Broadband Beamforming of Terahertz Pulses with a Single-Chip 4×2 Array in Silicon

M. Mahdi Assefzadeh and Aydin Babakhani Rice University, Houston, Texas, USA

Abstract: In this paper, a single-chip impulse antenna array is presented that performs spatial combining of picosecond impulses radiated from 8 elements. A new broadband beamforming architecture is introduced that controls the timing of impulses radiated from each antenna by delaying a trigger signal, with resolution steps of 300fsec. This method eliminates the distortive and narrowband effects of delay blocks in conventional phased arrays by separating the delay path from the information path. Frequency domain measurements are performed up to 1.03THz and array directivities of 22dBi at 0.33THz, 25dBi at 0.57THz, and 27dBi at 0.75THz are achieved. The 8-element array is fabricated in a 90nm Silicon Germanium BiCMOS process technology.

Keywords: On-chip Antennas; Terahertz Arrays; Coherent Spatial Combining; Beamforming; Slot Bow-Tie; Silicon; SiGe.

References:


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Outline

• Current techniques for picosecond pulse generation
  – Applications of THz pulse generators
  – Limitations of conventional methods
• Silicon-based solution
  – Single-chip 4x2 picosecond pulse radiating array
• Design of a single element
• Broadband array architecture
• Array chip measurements
• Gas spectroscopy and THz imaging measurements
• Comparison with prior work and conclusions
Applications of THz Pulses

- 3D Hyper-spectral Imaging
- Medical imaging and pharmaceutical applications
- Security imaging and explosive detection
- Gas sensing and broadband spectroscopy
Broadband Spectroscopy with THz Pulses

- Frequency-comb generation with an impulse train
- Fine tuning of THz tones by controlling the repetition rate

\[ y(t) = \sum_{k=-\infty}^{\infty} x(t - kT) \]

\[ |Y(f)| = \frac{1}{T} |X(f)| \sum_{k=-\infty}^{\infty} \delta(f - k\frac{1}{T}) \]
fsec-Laser Based THz-TDS Systems

- THz-TDS systems require a femtosecond laser and Photoconductive Antennas (PCA)
Photoconductive Antennas (PCA)

- PCA: emitter and detector of terahertz pulses
- THz antenna on high-mobility semiconductor substrate
- DC bias applied
- Sub-psec laser pulse causes THz pulse emission or detection
Limitations of THz-TDS Systems

1. Need for fsec laser
   - Expensive and bulky laser
   - High power consumption
   - Optical alignments

2. Limited repetition rate (<100MHz)

3. Mechanical scanning of object

4. Limited radiated power (~µW avg. power)

5. Mechanical control of delay line
How to Overcome These Limitations?

• A silicon-based laser-free THz pulse radiating array with integrated antennas
  – No need for a fsec laser
  – No optical alignment
  – High yield and low-cost solution
  – Low power digital trigger instead of optical laser pump
  – Up to 10GHz repetition rate

• The reported silicon-based solution enables
  – Scalable, power efficient pulse generation method
  – Broadband array beamforming technique
Conventional Electronic Techniques

• Based on step-recovery or Schottky diodes
  – III-V and expensive process nodes, 20-ps PW

• Based on oscillators and switches
  – Turning on/off the oscillator
  – Turning on/off the power amplifier as a switch

![Diagram of Oscillator and Switch](image-url)
Limitations of Conventional Techniques

- Limited bandwidth (long pulse width)
  - Turn-off time of the oscillator
  - Transient time of the switch

- Low isolation when the switch is off
  - RF leakage to receiver limits its dynamic range

- Low power efficiency
  - VCO constantly ON
  - Power-hungry PLLs

- Limited scalability
  - Area-consuming phase-locked loop (PLL) and delay-locked loop (DLL) for each element
Direct Digital-to-Impulse Radiation (D2I)

- Impulse radiation mechanism in Direct Digital-to-Impulse (D2I)
  - An oscillator-less design
  - Storing current in an antenna
  - Disconnecting the current by a fast switch
Broadband On-chip Impulse Antenna

- Requirements in the design
  - Broadband flat gain, linear phase
- On-chip slot bow-tie antenna
  - No ground plane to achieve large bandwidth
  - Silicon lens on the back of the chip to increase efficiency
  - Curved the edges to improve the bandwidth
Antenna Impulse Response

- Simulated impulse response

- Simulated near-field E-field
Circuit Architecture

- Impulse shaping network
  - Distributed array of high SRF capacitors
Electronic Beam-Steering

- Highly-scalable architecture enables a low-cost massive array
  - Electronic scanning by delaying the digital trigger
  - $N$ elements result in $N^2$ improvement in EIRP
Broadband Beam-Steering with D2I

- Current phased-array techniques
  - Delaying RF signal: nonlinear delay lines
  - Phase-shifting LO: narrowband
- Proposed solution: Trigger-based beam-steering
  - Separating delay path from the information path
Single-chip 4x2 D2I Array in SiGe BiCMOS

- H-tree distribution of input trigger to 8 elements
- Programmable delay generator per element
Circuit Schematic

- Current is stored in a slot bow-tie antenna
- A fast switch turns off the current. The on-chip antenna releases the stored energy and radiates a short impulse
- An impulse shaping network is used to minimize the ringing
Prototype Assembly

- A chip-on-board assembly with bond wires is used
- A trigger signal fed to the chip triggers radiation of a THz pulse
- Radiation is coupled to a 25mm diameter lens with 400µm extension
Time-Domain Characterization Setup

- A fsec-laser-based THz-TDS system is used to characterize the array chip.
- For the first time, a fully electronic chip is used as the emitter in a THz-TDS system.
Measured Time-Domain Waveforms

- 300fs delay resolution
- Amplitude modulation capability
Frequency-Domain Characterization Setup

- Single impulse

\[ y(t) = \sum_{k=-\infty}^{\infty} x(t - kT) \]

- Impulse train

\[ |X(f)| \]

\[ |Y(f)| = \frac{1}{T} |X(f)| \sum_{k=-\infty}^{\infty} \delta(f - k \frac{1}{T}) \]
Frequency-Domain Characterization Results

- 2-Hz spectral line-width at 0.75THz
Radiation Pattern Measurements

- Directivities of 22dB, 24dB and 28dB at 0.33THz, 0.57THz and 0.75THz, respectively
Array Chip Micrograph

- Process technology: 90nm SiGe BiCMOS
- A single element only occupies 300µm x 650µm
Gas Spectroscopy Measurement Setup

- The repetition rate is changed with steps of 10MHz to tune the generated harmonic tones at the desired THz frequencies
Gas Cell

- Aluminum tube with 50mm diameter and 150mm length with Teflon lens windows on both sides
- Controlled pressure
- Received power is measured in two cases:
  - Gas cell is filled with the target gas
  - Gas cell is filled with pure nitrogen
Gas Spectroscopy Measurement Results

- **NH₃** at 572GHz
  - 1% concentration
  - Pressure varied to demonstrate broadening effect

- **H₂O** at 753GHz
  - 50% humidity (0.75% concentration)
THz Imaging Setup

• Setup:
  – Four off-axis parabolic mirrors focus the beam on the sample
  – A 2D translation stage

• Spectral information: 0.03-1.03THz
Image at 330GHz

- Materials: metal and plastic
Image at 609GHz

- Materials: metal, empty and filled cellulose capsules
### Comparison with Prior Work

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<td>Highest Frequency Measured with SNR&gt;1</td>
<td>1.032THz</td>
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<td>Shortest Radiated FWHM</td>
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<td>Peak EIRP (dBm)</td>
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<td>Array Architecture</td>
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<td>LO-path phase shift (narrowband)</td>
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<td>Delay Resolution/Range</td>
<td>300fs/95ps</td>
<td>N/A</td>
<td>5° at 40GHz LO (350fs) / 90°</td>
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<td>Time-Domain Measurement</td>
<td>Yes (with locking,THz-TDS)</td>
<td>Yes (w/o locking)</td>
<td>No</td>
<td>Yes (with locking)</td>
<td>Yes (with locking)</td>
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<td>Direct Digital-to-Impulse (D2I)</td>
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<td>TX/RX</td>
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<td>Power Consumption</td>
<td>710mW</td>
<td>580mW</td>
<td>1.2W</td>
<td>220mW</td>
<td>260mW</td>
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<td>Die Area</td>
<td>2.4mm²</td>
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<td>Technology</td>
<td>90nm SiGe BiCMOS</td>
<td>130nm SiGe BiCMOS</td>
<td>65nm CMOS</td>
<td>130nm SiGe BiCMOS</td>
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Conclusions

• A single-chip 4x2 THz pulse radiating array is presented
• A broadband pulse beamforming method is introduced that excludes any delay, hence nonlinearity, from the information path
• Coherent spatial combining of 8 elements achieves a FWHM of 5.4ps, a peak EIRP of 30dBm, and directivities of 22dBi, 25dBi and 27dBi at 0.33THz, 0.57THz and 0.75THz, respectively
• THz imaging (330GHz and 609GHz) and gas spectroscopy is demonstrated using the single-chip array
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