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High Power Pulsed Terahertz Light Generation from Superconducting Antenna Arrays

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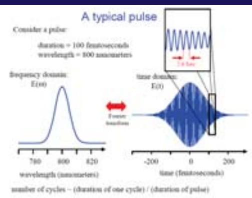
Abstract

Terahertz radiation is invaluable in spectroscopy and imaging due to its nondestructive nature. It has become a key focus for those wishing to develop sensors capable of detecting weapons and narcotics unobtrusively and at a distance. An ultrafast pulsed (femtoseconds) laser incident on a superconducting ring causes the emission of terahertz (THz) radiation. It is theorized that the radiation is a result of the supercurrent being modulated by the breaking and recombining of Cooper pairs on the order of picoseconds, where the time scale determines the frequency of the emitted radiation. We propose to investigate the terahertz emission from Yttrium barium copper oxide (YBCO) superconducting ring arrays of various geometries. Specifically, we will investigate the dependence of the time dynamics of the terahertz radiation, the ultrafast femtosecond laser pump power dependence and time dynamics, the antenna geometry, and the efficiency of the system. The theoretical work completed thus far anticipates high power and bandwidth in the terahertz regime. Furthermore, a complete characterization of the emitted radiation will provide insight into the microscopic properties of the superconductor's supercarriers.

Pulsed Terahertz Light Using a Photoconductive Antenna

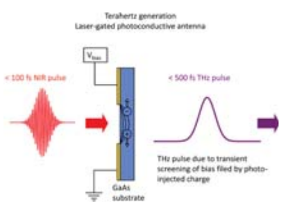
An Ultrafast Laser: Pulse

An ultrafast laser is distinct from a continuous wave laser, such as a laser pointer. An ultrafast laser emits a brief burst of light that typically lasts less than 100 femtoseconds. For a basic ultrafast oscillator system, a typical repetition rate is 80 MHz.



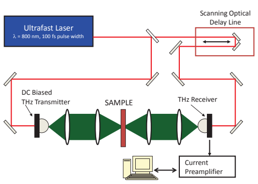
Pulsed Terahertz Emission

- An ultrafast laser **pump pulse** is incident on a dipole antenna on a gallium arsenide semiconductor substrate.
- The pump pulse excites electrons from the valence band to the conduction band, i.e., the photoconductive effect.
- A voltage, applied across the antenna gap, accelerates the charge carriers.
- A terahertz pulse is emitted as a result of this induces a time-varying current.



Vincent Wallace, http://spie.org/x32216.xml

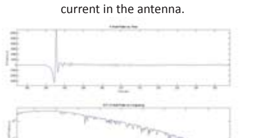
Terahertz Time-Domain (TD) System

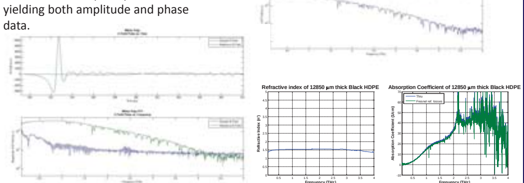


- Terahertz light is detected by using a **probe pulse** that is split from the main beam.
- The probe pulse travels along the delay line, a set of mirrors that can vary in distance.
- By varying the optical delay using a delay line, time-domain scanning is achieved.
- A second photoconductive antenna (LTG-GaAs) is used for detection.
- The terahertz electric field induces a current in the antenna.

Terahertz TD Spectroscopy

The terahertz electric field in the time domain is directly measured. A Fast Fourier Transform (FFT) transforms the data into the frequency-domain, yielding both amplitude and phase data.





Comparison of the Fourier spectrum yields... → $$\frac{E_s}{E_r} = \frac{A_s e^{j\phi}}{A_r e^{j\varphi}} = T(n) * \exp\left[\frac{-\alpha d}{2} + \frac{in\omega d}{c_0}\right]$$

From which, we can find the absorption coefficient → $$(\alpha d) = -20 * \log\left[\left[\frac{A_s}{A_r}\right] / T(n)\right]$$

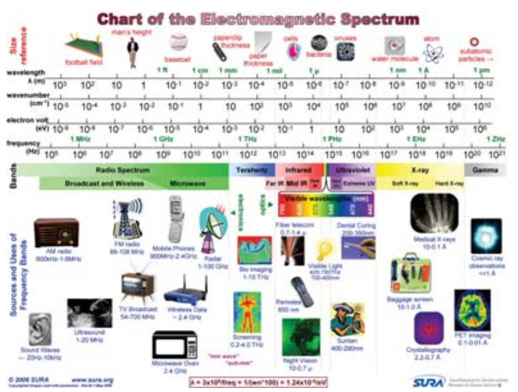
and the refractive index → $$(nd) = 1 + \frac{c}{\omega}[\phi - \varphi]$$

$$(n_{real} + \alpha i)^2 = (n(\omega))^2 = \varepsilon(\omega) = \varepsilon_\infty + \frac{i\sigma(\omega)}{\omega\varepsilon_0} = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\Gamma)}$$

Superconductors

- Yttrium barium copper oxide (YBCO) is a high temperature superconductor (HTSC) with a critical temperature of approximately 92K, the first material observed to demonstrate superconductivity above the boiling point of nitrogen (77K).
- When cooled to less than the critical temperature ($T < T_c$) and charged with less than the critical current ($I < I_c$), the superconductor exhibits zero resistivity.
- According to BCS theory , at $T < T_c$, the electrons experience an attractive force due to lattice vibrations in the material, and with little thermal excitation to disturb them, they condense into pairs with one spin-up and one spin-down and opposite momentum.
- These Cooper pairs are boson-like, allowing the electrons to settle into a lower energy state than would otherwise be permissible according to the Pauli exclusion principle.
- The Cooper pairs, instead, form a single wave in the material, and thus, a disturbance in a 'single' electron does not disturb the unified wave. **Resistivity goes to zero.**

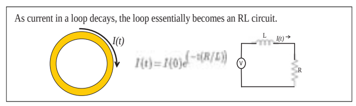
Terahertz Radiation



(BERST) Antennas

Ring Antenna Theory

A decaying RL circuit is an approximate model for the changing current in a superconducting ring due to an incident ultrafast laser pulse



$$P_{rad}(t) = \frac{\pi a^4}{6\varepsilon_0 c^5}\left[\ddot{I}\left(t - \frac{r}{c}\right)\right]^2 \Rightarrow P_{rad} \sim \frac{\pi a^4}{6\varepsilon_0 c^5}\frac{I^2(0)}{\tau^4}$$

The power is proportional to the second time derivative of the current.

The radiating efficiency

$$\eta = \frac{\pi a^4}{6\varepsilon_0 c^5}\frac{R^3}{L^4}$$

Approaches 1 when the characteristic decay time

$$\tau \sim \left(\frac{\pi a^4}{3L\varepsilon_0 c^5}\right)^{1/3}$$

Approaches 2E-11 s

Efficiency

- For a = 1cm and wire diameter of 1 mm,
- ***$\tau \sim 2 \cdot 10^{-11}$* sec would achieve 100% radiation efficiency**

BERST Antenna Array

BERST antenna array consists of 2-D array of superconducting rings. Instead of connecting electrodes to each ring individually, a current is varied in a solenoid, and the changing magnetic field induces a current in the rings.

Cooper Pairs Break and Recombine

- An ultrafast laser pulse is incident on a superconducting ring in a superconducting state with a current $I < I_c$.
- The incident pulse breaks the Cooper pairs, restoring resistivity in the ring for approximately 20 picoseconds.
- The superconducting current decreases in magnitude in response to the resistance, decelerating the flowing electrons temporarily and causing the emission of the terahertz radiation.
- The Cooper pairs then recombine, and superconductivity resumes.
- It has been theoretically shown and experimentally verified that the sub-picosecond timescale results in terahertz radiation.

Brian Dolasinski, et al.
"Ultrafast photo-response in superconductive isotropic radiators for microwave generation", Proc. SPIE9347, Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications XIV, 93470H (2015); doi:10.1117/12.2083505;

Testing Plan and Parameters

Preliminary tests are necessary to verify the integrity of the electro-optic detection system. To do this, we will use a p-doped indium arsenide (p-InAs) chip as an antenna, as it is a well-understood emitter of terahertz radiation.

Basic research of terahertz emission from superconducting rings requires an investigation of the following:

- Time dynamics of the emitted terahertz radiation
- The ultrafast laser pump power dependence
- The antenna geometry
- The efficiency of the system
- Verification of the theoretical power output and efficiency of BERST antenna arrays in the terahertz regime
- Theoretical understanding of the superconducting-to-normal transition (SN)

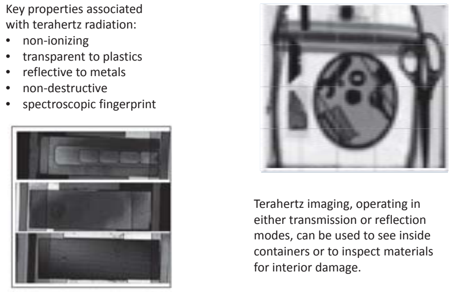
References

1. *Vincent Wallace, http://spie.org/x32216.xml*
2. *Brian Dolasinski, et al. "Ultrafast photo-response in superconductive isotropic radiators for microwave generation", Proc. SPIE9347, Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications XIV, 93470H (2015); doi:10.1117/12.2083505;*

Motivation

Key properties associated with terahertz radiation:

- non-ionizing
- transparent to plastics
- reflective to metals
- non-destructive
- spectroscopic fingerprint



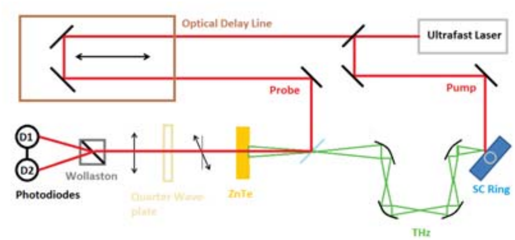
Terahertz imaging, operating in either transmission or reflection modes, can be used to see inside containers or to inspect materials for interior damage.

Terahertz radiation has already found use in non-destructive imaging of valuable artwork. It has been proposed as a sensor for weapons and narcotics and as a means of imaging cancer of the skin.

Experimental Setup

Primary experimental equipment:

- Ultrafast laser (15 femtoseconds)
- Superconducting yttrium barium copper oxide ring (BERST antenna)
- Electro-optic sampling detection (ZnTe or GaP)



Detection Scheme: Electro-optic Sampling

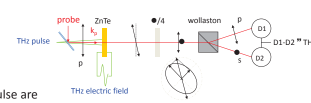
Theory

$$n_o(E) \cong n_o - \frac{1}{2}n_o^3 r_{13} E$$

Electro-optic sampling exploits birefringence of the first order, Pockel's effect. The index of refraction is a function of an applied electric field. An incident THz pulse can change the indices of refraction, which can be detected as a change the polarization of the pulse.

Setup

- As before, an ultrafast laser is used as both the pump pulse for generating the terahertz radiation as well as a probe pulse for detection.
- The THz pulse and the probe pulse are simultaneously transmitted through the detection crystal (ZnTe).
- The polarization change is measured via a quarter wave-plate and wollaston beam splitter.



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