Ultra-sensitive, room-temperature THz detector using nonlinear parametric upconversion

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Outline

• Motivation

• Optical Detection of THz
  – Experiment
  – Results
  – Conversion efficiency enhancements

• Summary and Future Work
Some Terahertz Applications

**THz Imaging**

*Concealed Weapon Detection*

*Medical Applications*

*Voids in Space Shuttle Foam*

**THz Vibrometry**

**THz Spectroscopy**

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UNCLASSIFIED – Approved for Public Release; Distribution is Unlimited
State-of-Art THz Direct Detectors
Significantly above Quantum Limit

Comparison of Optical and THz Direct Detectors

**THz Receiver Challenges**
- Low-noise (quantum limited)
- High bandwidth
- Frequency agile
- Room Temperature

Receiver technology at optical frequencies has significantly better performance
Leveraging IR Technology by Terahertz to Optical Conversion

- THz Photon
  - Uncoated
  - Large

- THz Optics
  - Inefficient
  - Cryogenic
  - Slow

- THz Detector
  - Photon-counting
  - Large bandwidth
  - Room temperature
  - Efficient

- Processing

Leverages mature technology at IR regime to address THz “gap”
Second-order - $\chi^{(2)}$- Nonlinear Optical Interactions

Polarization = $\chi^{(1)} E + \chi^{(2)} E^2$

- Frequency mixing via non-linear polarization current density
- Very fast
- Pump photons are down-converted to signal and idler
- Efficiency is highly sensitive to phase-matching

Detection of optical sideband photon implies presence of THz photon
Optical Detection of THz: Laboratory Implementation

- THz source: Backward Wave Oscillator (2.5 mW at 700 GHz)
- Optical Source: 1550 nm, 1 W avg, 10 ns pulses, 200 kHz rep rate
- Commercial telecomm thin film band-edge and band-pass filters
- Optical Receiver: Geiger-mode Avalanche Photodiode (GM-APD) dark count 20kHz and $\eta \sim 20\%$
Optical Detection of THz: Geiger-mode Avalanche Photo Diode Experimental Results

- GM-APD counts number of 1-ns gates with photons in 1 s
- 200K pulses / 1 s
- $P_{\text{Idler}} = K P_{\text{THz}}$: Idler attenuated by 69 dB to reach noise level
- Min detectable energy: $3.2 \times 10^{-19}$ J / 1 ns gate
- $\text{NEP}_{\text{THz}} \approx 4.5 \text{ pW/Hz}^{1/2}$
Improving Conversion Efficiency using Quasi Phase Matching (QPM)

- Efficient nonlinear conversion requires phase-matched process
- Phase-match by reversing polarity of nonlinearity periodically
- Achieved by bonding orthogonal orientations
- Phase-matched conversion scales as $L^2$
Quasi Phase-matching by Diffusion-Bonding Bulk GaAs

**Initial Results**
- Initially exposed surfaces marred by contact layers;
- Improved polish quality of top and bottom surfaces
- Experimented with different contact layers
- Bond interface is clean

**Improved Process**
- Top Surface
- Bond Interface
Efficient Upconversion: Bulk GaAs vs. Diffusion-bonded QPM GaAs

- Phase-matching is necessary to enhance conversion efficiency
- DB-GaAs (QPM5, QPM6) show efficiency enhancement > 5 dB.
- QPM4: orientation of bonded crystals was uncertain
- AR-coated QPM shows additional efficiency ~ 2.5 dB

Conversion efficiency enhanced in quasi-phase matched GaAs by 5 dB
THz Upconversion Detector Performance

Current Performance: NEP ~ 800 fW/Hz$^{1/2}$
Expect to scale NEP to 40 fW/Hz$^{1/2}$ in the near future
Summary

- Demonstrated sensitive optical detection Terahertz at room-temperature using commercial telecomm components
- Fabricated quasi-phase matched GaAs crystals using a diffusion bonding process
- Developed an AR coating for 1550nm radiation that absorbs minimally at THz
- Demonstrated conversion efficiency enhancements due to QPM AR-coated GaAs crystals
- THz detector NEP ~ 800 fW/Hz^{1/2}; comparable to liquid He cooled bolometer
- Expect significant improvements using more intense optical pump beam and longer QPM crystals.
Terahertz Transmission Properties

Material Attenuation at 326 GHz

- Data for typical sample thickness
- Loss increases significantly with frequency

Atmosphere Attenuation at THz

- Frequency (GHz)
- Atmospheric Absorption (dB/km)

- Bangkok
- Basra
- Berkeley
- Bellingham
- Boulder
- Buffalo
Optical Detection of THz: Comparison with Theory

**Experiment**

![Optical Idler at chopper frequency generated from THz upconversion](image1)

- Harmonics
- 3 dB discrepancy between theory and experiment
- Mode mismatch between optical pump and multimode THz beam
- Phase mismatch $\Delta k$ uncertainty
- Plane wave estimate used instead of Gaussian beams approximation

**Theory**

![Non-linear Crystal](image2)

\[
P_{\text{Idler}}(L) = \frac{1}{R_v} \int_{-\Delta f}^{+\Delta f} V^2 df \right]^{1/2}
\]

\[
P_{\text{Idler}} \approx 220 \text{ pW}
\]

\[
P_{\text{Pump}} = 100 \text{ [mW]}
\]

\[
P_{\text{Idler}}(L) \approx 440 \text{ pW}
\]

\[
\frac{P_{\text{Idler}}(L)}{P_{\text{THz}}(0)} = \frac{8\pi^2(d_{\text{eff}}')^2L^2I_{\text{Pump}}}{\epsilon_0n_Tn_tn_p\lambda_i^2} \left| \frac{\sin\left(\frac{\Delta kL}{2}\right)}{2} \right|^2 T_{\text{Filter}}
\]
Quasi Phase-matching by Diffusion-Bonding Bulk GaAs

- Fabricated 2 – layer, 3 – layer and 4 – layer diffusion bonded stacks
- Clean bond interfaces achieved
- Improved in-house polishing capability
- AR-coating 2-layer stack
Enhanced Upconversion using Quasi Phase-matched GaAs

- Demonstrated enhanced conversion efficiency with QPM crystal
- Upconverted THz signal is generated at chopper frequency
- Two-layer QPM crystal has ~5dB better performance than 4 mm bulk GaAs
- Two-layer QPM crystal has >20 dB better performance than 8 mm bulk GaAs
Optical Source Development and GaAs Characterization

Adaptable, High-power, Pulsed Optical Source

- Developed a highly adaptable high-power pulsed source; variable rep. rate, pulse width, center frequency
- SNR ~ 50dB; CW power > 4W; Peak power ~ 25kW

GaAs Characterization – Terahertz and Optical Frequencies

- Optical group index, \( n_g = 3.56 \); loss, \( \alpha = 0.065 \text{ cm}^{-1} \)
- Measured transmission spectral scans between 500-700 GHz
- Estimated THz loss, \( \alpha = 0.2 \text{ cm}^{-1} \);
Optimizing THz-to-Optical Conversion: Ongoing Experiments

- **New THz source: Virginia Diode Amplified Multiplier Chain**
  - Near Gaussian spatial mode
  - Spatial mode independent of frequency
- **Testing new QPM crystals**
- **Preliminary results indicate that better mode results in an improvement of > 3 dB**