2015</th>
<th>ISSCC2011</th>
<th>ISSCC2016</th>
<th>VLSI 2015</th>
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</thead>
<tbody>
<tr>
<td>Circuit Type</td>
<td>Oscillator Array (4f₀)</td>
<td>Active Multiplier (6f₀)</td>
<td>Active Multiplier (5f₀)</td>
<td>Passive Multiplier (10f₀)</td>
<td>Passive Multiplier (5f₀)</td>
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<td>Output Frequency (THz)</td>
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<td>Radiated Power (dBm)</td>
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<td>N/A</td>
<td>-22.7</td>
<td>-21.3</td>
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<td>EIRP (dBm)</td>
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<td>Input RF Power (dBm)</td>
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<td>DC Power (W)</td>
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<td>Chip Area (mm²)</td>
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<td>Technology</td>
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<td>0.25μm SiGe</td>
<td>0.25μm SiGe</td>
<td>65nm CMOS</td>
<td>65nm CMOS</td>
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</tbody>
</table>

- Highest total radiated power
- Highest EIRP
Conclusions

- A high-power 1-THz radiator featuring 2D-coupled array architecture
  - Large array scale
  - Directive radiated beam

- Compact multi-functional structure will be an important component in future THz circuits
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