# Generation of THz radiation by excitation of InAs with a femtosecond free-electron laser


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**Abstract:** Terahertz (THz) radiation is generated by exciting an un-doped InAs wafer with a femtosecond free-electron laser (FEL) at the Thomas Jefferson National Accelerator Facility. A microwatt level of THz radiation is detected from the unbiased InAs emitter when it is excited with the femtosecond FEL pulses operated at a wavelength of 1.06 μm and 10 W average power.


## 1. Introduction

A high power, pulsed terahertz (THz) radiation source is required for applications such as 2-D real-time THz imaging and studies of nonlinear effects at THz frequencies. It was reported that unbiased InAs emits THz radiation efficiently when it is excited with femtosecond IR pulses [1]. Because the radiation power increases quadratically with excitation laser intensity, it is expected that we can achieve a high THz radiation power of mW level using a high power laser.

In this paper we report our preliminary results of generating high power THz radiation by using a free-electron laser (FEL) at the Thomas Jefferson National Accelerator Facility (JLab). The FEL can generate femtosecond light pulses (~500 fsec) with more than 1 kW average power at a wavelength around 3 μm, and more than 200 W at its third harmonics (1.06 μm). We used this high power FEL to excite an unbiased InAs wafer as the THz emitter. During the first trial, we carried out an experiment using relatively low power for third harmonic lasing (THL) of the FEL. This was done because the THL wavelength is close to the wavelength of Ti: sapphire lasers, which is generally used for the excitation of the THz emitters, and thus it is easier for us to handle that power level and wavelength of the FEL beam with a minor change in our conventional optics.

## 2. Experiment

The FEL was operated at a repetition rate of 18.7 MHz for micro-pulses and 60 Hz for macro pulses. The FEL generated THL light pulses at a wavelength of 1.06 μm. The pulse width of the THL FEL, estimated from the spectral bandwidth, was about 0.5 ps. The width of the macro-pulse was changed from 200-μsec to 10 msec, by which the average FEL power was changed. On the other hand, the energy of each FEL pulse was kept constant (~ 2 μJ/pulse) during the experiment. The FEL beam was collimated to a diameter of 5 mm by a pair of concave reflecting mirrors, and directed to an un-doped (n-type) 2-inch InAs wafer mounted on a thick copper block using heat sink compound. The FEL beam was p-polarized and was incident on the InAs wafer at an angle close to the Brewster angle (76 deg) in order to increase the excitation efficiency and reduce the unwanted reflection of the pump beam. The maximum pump power was restricted to less than 10 W because the 1-inch optics used cannot handle a high power laser of more than 10 W. The THz radiation emitted in the direction of optical reflection of the pump beam was detected by a 4.2-K cooled InSb hot-electron bolometer, whose responsivity was carefully calibrated by using standard radiation sources (a high-pressure Hg lamp and black-body radiation), and well-characterized low-pass filters. To block the pump beam reflected from the emitter, a 0.5-mm thick Si plate and 3-mm thick black plastic plate were inserted between the bolometer and the emitter. A wire-grid THz polarizer was used to analyze the polarization of the radiation. To study the THz radiation spectrum, a reflection mirror in the FEL beam path was replaced with a Michelson interferometer, and the interferogram of the THz radiation, due to the double pump pulses, was measured.

## 3. Results and discussion

Figure 1 shows the dependence of the bolometer signal on the rotation angle θ of the wire-grid polarizer when the emitter was pumped with 0.55 W of FEL power. The $\sin^2\theta$ dependence indicates that the detected radiation is almost linearly polarized to the horizontal direction (p-polarized): the detected signal is due to the coherent THz radiation and not due to the residual FEL beam incident on the bolometer (the polarizer is not sensitive to 1 μm light) or the thermal radiation induced by the heat on the sample (thermal radiation is usually un-polarized).

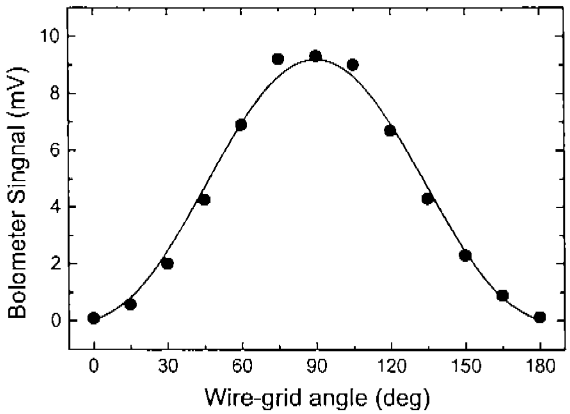


**Fig. 1.** The dependence of the signal on the rotation angle of a wire-grid polarization filter (solid circle). The solid line indicates a $\sin^2\theta$ dependence, which is expected for linearly polarized radiation.

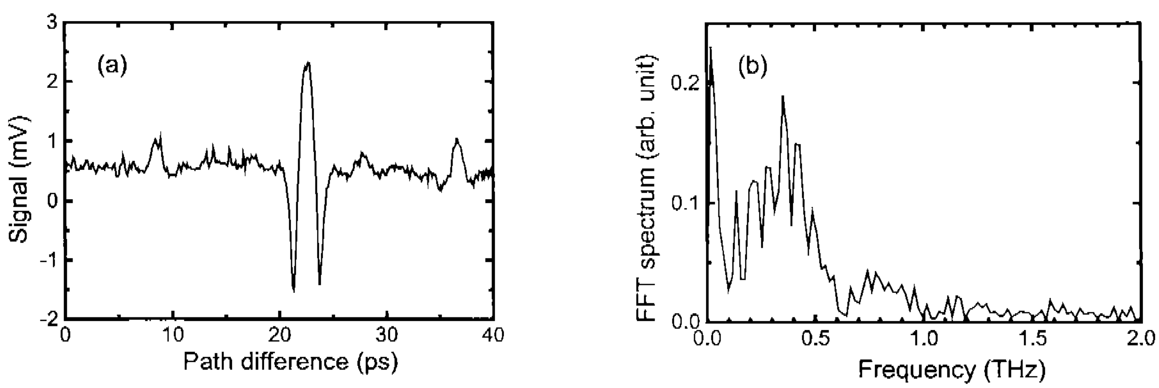


**Fig. 2.** (a) Interferogram for the THz radiation generated from InAs and (b) its FFT spectrum.

Figure 2(a) shows the interferogram of the THz radiation measured with the Michelson interferometer, and Fig. 2(b) shows its FFT power spectrum. The peak-to-peak interval of the interferogram is 2.4 ps and the spectral peak is about 0.4 THz, corresponding with the peak interval. The side peaks observed at 13 ps away from the center peak correspond to multiple reflections in the Si plate and manifests in the FFT spectrum as equally spaced peaks. Although the spectral distribution is not so broad, it seems reasonable when we consider the relatively wide pulse width of the FEL and the strong absorption for high-frequency components of THz radiation in the black plastic plate (~ 99% at 1 THz).

The maximum power directly detected with the bolometer was estimated to be about 1 μW for a 10 W FEL power. Considering the reflection and absorption loss due to the Si (70% loss) and plastic plates (60% loss), the generated power was estimated to be about 8 μW. This suggests the efficiency of the THz radiation from the InAs emitter is on the order of $10^{-7}$. The observed efficiency for excitation with a mode-locked Ti: sapphire laser ($\lambda \sim 800$ nm, pulse energy ~ 10 nJ/pulse) was on the order of $10^{-6}$. The reason for the low emission efficiency with FEL excitation can be explained by the saturation effect. Fig. 3 shows the FEL intensity dependence of the bolometer signal measured by using a variable optical attenuator. The unit for the FEL intensity was normalized by the intensity without the attenuator. As clearly shown in Fig. 3, the THz radiation power is strongly saturated at higher intensities. The THz radiation power expected at the maximum pump intensity (without the attenuator) is estimated to be about 30 times higher than the measured value when we assume a quadratic dependence of the THz radiation power on the FEL intensity (shown by a dashed line in Fig. 3) as observed at lower intensities (un-saturated regime).

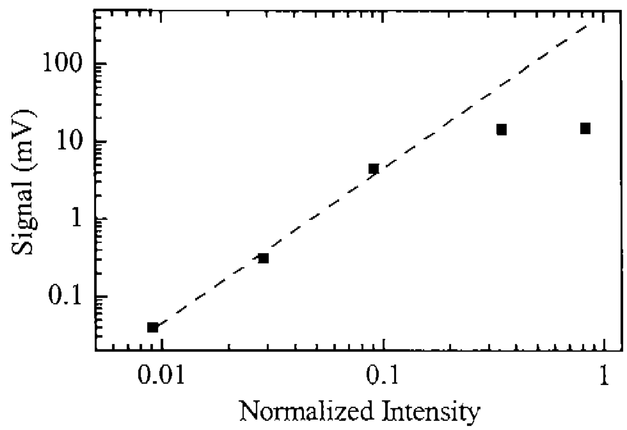


**Fig. 3.** Intensity dependence of THz power signal from bolometer. The intensity was normalized to that without any optical attenuator. The dashed line indicates a quadratic dependence (slope 2) on the excitation intensity.

Although we didn't apply any magnetic field bias to the InAs emitter in this experiment, it was reported that the THz emission efficiency could be improved by a factor of 20 when a strong magnetic field (~ 2T) is applied to InAs [1]. Therefore, by reducing the saturation effect (using a larger excitation area) and by applying a strong magnetic field, we believe it is quite feasible to achieve 1 mW level THz radiation with the femtosecond FEL excitation of the InAs emitter.

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**Reference:**

[1] Sarukura *et al*, J. Appl. Phys. 84, 654 (1998).