MEASUREMENT OF BUNCH LENGTH USING INTENSITY INTERFEROMETRY

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Abstract

Intensity interferometry is one of the most conventional methods for measuring the length of a short light pulse (from ps to sub-ps). We attempted to apply this method to the measurement of bunch length at the Photon Factory. We tested both the second-harmonic autocorrelation method and the two-photon interference method. With both methods, we observed the autocorrelation signal of the bunch envelope. The bunch length measured via two-photon interference method is in good agreement with the value measured by the conventional streak camera technique.

1 INTRODUCTION

Since the initial photon correlation experiments by Hanbury-Brown and Twiss [1], the intensity interference and two-photon interference techniques are widely employed to measure the temporal or spatial coherence of light via second order coherence. In addition, the development of the second-harmonic (SH) autocorrelation technique by the use of non-linear crystals [2], and intensity interferometry [4][5] allow us to measure the temporal structure of ultra-short (ps or sub-ps order) optical pulses. Nowadays, these intensity interferometry techniques have become the standard methods for evaluating the width of ultra-short pulses in the range from ps to sub-ps with nearly unlimited time resolution.

Recently, attention has been focused on the production of sub-ps bunches in FELs and ERLs. In these fields, peoples are attempting to realize 100fs bunch length. We usually use a streak camera to measure the bunch length. Since the time resolution of a streak camera is typically 200fs, the bunch length measurements have been performed with this limit on time resolution. So we attempt to use the intensity interference method to measure the bunch length. First, we tested the second-harmonic (SH) autocorrelation technique, then intensity interferometry. The results are compared with the result via conventional streak camera measurement.

2 BUNCH LENGTH MEASUREMENT BY SECOND HARMONIC AUTOCORRELATION

The design of the autocorrelator is based on the conventional colinear arrangement [2]. The experimental set up is shown in Fig. 1. Since the coherence length is too short in the case of a white beam, we applied a monochromator to limit the bandwidth to 0.1 nm at a wavelength of 633nm. We used a nonlinear crystal BBO (β-Barium Borate) with type I phase-matching arrangement to obtain the SH signal [3]. The oscillation term in the SH autocorrelation curve is averaged out by the fluctuation of air refractivity during the measurement interval. The measurement was performed at the optical line at BL27 (bending source). The ring was operated in single bunch mode and the ring current was 30mA. The resulting SH autocorrelation curve as a function of corner-cube displacement is shown in Fig. 2. The SH signal is very week, but we can still see the autocorrelation signal of the bunch envelope.

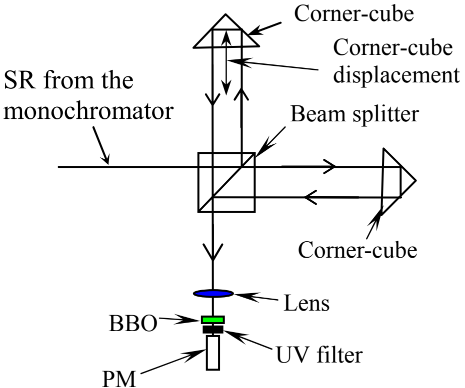

Figure 1: Measurement scheme.

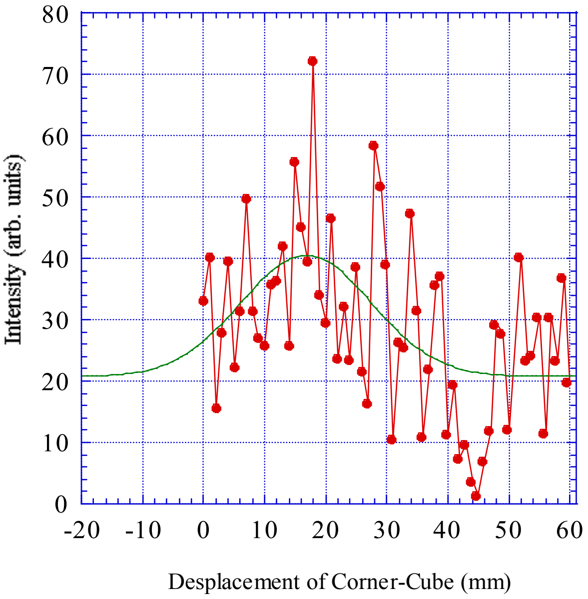

Figure 2: SH autocorrelation curve for bunch envelope.

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3 BUNCH LENGTH MEASUREMENT BY INTENSITY INTERFEROMETRY

We applied the intensity interferometry technique to the measurement of bunch envelope. We describe this method including an outline of the theory [4][5].

3.1 Theoretical outline of intensity interferometry

The principle of intensity interferometry by using a Michelson type interferometer is illustrated in Fig. 3. With this scheme, input electric fields E_1 and E_2 for the two detectors D_1 and D_2 are given by,

$$\begin{aligned} E_1(t) &= \sqrt{T}\cdot E_A(t) + i\sqrt{R}\cdot E_B(t+\delta\tau) \\ E_2(t) &= \sqrt{T}\cdot E_B(t+\delta\tau) + i\sqrt{R}\cdot E_A(t)\ . \end{aligned} \qquad (1)$$

Where T and R denote transmittance and reflectivity of the beam splitter, and T+R=1. $c\delta\tau/2$ denotes corner-cube displacement. Then the coincidence count rate between the two detectors D_1 and D_2 is expressed as,

$$\mathrm{Count}_{12}(\delta\tau) = K\int_{-\frac{T_m}{2}}^{\frac{T_m}{2}} dt \int_{-\frac{T_r}{2}}^{\frac{T_r}{2}} d\tau\, \langle E_1{}^*(t)E_2{}^*(t+\tau) \times E_2(t+\tau)E_1(t)\rangle\ , \qquad (2)$$

where K is an appropriate constant, T_r is the detector response time, and T_m is the measurement time. Let us represent the incident optical field by the complex field ,

$$\begin{aligned} E_A(t) &= C_A(t)A_A(t) \\ E_B(t) &= C_A(t)A_A(t)\ . \end{aligned} \qquad (3)$$

Here C(t) is the pulse envelope having a pulse width (bunch length) σ_p, and A(t) is a stationary random variable having coherence time τ_c. We assume Gaussian random statistics for A(t), and that the correlation function of A(t) and C(t) have Gaussian shape. We also assume that E_A and E_B of two photons have no first order coherence. We thus obtain from Eq. (2), remormalizing the proportional constant K,

$$\mathrm{Count}_{12}(\delta\tau) = K\sigma_p{}^2\left(1+\frac{\tau^*}{\sigma_p}\left[1-\frac{1}{2}\exp\left(-\frac{\delta\tau^2}{4\sigma_p{}^2}\right)\right]\right), \qquad (4)$$

where

$$\frac{1}{\tau^{*2}} = \frac{1}{\sigma_p{}^2} + \frac{1}{\tau_c{}^2}\ . \qquad (5)$$

The coincidence count rate curve decreases at $\delta\tau \approx 0$ corresponding to the Gaussian term of Eq.(4). This allows us to evaluate σ_p from this dip in the same manner as from the SH autocorrelation curve.

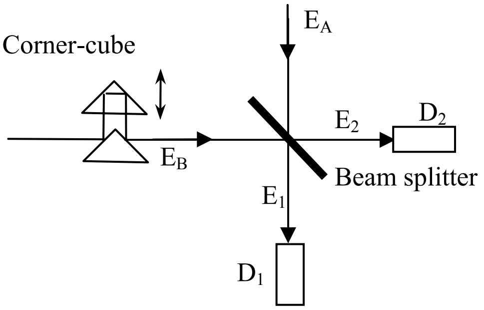

Figure 3: Input fields for a beam splitter in intensity interferometry.

3.2 Measurement of bunch envelope

The actual measurement set-up is shown in Fig.4. The incident SR passes through a first-stage system that consists of a first-stage collimating system, spatial filter, second collimating lens, polarizing prism (Glan-Taylor type), and band-pass filter. The first-stage collimating system produces a roughly collimated beam for the spatial filter. The spatial filter is applied to increase the first-order spatial coherence of incident SR. Output light from the spatial filter is again collimated by a collimating lens. Then a Glan-Taylor prism is applied to choose the σ–polarized component.

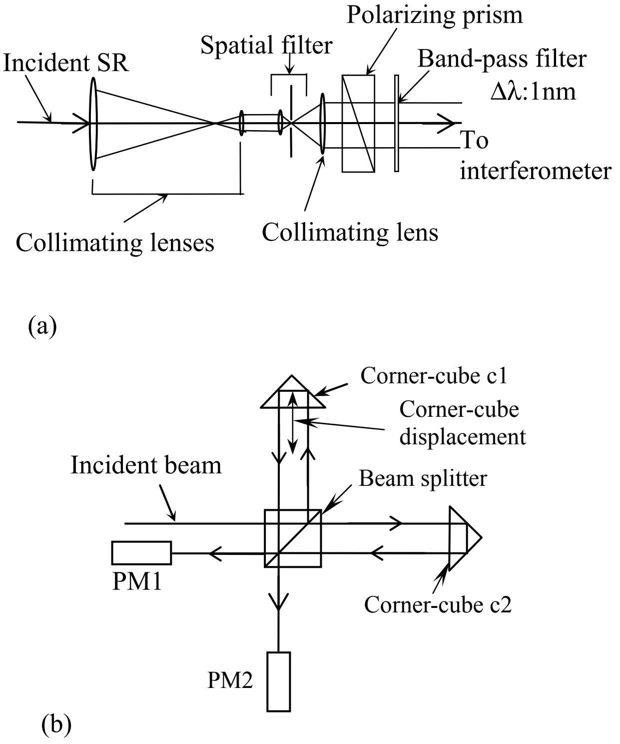

Figure 4: Experimental set-up for the measurement of bunch envelope by intensity interferometry. (a): Set up of first-stage system to produce an incidence beam for the interferometer. (b): Set-up of intensity interferometer.

A band-pass filter having a bandwidth of 1nm at 633nm is applied to produce quasi-monochromatic incidence in order to increase the contrast of the Gaussian term in Eq.(4). The set-up of the intensity interferometer is shown in Fig. 4.(b). A cube beam splitter is used to split the incident beam into two beams. This cube splitter is also used to interfere the two beams. As in the SH autocorrelation curve measurement, the oscillation term in Eq. (2) is averaged out by the fluctuation of air refractivity during the measurement interval. Two precise corner-cubes (error in reflection angle less than 2 arc-seconds) are used as reflectors. A stepping motor translates corner cube c1. The photon counting is performed with two photomultiplier tubes.

The resulting normalized coincidence count is plotted as a function of corner-cube displacement, $c\delta\tau/2$, in Fig. 5, which shows the theoretically predicted dip. The solid curve in Fig. 5 is the best-fit curve from a least-squares fit of Eq. (4).

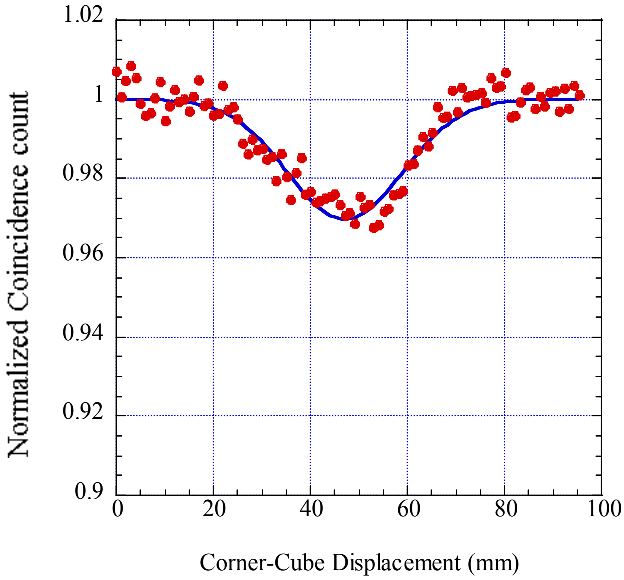

Figure 5: Plot of the normalized coincident count as a function of corner-cube displacement, $c\delta\tau/2$. The points represent the experimental data, and the solid line is the theoretical curve with bunch length σ_p which best fits the data.

We can see a small asymmetry in the dip of the experimental data in Fig. 5. This asymmetry in the dip probably owes to imperfect collimation in the optical set up. Otherwise the experiment and theory are in good agreement within the Gaussian bunch-shape assumption. The value of σ_p from this fitting is 16.8±0.6mm.

4 BUNCH LENGTH MEASUREMENT BY STREAK CAMERA

The bunch length is also measured by the conventional streak camera method. A focusing system with band-pass filter ($\Delta\lambda$=50nm at λ=550nm) and dichroic polarizing filter is placed in front of the streak camera. We used a Hamamatsu C5680 streak camera. The resulting bunch length by this method is 16.5mm.

5 CONCLUSIONS

We applied the intensity interferometry method to measure the bunch length of the Photon Factory. We tested both the second-harmonic autocorrelation method and the two-photon interference method. With the SH autocorrelation method we observed the existence of the autocorrelation signal of the bunch envelope. But since the autocorrelation signal is very weak, we cannot evaluate the bunch length. This method is not useful for the bunch length measurement with the relatively weak SR from the bending source, because in such a source, light is non-degenerate. This method will be useful for bunch length measurement using the intense laser beam from the FEL, in which the light will be highly degenerate. The second method, intensity intererometry, is more suitable for weak sources, and we observed the autocorrelation dip by bunch shape in the plot of normalized coincidence count. The resulting bunch length via this method was 16.8mm, and this result is in good agreement with the streak camera measurement result of 16.5mm. Since this method is applicable to less intense beams and a wide range of wavelengths, it will be useful for the evaluation of pulse length of ERL beams with nearly no limit on time resolution.

6 REFERENCES

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