Efficient Optical to Terahertz Wave Conversion through Plasmonic Antennas

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Abstract: Although unique potentials of terahertz wave for chemical identification, material characterization, biological sensing, and medical imaging have been recognized for quite a while, the relatively poor performance, higher costs, and bulky nature of current terahertz systems continue to impede their deployment in field settings. In this talk, I will describe some of our recent results on developing fundamentally new terahertz electronic/optoelectronic components and imaging/spectrometry architectures to mitigate performance limitations of existing terahertz systems. In specific, I will introduce new designs of high-performance photoconductive terahertz sources that utilize plasmonic antennas to offer terahertz radiation at record-high power levels of several milliwatts – demonstrating more than three orders of magnitude increase compared to the state of the art. I will describe that the unique capabilities of these plasmonic antennas can be further extended to develop terahertz detectors and heterodyne spectrometers with single-photon detection sensitivities over a broad terahertz bandwidth at room temperatures, which has not been possible through existing technologies. To achieve this significant performance improvement, plasmonic antennas and device architectures are optimized for operation at telecommunication wavelengths, where very high power, narrow linewidth, wavelength tunable, compact and cost-effective optical sources are commercially available. Therefore, our results pave the way to compact and low-cost terahertz sources, detectors, and spectrometers that could offer numerous opportunities for e.g., medical imaging and diagnostics, atmospheric sensing, pharmaceutical quality control, and security screening systems.

Mona Jarrahi received her B.S. degree in Electrical Engineering from Sharif University of Technology in 2000 and her M.S. and Ph.D. degrees in Electrical Engineering from Stanford University in 2003 and 2007. She served as a Postdoctoral Scholar at University of California Berkeley from 2007 to 2008. After serving as an Assistant Professor at University of Michigan Ann Arbor, she joined University of California Los Angeles in 2013 as an Associate Professor of Electrical Engineering and the Director of the Terahertz Electronics Laboratory. Her research group focuses on Terahertz, Millimeter-Wave Electronics and Optoelectronics; Imaging and Spectroscopy Systems; and Microwave Photonics. Prof. Jarrahi has made significant contributions to the development of ultrafast electronic and optoelectronic devices and integrated systems for
terahertz and millimeter-wave sensing, imaging, computing, and communication systems by utilizing novel materials, nanostructures, and quantum well structures as well as innovative plasmonic and optical concepts. In recognition of her outstanding achievements, Prof. Jarrahi has received several prestigious awards in her career including the Presidential Early Career Award for Scientists and Engineers (PECASE); Early Career Award in Nanotechnology from the IEEE Nanotechnology Council; Outstanding Young Engineer Award from the IEEE Microwave Theory and Techniques Society; Booker Fellowship from the United States National Committee of the International Union of Radio Science (USNC/URSI); Lot Shafai Mid-Career Distinguished Achievement Award from the IEEE Antennas and Propagation Society; Grainger Foundation Frontiers of Engineering Award from National Academy of Engineering; Friedrich Wilhelm Bessel Research Award from Alexander von Humboldt Foundation; Young Investigator Awards from the Army Research Office (ARO), the Office of Naval Research (ONR), and the Defense Advanced Research Projects Agency (DARPA); Early Career Award from the National Science Foundation (NSF); the Elizabeth C. Crosby Research Award from the University of Michigan; and best-paper awards at the International Microwave Symposium, International Symposium on Antennas and Propagation, and International Conference on Infrared, Millimeter, and Terahertz Waves. She has also been named a Kavli Fellow by the National Academy of Sciences. Prof. Jarrahi is actively involved in several professional societies and has been on program committees of several conferences from IEEE, OSA, and SPIE societies. She is a senior member of IEEE, OSA, and SPIE societies and serves as a member of the Terahertz Technology and Applications Committee of IEEE Microwave Theory and Techniques, an editorial board member of Journal of Infrared, Millimeter and Terahertz Waves, a Distinguished Lecturer of IEEE Microwave Theory and Techniques Society, a Traveling Lecturer of OSA, and a Visiting Lecturer of SPIE. In addition, she serves as a panelist and reviewer for National Science Foundation (NSF), National Institutes of Health (NIH), and Department of Energy (DOE).

Keywords: Terahertz Source, Terahertz Detector, Terahertz Imaging, Terahertz Spectroscopy, Plasmonics

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Significance of terahertz waves

Unique specifications of terahertz waves
- Rotational & vibrational frequencies of most molecules lie in terahertz region
- Terahertz waves can see through opaque materials with spectral fingerprints
- Several absorption lines for water lie in terahertz range
- Terahertz radiation is non-ionizing & non-destructive

Applications of terahertz waves
- Chemical sensing, material characterization, security screening, medical imaging and diagnostics, atmospheric and space studies
Significance of terahertz waves

Medical Imaging

Biological and Genomic studies
Nagel et. al, (RWTH Aachen)

Security Screening
http://www.teraview.com

Pharmaceutical Industry

Industrial Quality Control
Hu et. al, Optics Lett. 20 (1995)

Atmospheric /space studies
Physical limitations of existing terahertz sources

Electronic Sources

- At least two poles for current: \( \frac{1}{2\pi \tau_p} \) and \( \frac{1}{2\pi \tau_{RC}} \)

=> power roll-off \( \propto \frac{1}{f^4} \)

Optical Sources

- No radiation at photon energies lower than the lowest natural bandgap energy of \( \sim 40 \) meV (\( \sim 10 \) THz)

- Artificially engineered lower bandgap energies using quantum wells

Same physical limitations exist in optical & electrical terahertz detection schemes
Physical limitations of existing terahertz sources

Survey on the output power of various terahertz sources

Conventional photoconductive terahertz sources

Limitations of conventional schemes

- Extremely low quantum efficiencies due to long carrier transport path to bias electrodes
- Contact electrode spacing is limited by capacitive loading and diffraction limit
- Maximum output power limitation due to the carrier screening effect and thermal breakdown within small device active areas
Plasmonic photoconductive terahertz sources

Limitations of conventional schemes
- Extremely low quantum efficiencies due to long carrier transport path to bias electrodes
- Contact electrode spacing is limited by capacitive loading and diffraction limit
- Maximum output power limitation due to the carrier screening effect and thermal breakdown within small device active areas

Advantages of plasmonic contact electrodes
- Ultrafast response is achieved by reducing photo-carrier transport path to contact electrodes.
- High output power levels can be achieved by using large nano-aperture active areas without increasing the capacitive loading to the terahertz antenna
Design of plasmonic contact electrode gratings

- Several guided modes exist at wavelengths much larger than the slit periodicity: $\lambda_{\text{cutoff}} \approx d \sqrt{\varepsilon_s / \varepsilon_0}$

- The first guided mode is at the wavelength range much larger than the slit height ($l \gg h$), and the rest of guided modes are at the resonant wavelengths of the subwavelength slab waveguide formed by the subwavelength metallic slits.
First generation plasmonic source

Quantum efficiency enhancement by using plasmonic electrodes
- No shadowing by the contact electrodes
- Photocarrier concentration enhancement near the contact electrode
First generation plasmonic source

- Two conventional and plasmonic photoconductive emitters are integrated with identical bowtie antennas and fabricated side-by-side on the same LT-GaAs substrate and tested under the same conditions.
- Laser beam focus and polarization was optimized for each emitter by maximizing radiated power.

50 times enhancement in optical-to-terahertz conversion efficiencies offered by the plasmonic photoconductive terahertz source

Berry et al., Nature Communications 4 (2013)
Terahertz detection sensitivity enhancement by utilizing plasmonic contact electrodes
Demonstration of terahertz detection responsivity enhancement

30 times higher responsivity levels are offered by the plasmonic photoconductive detector compared to the conventional detector over the 0.1-1.5 THz frequency range

Berry et al., Nature Communications 4 (2013)
Noise analysis of plasmonic and conventional photoconductive terahertz detectors

- The output noise level of the photoconductive detectors is estimated by measuring the time-domain output photocurrent of each photoconductive detector while blocking the incident terahertz radiation, and calculating the frequency components of the measured time-domain output photocurrents, subsequently.

- Conventional and plasmonic photoconductive detector prototypes have similar output noise current levels at 50 mW optical pump power. This is due to the fact that the dominant noise source in both photoconductive detector prototypes is the Johnson–Nyquist noise rather than the photoconductor Shot noise.

Because of the same output noise levels, the 30 times responsivity enhancement offered by the plasmonic photoconductive detector over the 0.1-1.5 THz frequency range, implied 30 times detection sensitivity enhancement over this frequency range.

Berry et al., Nature Communications 4 (2013)
Large area plasmonic photoconductive emitters

- Extending radiation bandwidth
- Suppressing the carrier screening effect and thermal breakdown at high pump power levels

Second generation plasmonic source

- A high-aspect ratio plasmonic grating is employed to allow efficient optical pump transmission into the nanoscale photoconductor active regions, localizing the majority of the photocarriers in close proximity to the contact electrodes.
- A logarithmic spiral antenna is employed as the terahertz radiating element to offer broadband radiation properties required for pulsed terahertz generation.
Second generation plasmonic source

Quantum efficiency enhancement by using 3D plasmonic electrodes

- Photocarriers generated away from the surface of the substrate do not efficiently contribute to terahertz generation when using 2D plasmonic contacts.
- Photocarriers generated deep in the substrate can efficiently contribute to terahertz generation when using 3D plasmonic contacts.
Several guided modes exist at wavelengths much larger than the slit periodicity: $\lambda_{\text{cutoff}} \approx d \sqrt{\varepsilon_s / \varepsilon_0}$.

The first guided mode is at the wavelength range much larger than the slit height ($\lambda \gg h$), and the rest of guided modes are at the resonant wavelengths of the subwavelength slab waveguide formed by the subwavelength metallic slits.
Design of 3D plasmonic gratings

- The high-aspect ratio grating is designed to excite the 4th order TEM guided mode of the subwavelength slab waveguides formed by the metallic gratings in response to a TM-polarized optical pump.

- Optical pump transmission through the high-aspect ratio gratings is greatly dependent on the grating height.

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Fabrication of 3D plasmonic gratings

Step 1: Depositing a 200nm thick SiO₂ film on top of GaAs substrate

Step 2: Electron beam lithography, Ni (80nm) deposition and liftoff to pattern a hard mask grating layer.

Step 3: Etching 200nm-height SiO₂ grating followed by etching (ICP-RIE) 400nm high-aspect ratio GaAs grating

Step 4: Sputtering Ti/Au (20Å/200Å) on the SiO₂/GaAs grating to form ohmic contact

Step 5: Wet Etching SiO₂ grating and liftoff Au above the SiO₂/GaAs grating interface.

Step 6: Depositing anti-reflection coating (2000Å) to reduce Fresnel reflection loss.

Characterization of 3D plasmonic gratings

- 70% optical pump transmission through the high-aspect ratio plasmonic gratings at 800 nm
- Strong dependence of the optical pump transmission on the grating height

Second generation plasmonic source

- Two plasmonic photoconductive emitters with 2D and 3D plasmonic electrodes integrated with identical log-spiral antennas and fabricated side-by-side on the same LT-GaAs substrate and tested under the same conditions.
- Laser beam focus and polarization was optimized for each emitter by maximizing radiated power.

The photoconductive source with 3D plasmonic contact electrodes generates an order of magnitude higher terahertz power in the 0.1-2 THz frequency range, exhibiting a record-high optical-to-terahertz conversion efficiency of 7.5%

Yang et al., Trans. THz Sci. Technol.. 4 (2014)
First generation plasmonic photomixers

Tradeoff between radiation power and linewidth

Pushing toward higher radiation powers

**Employing a 2D array of terahertz emitters**
- Further reduction of the carrier screening effect and thermal breakdown

**Employing Spiral terahertz antennas**
- Radiation efficiency-bandwidth optimization

*Berry et al., Appl. Phys. Lett. 104 (2014)*
Pushing toward fully integrated terahertz systems

Yang et al., Opt. Express. 23 (2015)
Pushing toward fully integrated terahertz systems

Yang et al., Opt. Express. 23 (2015)
Application of plasmonic terahertz emitters for communication

- The required data rate is projected to be 100 Gbit/s by 2020.
- The speed of today's wireless communication systems is limited by carrier frequencies less than 300 GHz.

*T. Nagatsuma et. Al., IMS Digest (2014)*
Heterodyne terahertz spectrometry using plasmonic photoconductors

- Heterodyne terahertz detectors with optical pump eliminate the need for terahertz local oscillators and, therefore, offer significantly high spectrometry bandwidths.
- Combination of plasmonic photomixers with widely tunable optical sources with high spectral purity and narrow linewidths offer broadband terahertz spectrometry with high spectral resolution and unprecedented sensitivity levels.
Heterodyne terahertz spectrometry using plasmonic photoconductors

$P_{\text{opt}} = 100 \text{ mW, 1\% duty cycle}$

~ 300K DSB noise temperature @ 100 GHz
Summary

- Demonstration of efficiency and output power enhancement by using plasmonic photoconductive terahertz sources
- Demonstration of detection sensitivity and bandwidth enhancement by using plasmonic photoconductive terahertz detectors and spectrometers
- Demonstration of multi-spectral metallic gratings enabling optical-pump terahertz-probe measurements at nan-scale
- The significant performance enhancements offered by plasmonic terahertz optoelectronics have a transformational impact on future terahertz imaging and sensing systems.
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