A Tunable THz Source for Spectroscopy and Imaging Applications

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Abstract

A Tunable Terahertz Source (TTS) is being developed for commercial use by Vermont Photonics under exclusive license. The TTS is based on the Smith-Purcell free electron laser first reported by the late Professor John E. Walsh and his co-workers.[1] The TTS is continuously tunable from less than 0.3 THz to more than 3 THz (10-100 cm^{-1}). It can be operated CW or pulsed, with repetition rates from DC to kHz. Detailed output characteristics will be presented along with examples of use in spectroscopy systems using a grating monochromator, a Fourier transform interferometer or a scanning Fabry Perot etalon.

Introduction

The Smith-Purcell Tunable Terahertz Source ™ (TTS) was invented by the late John E. Walsh at Dartmouth College in the same laboratory in which Ernest Fox Nichols first observed far infrared radiation in the early 20th century. From the late 1980's until his untimely death last year, Professor Walsh and his co-workers continued to study the physics of what they called a grating-coupled or Smith-Purcell free electron laser. The work culminated in the publication of the Physical Review Letter cited in the abstract above, in the issuance of a United States Patent[2] (European patents are pending), and contributed to the award to Professor Walsh of the International Prize for Free Electron Laser Physics in 1998.

Figure 1 shows a schematic of the Smith-Purcell grating coupled free electron laser. This elegant structure is reminiscent of the simplicity of the fundamental device for making microwaves, the magnetron. Like the magnetron, the present device incorporates the shortest possible path for energy flow between the free energy of an electron stream as it is converted into the energy in the radiating electromagnetic field, in this case in the range of frequencies from about 0.3 THz to 3.0 THz. Like the magnetron, the Smith-Purcell Tunable Terahertz Source can be seen as a kind of light flute or whistle. The fundamental interaction between the electrons in the beam and the electrons in the conducting material of the grating couples the kinetic energy of the free electrons in the electron beam into an oscillation. The interaction then amplifies the electromagnetic field generated by both the beam electrons and the electrons in the conducting material. The component of the electric field thus generated that is along the electron beam trajectory has a frequency which dictates a certain phase velocity along that trajectory which is slightly less than the velocity of an electron in the beam. Consequently, it will experience amplification as the electric field energy grows at the expense of the electron's kinetic energy, which is being reduced as the electron is being slowed by the wave that the electron was initially trying to overtake. An excellent intuitive description of the Smith-Purcell effect is given by Shurcliff and Ballard [4]

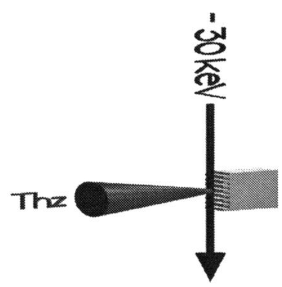

Fig. 1: Fundamental Smith Purcell structure. "It's simple. It's just a kind of whistle", I. I. Rabi describing the British magnetron to colleagues at the MIT Rad Lab [3].

Vermont Photonics, under exclusive license, has been supporting the work at Dartmouth and collaborating with the staff there since 1988. Much theoretical and experimental work is being carried on by the Dartmouth group now headed by Prof. Hayden Brownell [5], while Vermont Photonics continues a program of engineering development to improve the utility of the source for a wide variety of researchers in the terahertz or far infrared field.

Results

Figure 2 shows a plot of four successive manual scans of a Fabry Perot etalon at four different electron beam voltages. Part of the TTS output was split off to a second detector so that

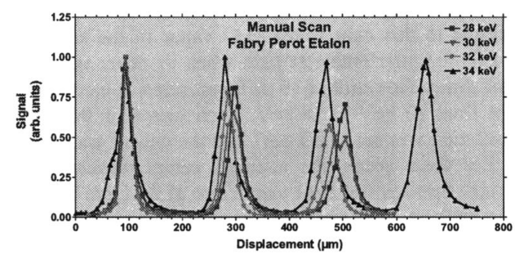

Fig. 2: Manual Scan of Fabry Perot Etalon.

the total power output could be monitored during the time it takes to make a manual scan of the etalon and record the data. The power through the etalon was normalized to the reference signal for each data point. The data show the spacing between peaks (a measure of the peak wavelength) decreasing with increasing beam voltage. The dip in the 3rd peak for 30keV is the H_2O vapor line..

Figure 3 shows a plot of five successive scans using a grating monochromator. As in the previous case, the data are normalized to the reference signal. The data clearly show the absorption line of water vapor centered at 25.1 cm^{-1} (about 398 μm wavelength).

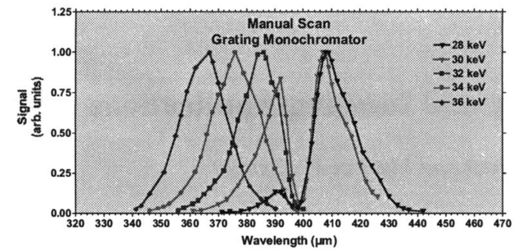

Fig. 3: Manual Scan of Grating Monochromator.

The next set of data shows the results of a variety of scans with the FTIR Spectrometer. All of the scans were made using the same grating structure. The electron beam is pulsed with a rectangular pulse of 1 millisecond width and 100 Hz repetition rate. These measurements could be made without a lock-in amplifier since the signal to noise ratio and source brightness are sufficiently good, but we choose to use the lock-in

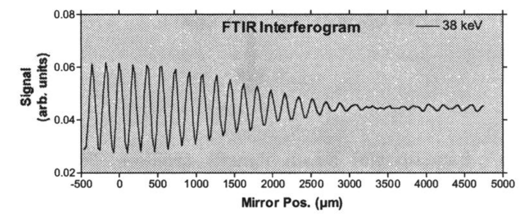

Fig. 4: FTIR Interferogram

amplifier to increase the signal to noise ratio even further. A very stable reference frequency is provided by the same pulser which turns the electron beam on and off so no external chopper is necessary. The time taken for each FTIR scan shown here ranges from 60 seconds to 360 seconds depending on the resolution and cut-off wavenumber of the scan. Figure 4 shows an interferogram generated by a single scan with cut-off set at 100 cm^{-1} and resolution at 1 cm^{-1}. Figure 5 shows the transformed spectrum resulting from this interferogram. Figure 6 shows spectral plots of FTIR scans at three different electron beam voltages showing the tuning of the source. These voltages were chosen to avoid the absorption peak at 25.1 cm^{-1}. The next set of FTIR scans shown in Figure 7 demonstrates how the source can be used for THz absorption spectroscopy. The sample in this case is the H_2O vapor in the ambient air which fills the interferometer path when its cover is not used. The plot shows the result of 19 different scans at electron beam voltages from 20 keV to 38 keV. Each scan took 90 seconds. The resolution was set to 0.3 cm^{-1} and the cut-off was set to 30 cm^{-1}. For these scans, the source's center wavelength was tuned right through the H_2O vapor line at 25.1 cm^{-1}. In these plots the peak value of each trace is set to one, and all the data in that trace are normalized to the peak. This procedure distorts the traces whose peaks are reduced by the water line absorption and makes these traces appear to have wider full-widths at half-maximum than the traces whose peaks are not reduced by the absorption. However, the method produces a plot that allows the main absorption peak at 25.1 cm^{-1} (398 μm wavelength) to be clearly seen. One can also easily see the distortion of the traces, which indicates the existence of more structure in the absorption spectrum, to either side of the main peak. Clearly there is much information available in this set of scans. To examine the resolution of the system further, the minor absorption peak evident at about 26.8 cm^{-1} was investigated by performing higher resolution scans using only one electron beam voltage setting. These results are shown in Figure 8.

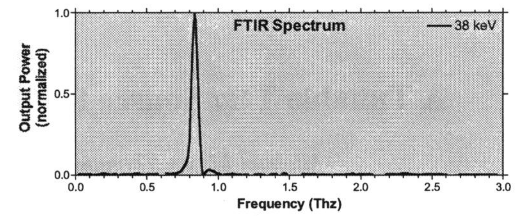

Fig. 5: FTIR Spectrum at 38 keV

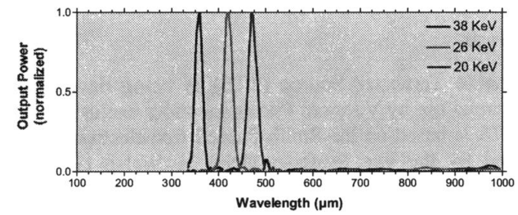

Fig. 6: FTIR Spectra

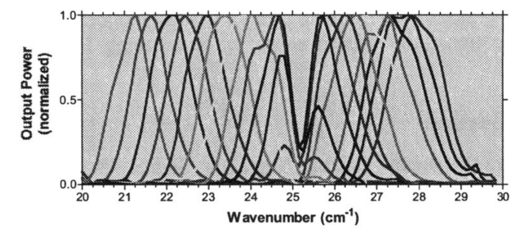

Fig. 7: FTIR Spectra showing H_2O vapor absorption.

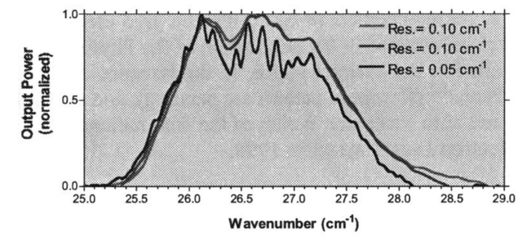

Fig. 8: High Resolution FTIR Spectra.

References

[1] Urata et al. Phys. Rev. Lett. **80**, 516 (1998)

[2] Walsh, John E., *Grating Coupled Free Electron Laser Apparatus and Method,* U.S. Patent Number 5,790,585 (1998)

[3] Jennet Conant, *Tuxedo Park: A Wall Street Tycoon and the Secret Palace of Science That Changed the Course of World War II* (Simon & Schuster, 2002) p.214.

[4] Wm. A. Shurcliff and Stanley S. Ballard, *Polarized Light* (Van Nostrand, Princeton, 1964) p. 139

[5] Brownell, Bakhtyari, Andrews and Kimmitt, THz Bridge Workshop, Capri, Italy, Sept. 29- Oct. 3, 2002.