Schottky Diode Based THz Electronics: Recent Advances and Challenges

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Outline

• Motivation
• Methodology
• THz receiver front ends
• Array Receivers
• Conclusion
Introduction and Motivation

- Submillimeter-wave heterodyne receivers have a long and noteworthy history in exploring our universe (MLS, MIRO, HIFI)
- Recent work has also demonstrated the use of this technology for concealed weapons detection
- Most receivers deployed at these frequencies have been single pixel and fairly bulky systems
- Two important considerations require a paradigm shift in terms of how we build these receivers for the future
  - This decade will witness a renewed focus on exploring planets in our solar system in the submillimeter-wave range. These missions, and especially the ones focused on the outer planets will require extremely light weight payloads.
  - Both for planetary science as well as applications on Earth, imaging arrays are now feasible (given the tremendous improvement in backend processing). Large count arrays will require that each receiver is low-mass, low-power and extremely small.
THz Receivers

Goal of this technology is to DETECT THz radiation

Illuminate sample with THz radiation and detect absorption/emission

Detect natural THz emission

Biomedical imaging
Security and concealed threats
Imaging etc

Space applications
Spectroscopy
Gas cloud identification etc

Radar

Radiometer
Heterodyne Receivers

THz Signal $f_S$ → Telescope → Optics

Mixer output $= |f_S - Nf_0|$

Low Noise IF Amplifier

Multiplier $Nf_0$

Power Amplifier

Oscillator at frequency $f_0$

Intermediate Frequency (IF)

Spectrometer

Local Oscillator (LO)

**NEP_H** = $2kT_R B_{IF}$

- RF signal magnitude and phase are preserved, time gated data (depth), narrowband spectral content, and interferometric imaging (the only way to reduce antenna size) are three key advantages of heterodyne operation.

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What Detector should be used?

Trade-off

- Sensitivity vs Operating Temperature
- Spectral resolution
- Scientific goals and objectives
1. Optimize Diode

Optimize diode size and find embedding impedances using harmonic balance simulator and diode model.

2. Design Linear Circuit

HFSS Model of Diodes in Waveguide + embedding impedances

3. Calculate Performance

Full Structure Analyzed at Input Frequency with HFSS

Diode Models

Full Structure Analyzed at Output Frequency with HFSS

Waveguide Input Port

Waveguide Output Port

HFSS Probe Model

HFSS Backshort
THz receiver development goals

1) Find a robust mixer architectures scalable to THz range.
   • MMIC approach is good for all frequencies, especially above 1 THz
   • Balanced architecture (introduced by Carlson) for sub-harmonic mixer is believed to be more suitable for frequencies above 1 THz than anti-parallel configuration.

(Figures from Carlson et al., IEEE MTT, Vol. 26, No.10, Oct. 1978)

2) Integrate the mixer and last multiplier stages
   • Reduced packaging mass and volume,
   • Lower losses of the input LO signal of the mixer at 280 GHz resulting in lower W-band input LO power,
   • Low standing wave ratio between tripler and mixer chip due to better consideration of matching during the design phase,
560 GHz integrated SHM + tripler

- 280 GHz tripler based on previous 260-340 GHz tripler
- 560 GHz SHM based on a previous 874 GHz balanced design
- Both MMICs on GaAs membrane using gold beamleads
- Design of each device done first separately and then optimized together for optimum LO coupling.
560 GHz receiver measurements

- Test performed in a vacuum chamber at 300 K and with IF output connected to an isolator.
- No correction for feed-horn losses and IF mismatches.
- LO power required: 30-80 mW at W-band
1200 GHz MMIC sub-harmonic mixer

- LO source includes a 540-640 GHz tripler and 180-220 GHz doubler based on HIFI heritage.
- 1200 GHz SHM scaled up from previous 874 GHz balanced design
- MMIC based on GaAs membrane using gold beamleads
- Biasable mixer version to allow for the reduction of LO power.
Generation of THz LO Requirements

- Figure of merit
  - Frequency
  - Power
  - Bandwidth
  - Efficiency

Approach:
Start with a ultra-stable DRO (MHz range)
Actively multiply to W-band.
Develop W-band PAs
THz Schottky diode multipliers
Recent Advances towards power generation

- **GaN power-combined power amplifiers providing more than 3 W at W-band**
  

- **Different power-combined multipliers demonstrated up to ~ 1 THz**
  
  

- **State-of-the-art Schottky diode based multipliers at THz frequencies providing conversion efficiencies within the theoretical limits**
  
THz Sources

Next generation Schottky multiplied LO sources could deliver:

- **GaN-HEMT Power-Combined Amplifier**
  - 89 GHz
  - 2-3 Watts

- **Power-combined Schottky doubler**
  - 400-600 mW
  - 178 GHz

- **Power-combined Schottky tripler**
  - 30-50 mW
  - 534 GHz

- **Power-combined Schottky tripler**
  - 0.8-1.2 mW
  - 1.6 THz

• To develop high-power room-temperature **biasable** multiplied sources to enable multi-pixel coherent receivers beyond 1 THz
  • Extend the use of Schottky multiplied sources beyond 3 THz

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QUAD-CHIP BIASED 1.6 THz TRIPLER

- Separation between waveguides determined by the DC bias through diameter (0.6 mm)
  → Increases input/output electrical path & waveguide losses

**IDEAL OUTPUT Y-JUNCTION**

- **OUTPUT LOSSES**
  20% 3-dB bandwidth (~ 2.4 % efficiency)

**Designed for 32 mW input power**
‘ON-CHIP’ POWER-COMBINING CONCEPT

SOLUTION: ‘ON-CHIP’ POWER-COMBINED MULTIPLIER

- Multiplier device 1 (x2 diodes)
- Multiplier device 2 (x2 diodes)
- Multiplier device 3 (x2 diodes)
- Multiplier device 4 (x2 diodes)

- E-probe 1
- E-probe 2
- E-probe 3
- E-probe 4

- DC Bias 1
- DC Bias 2
- DC Bias 3
- DC Bias 4

- TE_{10}(f_o)
- TE_{10}(3f_o)

- SHORTER BIAS LINES (GAP BETWEEN WAVEGUIDES SMALLER IN SI MM)
Technological Roadmap

Develop an ultra-compact receiver which is compatible with array architecture

SLS Receiver Front End (RFE)

Approx. 20 cm

x 50 reduction in volume & mass

SOA 500-600 GHz Receiver Front End
This novel architecture uses a stack of micro-machined wafers for waveguide components and interconnections, and MMIC based GaAs wafers for amplifiers, multipliers and mixers.
Instead of more expensive GaAs wafers use Si wafers with discretely mounted GaAs based devices.
Si metal waveguide interconnections

- **1st option**: from the side of the Si wafer.
- **2nd option**: from the flat of the Si wafer.

- Commonly used approach
- Our approach for interfacing
SI based W-band power amplifier

- 4 Si layers are required to package a pHEMT amplifier chip, waveguide transitions and bends.
- DC bias circuit is also included in the Si block.
Si based W-band PA assembly

pHEMT MMIC

Deep RIE technology used to fab Si

Completed module is only 7 g
Si based 560 GHz RFE

- Integrate in a Si package (4 layers) a 300 GHz MMIC tripler and 600 GHz MMIC sub-harmonic mixer
Si based 560 GHz RFE

- 20 x 25 x 3mm Si package
- WR-10 waveguide (input) & 560 GHz corrugated horn (output)
- SSMA and K-glass bead IF and DC connections
SI based 560 GHz RFE test

- IF frequency: 4 GHz. Not corrected for IF mismatch.
- Fundamental input power at W-band: 30-50 mW
Complete ROC front-end

- Si part is 8 mm thick.
- Size still dominated by UG387 flange.
Towards a 2D array sub-system

- RF Si-lenses & spacer
- Submm multiplier & mixer
- W-band PA
- LO signal distribution

W-band input waveguide

THz microlens made via photolithography and DRIE
THz Imaging Radar

**Operating Parameters**

**Standoff range:**
4 meters

**Operating frequency:**
575-605 GHz

**Range resolution**
<1 cm

**Cross-range resolution:**
<1 cm

**Output power:**
≤0.4 mW

**Time per pixel:**
6-25 ms (with single pixel)
Detection of Concealed Objects on People

- Plastic container of BB pellets
- BBs concealed by shirt
Conclusion

- Schottky diode based receiver electronics provide strategic advantages
  - Room temperature operation
  - Large operating temp range
  - System stability
  - THz operation

- Significant reduction of size and mass of current receiver front-end has been achieved with the new Silicon micro-machined approach

- Technology is well suited for development of array receivers

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