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Sub-picosecond electron bunch length measurement by terahertz radiation

S.Zhang S.Benson D.Douglas M.Shinn and G.Williams
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

This paper presents the measurement of sub-picosecond relativistic electron beam bunch length by analyzing the spectra of the coherent terahertz pulses through Kramers-Kronig transformation. The results are compared with autocorrelation from a scanning polarization autocorrelator that measures the coherent optical transition radiation. The limitations of the different methods to such a characterization are discussed.

Keywords: Terahertz, Coherent radiation, Electron beam bunch

1. Introduction

Very high-power THz radiation has been successfully generated at Jefferson Lab[1]. The powerful short pulse THz source provides unprecedented opportunity for applications such as THz imaging and material studies. Since these THz pulses come directly from relativistic electron bunches, they also carry important characteristic information for the electron bunches. Measurement of the electron bunch length or the bunch longitudinal distribution is very important to FEL and accelerator physics studies. Coherent radiation from relativistic bunched electrons provides an effective way for obtaining bunch information, and has been studied by different research groups [2-4].

Coherent Transitional Radiation (CTR) produced by the electron bunch interacting with a thin aluminum foil has provided important clue from which the bunch form factor can be retrieved. The Coherent Synchrotron Radiation (CSR), on the other hand, is generated by the electrons through bending magnets and therefore requires no foils. There is no interruption to the running beam while the measurement is going on. We will use the CSR that is conveniently available form our FEL facility for the beam bunch measurement.

The radiation spectral intensity produced by a bunch of N electrons can be expressed by

$$I(\omega) = I_1 + I_2 = NI_0(\omega) + N(N-1)I_0(\omega)\left|f(\omega)\right|^2 \qquad (1)$$

where I_1 and I_2 represent incoherent and coherent contribution at frequency ω, respectively. I_0 is the radiation intensity from a single electron and $f(\omega)$ is the bunch form factor[5,6] which is the Fourier Transform of the normalized electron density distribution $n(z)$

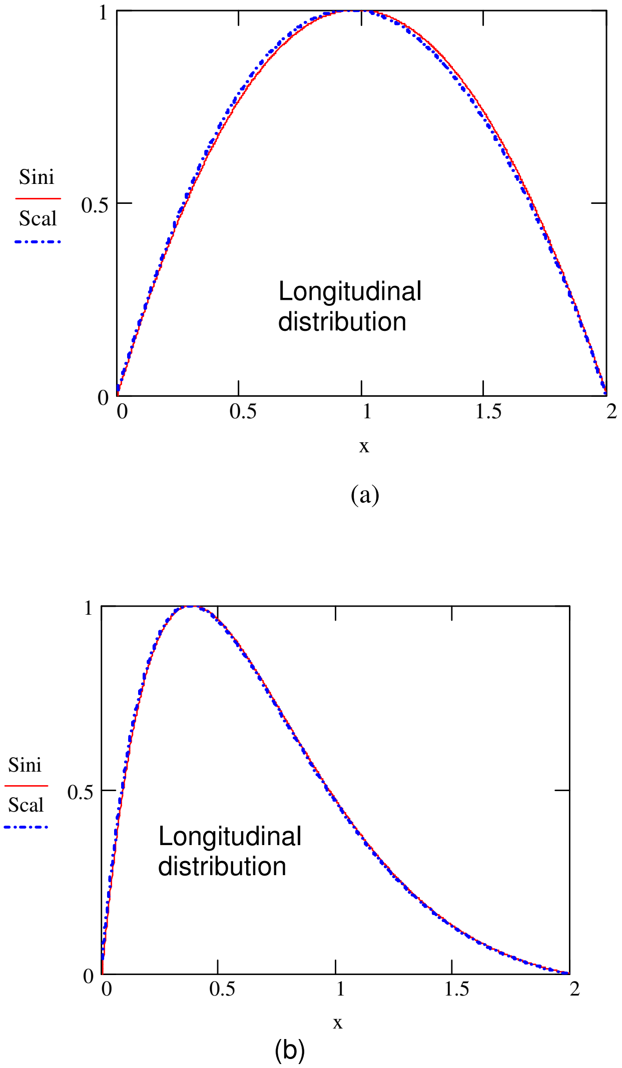
$$f(\omega) = \int n(z)\exp(i\omega z/c)dz \qquad (2)$$

Obviously, a measurement of the radiation spectrum will give the form factor and the electron density distribution as well through Fourier Transform. However, this always provides a symmetric distribution. By introducing a mini-phase under certain condition, the lost phase information can be recovered and the bunch distribution asymmetry may be revealed[6]. This method requires a Kramers-Kronig transformation (KKT) analysis to calculate the mini-phase $\varphi(\omega)$ as follows,

$$\varphi(\omega) = -(2\omega/\pi)\int_0^{\infty} \ln[|f(u)|/|f(\omega)|]/(u^2-\omega^2)\,du \qquad (3)$$

An inverse Fourier transform will give the expected longitudinal electron density distribution

$$n(z) = \int |f(\omega)| \cos[\varphi(\omega) + \omega z/c]\,d\omega \qquad (4)$$



(a)

(b)

Fig.1 Comparison between the initial (denoted by Sini) longitudinal distribution and the calculated (Scal) from spectrum by KKT. (a)A symmetric shape and, (b)An asymmetric shape. The calculated distributions well recover the original distributions.

A simulation is shown in Fig.1 where good agreement can be seen between the initial and the calculated by KKT. In later sections, we will present the measurement of the THz spectral and the analysis on the bunch length. Discussion and comparison with other measurement method will also be addressed.

2. Experimental setup and measurement

Fig.1 is an overall sketch of the Jefferson Lab 10KW upgrade FEL facility. Electrons coming from the gun are accelerated by linac and then compressed to very short bunches before traveling to the optical cavity. Synchrotron radiation is generated in several locations where the magnets bend the beam orbit. The primary instrument used in this experiment is a Nicolet FT-IR spectrometer. Fig.2 shows the optical layout of the experimental setup with a simplified spectrometer schematic. The THz pulses from relativistic electrons exit a diamond window through a vacuum beam port near the bending magnet that directs the 89Mev electron beam into optical cavity and wiggler. Several silver mirrors are used to bring the THz beam into the spectrometer bench. To minimize the water absorption by THz pulses, the whole optical beam path was purged with nitrogen.

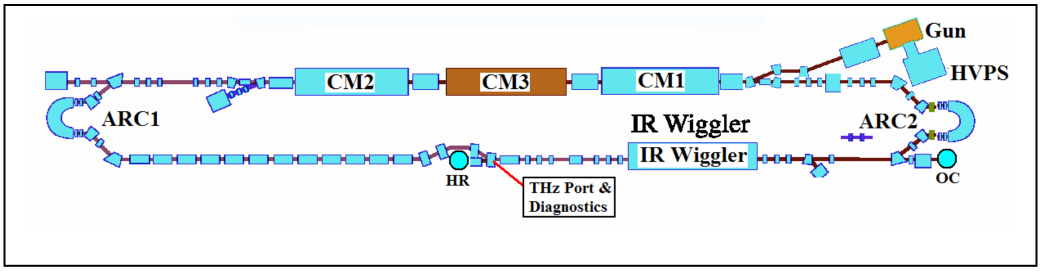


Fig.1. Layout of FEL facility and THz beam port. GUN, photo-cathode electron source. HPVS, high-voltage power supply. CM, Linac cryo-module. HR, high-reflector. OC, output coupler.

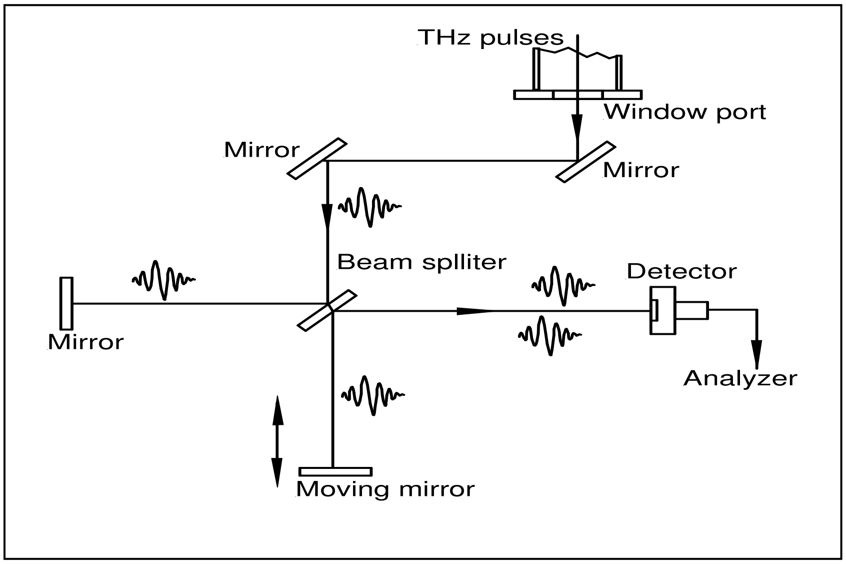
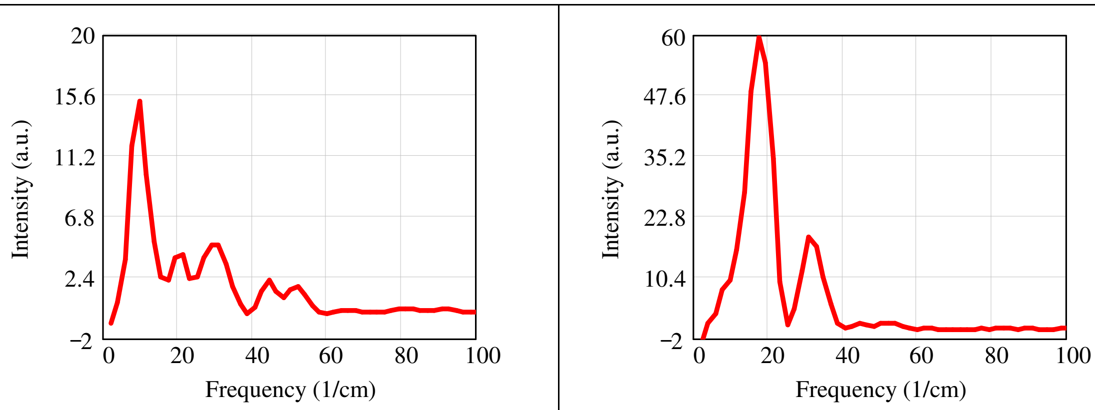
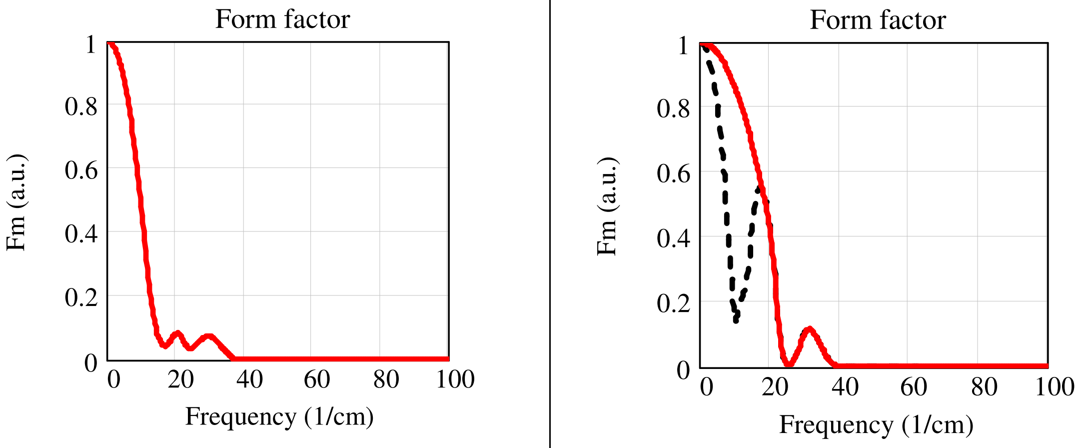


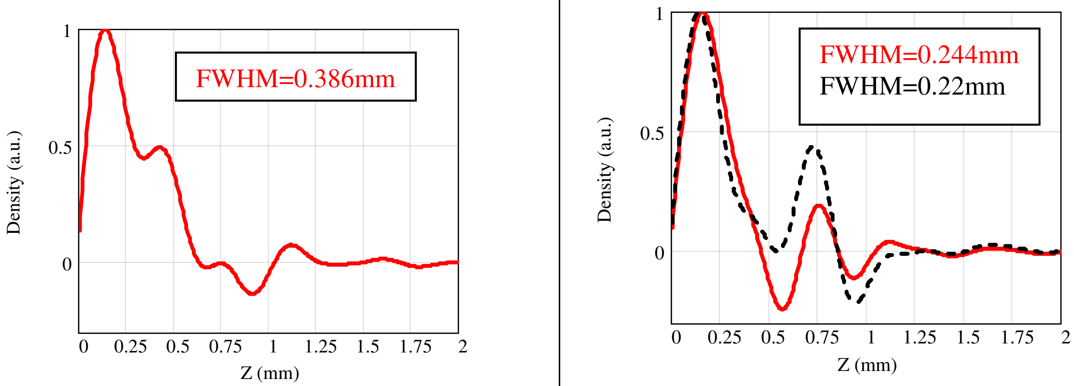
Fig.2. Schematic of the FT-IR spectrometer setup for THz spectral measurement.



(a1) Spectrum (a2) Spectrum



(b1) Form factor (b2) Form factor



(c1) electron density (c2) electron density

Fig.3 Two sets of measurement and analysis with different beam settings. (a) Typical THz radiation spectrum, (b) Form factor extracted from the THz spectrum, (c) Retrieved longitudinal electron density distribution. The FWHM width is 0.386mm (about 1.29ps in time duration) for in (c1) and 0.244mm (about 0.81ps) for (c2). The bunch is much shorter for the latter. The dashed curves in (b2) and (c2) are explained in text.

3. Results, analysis and discussions

Typical spectra taken from the spectrometer is shown in Fig.3. A Potassium bromide detector was used for getting FIR. The window on the detector has a spectral roll-off on the low frequency side. This can be also seen from the spectrum. Another major factor contributing to the low frequency cut-off is the limited diamond window aperture that blocks the diffracted beam from reaching the optical bench. This has always been an issue with other similar methods using SCR as a detection source. Appropriate spectral fitting in the low and high frequency region helps to reconstruct the whole spectra and has turned out to be very effective.

Before the extraction of the form factor, the spectrum was corrected by the $\omega^{2/3}$ frequency dependence of the single electron emittance. Since the form factor must be parabolic functions at low frequencies, $f(\omega) = 1 - a\omega^2$ will be a good asymptotic formula. At the high frequencies, $f(\omega) = b\omega^{-4}$ applies (a and b are constants, depending on and decided by each specific spectral distribution). With these asymptotic attachments to each respective side, a reconstructed form factor can be obtained. Applying the KKT to the new form factor, we were able to retrieve the longitudinal electron density distribution or the beam bunch shape. Fig.3 presents the calculated results based on two groups of measured THz spectra. The electron beam energy is 89MeV. Both profiles show clear asymmetry.

The asymptotic attachment on both ends only has limited influence on the overall shape of the distribution, especially within small distance from the point where z=0[6]. Fortunately this is the region where the bunch shape and length is decided. More precise measurement on the lower frequency will only lead to better bunch shape at large distance. The negative values in the density distribution are non-physical and were partly due to the low frequency attachment. With low frequency attachment pushed farther to the left, as shown in the dashed curves in Fig.3, the negative values in calculated density distribution are apparently reduced. The overall shape of the density distribution basically remains unchanged while small reduction on the width can be seen.

The data in the right column of Fig.3 shows apparently shorter bunch length than that in the left. The observed higher FEL output power can also be an indication of this shorter bunch. So it is possible to get a fairly good idea about how the beam setting is by just looking at the THz spectrum while tuning the electron beams. We also did calculation on the CSR based on the experimental electron beam parameters. The spectra at different bunch length are shown in Fig.4. The two sets of spectral are the same as those in Fig.3. Each of them falls into the expected bunch length range given by the results from Fig.3. Compared with the spectral calculation, the lack of the low frequency experimental data is once again clearly depicted here. It can be imagined that a good estimate on the bunch can be made by comparing the predicted and the measured data that includes more low frequencies. One aspect worth of mentioning is that the shorter bunch tends to push the spectrum to higher frequencies.

Since we are dealing with THz pulses with time duration on the order of a few picoseconds or shorter, the electric field of each individual pulse only has a few cycles or less. This has been referred to as single-cycle electric field that has drawn much research interests from physicists. Compared with other ultrashort optical pulses in the visible and near IR, this type of pulse imposes certain difficulty in the determination of its temporal pulse width measurement because of the limited number of fringes in the time window. The clear temporal intensity profile does not exist anymore and the electric field may give better idea for the temporal characteristics. This is especially true for the measurement with polarization autocorrelation method.

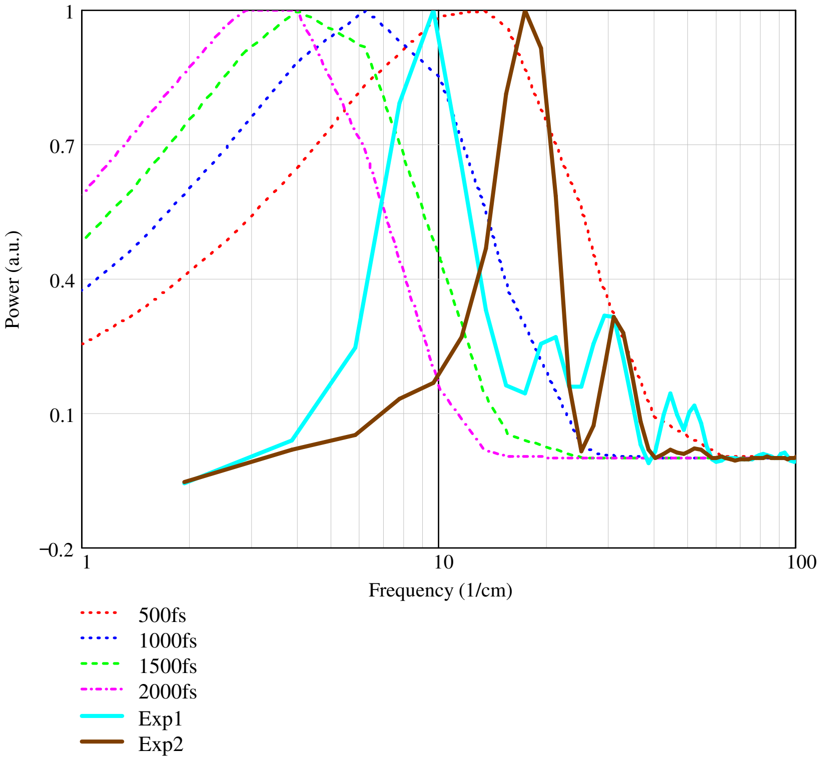


Fig.4. Comparison between the measured THz spectra and calculations with different bunch lengths. Exp1 and Exp2 correspond to the spectra shown in the left and the right column in Fig.3, respectively. The estimated bunch lengths agree with the KKT results.

To have a further look at the issue, we took data from an autocorrelator, or the so-called Martin-Puplett interferometer (MPI)[7]. Fig.5 is an optical schematic of the MPI. It was set to measure the coherent optical transitional radiation (CTR) when a thin aluminum foil was inserted into the electron beam path. MPI is a modified Michelson interferometer with thin wire grid polarizors and beam splitters. A Golay cell was used to detect interferogram signal. MPI is actually a polarization autocorrelator and the detected signal is the electric field correlation of two input replica pulses. The width of the autocorrelation traces is an indication of the input pulse width, but is not exactly the width of the temporal intensity profile which is usually taken for the determination of an ultrashort pulse length. For Gaussian distribution, a factor of 0.7 applies. The measured autocorrelation trace from our experiment is given in Fig.6 along with a Gaussian fitted center peak and the envelope. The FWHM values obtained from KKT method and MPI are in agreement to each other. The error comes from many factors and can be above 10%. The precision is primarily limited by the number of available fringes in the pulse. In this case, it may make better sense to just look at the center peak for quick and easy estimate of the pulse length, though it is not exactly the real data we are looking for. To facility the fitting, the mirror image of the original field distribution is used. Although obvious asymmetry can be seen from the electron density distribution obtained from KKT, this information will always be lost in the autocorrelation traces.

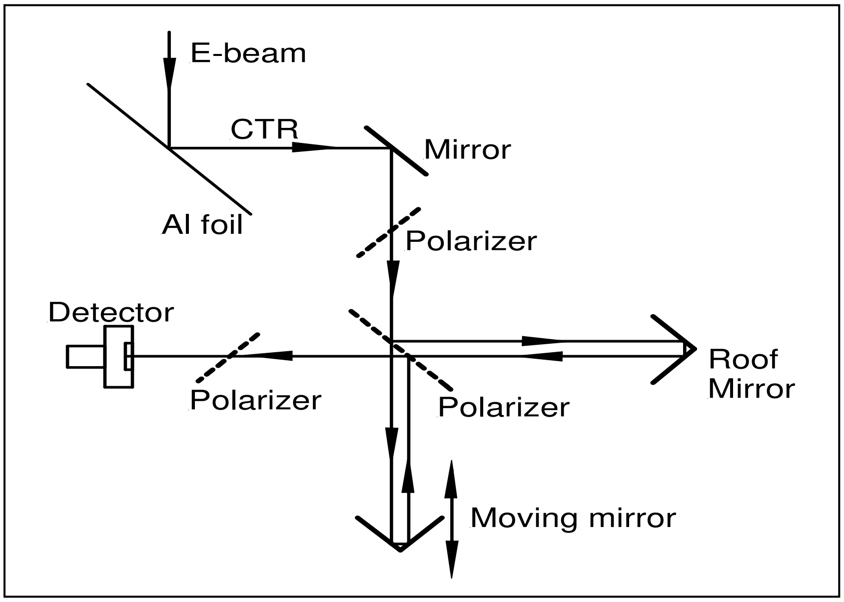


Fig.5 Simplified optical layout of a polarization autocorrelator(Martin-Pupllet interferometer). The optical pulses come from the optical transitional radiation generated by the short electron bunches interacting with a thin aluminum foil.

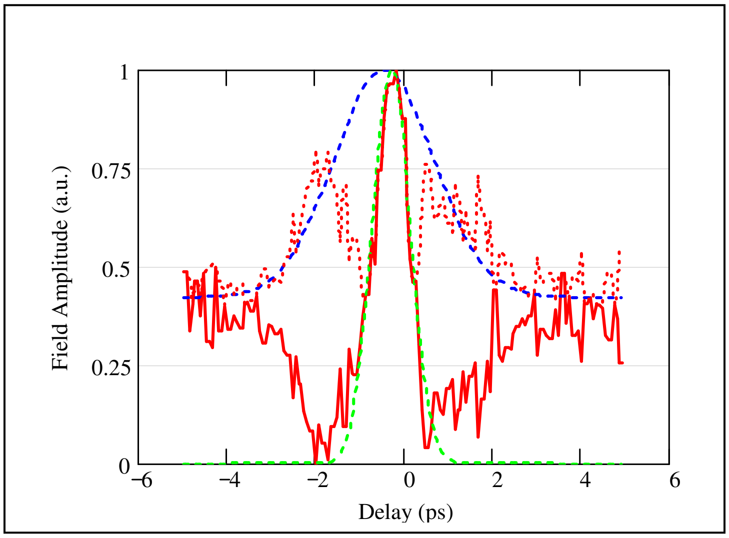


Fig.6 The red solid line is an CTR autocorrelation trace from MPI. Blue dotted curve is the fitted envelope with 1.34ps FWHM. Fitted central peak 0.71ps FWHM(green dashed line). The red dotted curve is the mirror image of the red solid curve with respect to the base line.

4. Summary

The temporal characterization of sub-picosecond relativistic electron bunches is performed through the measurement of Thz radiation and KKT analysis. Comparisons with a CSR calculation and the result from a MPI that measures the CTR are presented. The issues with the determination of short THz pulse length are also discussed. The KKT analysis of the CSR presents a useful tool for bunch shape measurement while the precision primarily depends on the spectral measurement, especially on lower frequency end in our case. Further studies and comparison with other method such as electro-optical sampling will be helpful to clarify the above mentioned issues.

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References

[1] G.Carr, M.Martin,W.McKinney, K.Jordan, G.Neil,G.Williams, Nature, Vol.420/14, 153-156 (2002).
[2] K.Ishi et al., Phys. Rev. A43, 5597(1991).
[3] J. S. Nodvick, D. S. Saxon, Phys. Rev., **96**, No. 180(1954).
[4] E. B. Blum, U. Happek,A. J. Sievers, Nucl. Instr. Meth. A307, 568(1991).
[5] R. Lai, A. J. Sievers, Nucl. Instr. Meth. A397, 221 -231(1997).
[6] R. Lai, A. J. Sievers,, Phys. Rev. E52, No.4, 4576-4579(1995).
[7] D.Martin, Polarizing Interferometric Spectrometers for the Near and Sub-millimeter Spectra, Chpt.2, New York, Academic Press,(1982).