Single Shot High Resolution THz Upconversion Spectrometer

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***Abstract*— We have designed an upconversion spectrometer that has been used to measure the frequency of individual pulses from the UCSB Free Electron Lasers (FEL). The FEL THz radiation is mixed with NIR radiation in a non-linear optical crystal to generate sum and difference frequency radiation. The FEL frequency is obtained by measuring the frequency difference between the fundamental radiation and the sum or difference frequency sideband, which is accomplished using a 1 m focal length Czerny-Turner spectrometer. Single shot sum and difference frequency generation of NIR and THz radiation is demonstrated with accuracy up to 0.1 cm^{-1} and with signal to noise ratios of greater than 100:1.**

I. Introduction And Background

UCSB currently has 2 high power, narrow band, Free Electron Laser (FEL) beams, the Millimeter (MM) and Far Infrared (FIR) FELs. For a variety of reasons, it is necessary to be able to precisely measure the frequency of these lasers, but currently there is a lack of detectors with this capability. It is very difficult to do THz spectroscopy due to a lack of CCD's and gratings that function efficiently in the THz regime. The frequency of the THz radiation can be measured by an interferometer but there are problems with moving parts, a lack of high resolution and an inability to measure individual FEL pulses. We have proposed and developed a single shot high resolution FEL upconversion spectrometer that requires no moving parts with a design that utilizes sum and difference frequency generation (SFG and DFG) in a non-linear optical crystal to measure FEL frequencies.

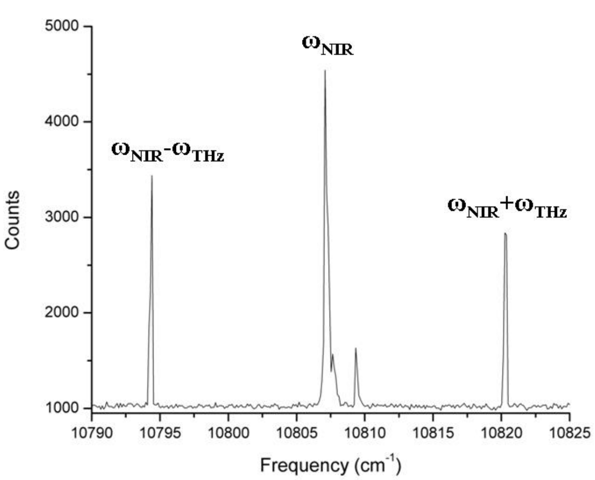

Figure 1: The spectrum of the NIR laser, with sidebands (SFG and DFG), during a single ~13 cm^{-1} FEL pulse. The small peak at ~10810 cm^{-1} is a second Titanium:Sapphire laser mode.

The frequency of the UCSB FELs is tuned by varying the terminal voltage of a National Electrostatics Corporation electrostatic accelerator between 2 and 6 MV. Precise knowledge of the FEL frequency is important to any experiment that uses a FEL, and as in any laser system, it is desirable to accurately calibrate the laser source. We have recently been able to measure the FEL frequency at a number of different terminal voltages, giving us the ability to calibrate the FELs with high precision.

Sum and difference frequency generation is a second order non-linear optical process, which makes it necessary to use a crystal with a large second order dielectric susceptibility in order to achieve high conversion efficiencies. We can estimate the maximum power that will be generated during sum and difference frequency generation by using the plane-wave fixed-field approximation [1], assuming that the power generated does not deplete the pump laser:

$$P_{SFG} = \frac{2^5\,\pi^2\,d_{eff}^2\,P_{NIR}\,P_{THz}}{\varepsilon_0\,c\,n_{THz}\,n_{NIR}^2\,\lambda_{SFG}^2\,A|\Delta k|^2} \qquad (1)$$

This power is strongly dependent on Δk, which is the phase matching condition. The tunable Titanium:Sapphire laser gave us the ability to change wavelengths between 800nm and 935nm to minimize the phase mismatch and maximize our signal. The power generated during an individual FEL pulse by sum or difference frequency generation in a GaP <110> crystal ranges from hundreds of nW to tens of μW depending on the FEL frequency and pump beam powers. Table 1 shows the approximate predicted values and measured values of SFG power assuming the following values: P_{NIR} = 10 mW, P_{FEL} = 100 W, d_{eff} = 100 pm/V [2], A=1 mm^2 and λ_{NIR} = 925 nm.

FEL Frequency (THz)	FEL Frequency (cm^{-1})	Predicted SFG Power (μW)	Approximate Measured Power (μW)
0.3	10	350	30
0.6	20	200	10
1.5	50	30	2
3	100	6	.75 (at 84 cm^{-1})

Table 1: Predicted and measured values of SFG power for a number of FEL frequencies.

Though the predicted values for the power of a sum or difference frequency sideband are higher than the actual values, they are still within about one order of magnitude of

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the measured power and we believe the previous equation provides a reasonable approximation of our system.

II. Experiment and Results

The FEL radiation is collected by a 4" focal length, 2" clear aperture parabolic mirror, reflected by a dichroic mirror (ITO coated glass), and then focused onto a GaP mixing crystal. A 0.5 mm GaP <110> crystal is mounted in a rotation stage to optimize the polarization of the generated radiation.

The NIR radiation is provided by a Coherent 890 Titanum:Sapphire laser which is fiber coupled to the experiment by a 62 µm core cable. The NIR radiation then passes through a Glan Taylor polarizer set to transmit vertically polarized light. The NIR and FEL radiation are mixed at the dichroic mirror and fall onto the mixing crystal. The sum and difference frequency radiation propagates co-linear to the NIR beam but has a polarization dependent on the orientation of the mixing crystal. A Glan Taylor polarizer set to transmit horizontally polarized light attenuates the vertically polarized NIR beam, and the mixing crystal is adjusted so that the sidebands are transmitted.

The NIR beam is focused into the Czerny-Turner spectrometer using a 20 mm focal length lens, is then collimated by a 0.75 m focal length mirror, strikes a 50 mm wide diffraction grating and then the first order beam is sent to a 1 m focal length mirror and focused onto a linear CCD array (see Figure 2). This diffraction grating has 1800 grooves/mm, which gives us a resolving power of 90000, and leads to a maximum resolution of 0.1 cm^{-1} at NIR frequencies.

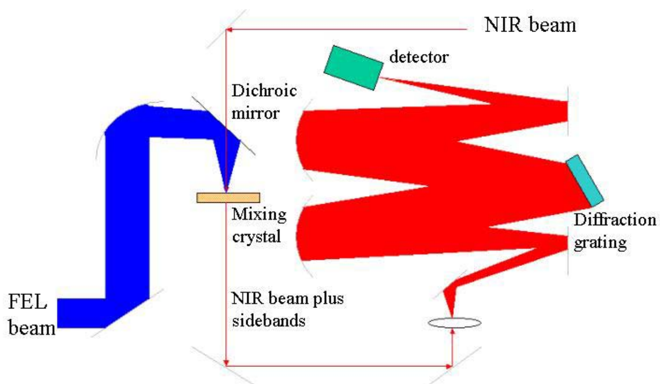

Figure 2: Schematic representation of experimental setup.

An Ocean Optics USB4000 card utilizes a 3648 pixel linear CCD array with each pixel having a width of 8 µm. The detector is run in hardware-triggered mode with a shutter time of 10 µs and is externally triggered by the FEL advanced trigger. The FEL pulse is usually between 3-8 µs and is timed such that the detector collects the full pulse during the 10 µs when the shutter is open. We use peak detect programs in Labview to find the difference in frequency between the NIR and sideband peaks, which yields us the FEL frequency.

We currently have been able to make single shot measurements of individual FEL pulses with resolution as good as 0.1 cm^{-1} at frequencies between ~13 and ~20 cm^{-1} on the MM FEL and between ~35 and ~85 cm^{-1} on the FIR FEL. For a sideband generated during an individual FEL pulse, we are able to obtain signal to noise ratios of better than 10:1 at 50 cm^{-1} and 100:1 at 13 cm^{-1} (see figure 1). Using these measured frequencies, we are able to perform highly precise calibrations of the Millimeter and Far Infrared FELs.

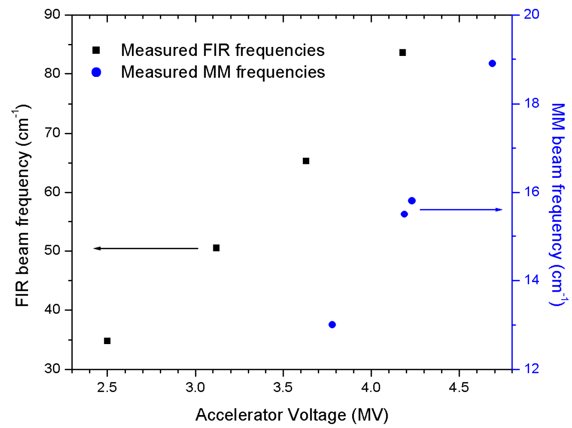

Figure 3: Plot of FEL frequency vs. accelerator voltage for the FIR and MM Free Electron Lasers.

In conclusion, we have demonstrated the ability to measure the frequency of individual THz pulses from a Free Electron Laser with 0.1 cm^{-1} resolution utilizing our single shot THz upconversion spectrometer.

References

1. Dmitriev, V.G., Gurzadyan G.G., Nikogosyan D.N., "Optics of Nonlinear Crystals: Calculation of Nonlinear Frequency-Conversion Efficiency" in *Handbook of Nonlinear Optical Crystals,* A.E. Siegman, Ed. New York:Springer-Verlag, 1991, pp.38-49.
2. Shoji, T. Kondo, A. Kitamoto, M. Shirane, and R. Ito, "Absolute scale of second-order nonlinear-optical coefficients," in *Journal of the Optical Society of America B*, vol. 14, 1997, pp. 2268-2294.