Controlling the Carrier-envelope Phase of a Few-cycle Optical Pulse

Atsushi Ishizawa and Hidetoshi Nakano

Abstract

Controlling the optical field waveform directly through precise control of the carrier-envelope phase (CEP) is a key to developing new techniques for optical signal processing. While optical signal processing has so far treated an optical waveform as a pulse envelope, we are seeking direct access and control of the rapidly oscillating optical field in the laser pulse envelope. In this paper, we show that the CEP variations of a few-cycle laser pulse can be made small. We also describe a technique that provides direct information about the CEP of a few-cycle laser pulse with low energy from an oscillator and present measurement results that demonstrate the technique's effectiveness.

1. Introduction

The development of ultrafast optics [1] was triggered by the invention of the mode-locked laser, which was first demonstrated in 1964 and produced nanosecond pulses [2]. However, it was the development of the mode-locked titanium-doped sapphire (Ti:S) laser that really revolutionized ultrafast laser technology. Ti:S crystal serves as the nonlinear material for mode locking and provides an enormous gain bandwidth for generating ultrashort pulses. In 1991, NTT succeeded in compressing pulses from a Ti:S laser to 50 fs [3]. These days, pulses with only a few optical cycles at the FWHM (full width at half maximum) at a center wavelength of 800 nm can be generated with mode-locked Ti:S lasers. Moreover, pulses have recently been compressed to 3.4 fs at a center wavelength of 655 nm by Hokkaido University, which was a world record [4]. The phase of the optical field of a few-cycle laser pulse influences light-matter interaction, high-order harmonic generation, attosecond pulse generation, and extremely nonlinear optics.

The carrier-envelope phase (CEP) is the phase shift between the peak of an ultrashort pulse's envelope function and the closest peak of the carrier wave. As a new parameter for characterizing few-cycle laser pulses, the CEP is of great importance for a number of modern directions in laser physics [5]. A few-cycle pulse is shown in **Fig. 1**. The electric field of the pulse can be expressed as

$$E(t) = A(t)\cos(\omega t + \phi), \quad (1)$$

where $A(t)$ is the pulse envelope, ω is the carrier frequency, and ϕ is the CEP. Controlling the CEP of a few-cycle laser pulse will enable us to precisely con-

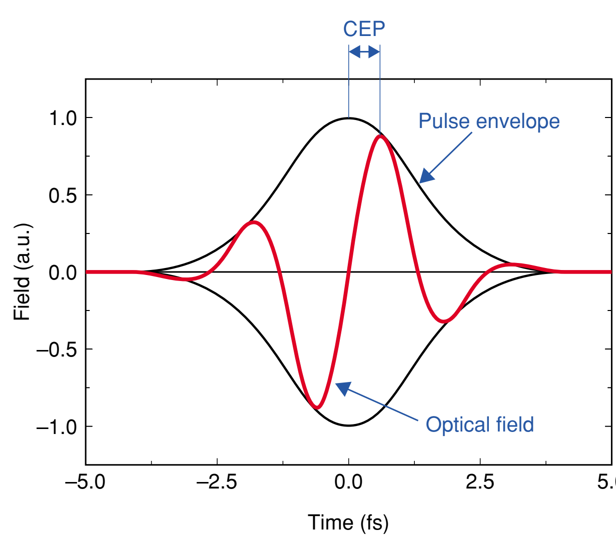

Fig. 1. Ultrashort laser pulse: The pulse intensity envelope is shown by the black line and the oscillating electric field by the red line.

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trol coherent laser-matter interactions and nonlinear phenomena, such as fast Rabi flopping [6] and quantum interference in injected photocurrents [7] in a semiconductor. It will also lead to the generation and application of attosecond pulses, which will provide better time resolution in the observation of ultrafast phenomena such as electronic flashes.

CEP control allows precise control of an optical field with sub-femtosecond time accuracy. When the spectra of two individual laser pulses overlap without CEP control, interference fringes are usually not produced. However, with CEP control, interference fringes are clearly produced in the overlap region. These fringes mean that two individual lasers can be synchronized [8]. This synthesis technique will lead to the development of optical function generators. On the other hand, in the frequency domain, CEP control allows the precise control of electromagnetic waves in the few-hundred-terahertz range, such as the electromagnetic waves generated from a mode-locked Ti:S laser. This is important because ultrabroadband light of a few hundred terahertz will be used in ultrafast optical signal processing. Recently, the National Institute of Standards and Technology (NIST) in the USA has used CEP control for precise measurements of optical frequencies [9], which will have applications in modern telecommunications. The pulse train generated by a mode-locked laser has a frequency spectrum that consists of a discrete, regularly spaced series of sharp lines, known as an "optical frequency comb" (**Fig. 2(a)**). An optical frequency comb generated by a few-cycle mode-locked laser pulse contains various regularly spaced frequency components in the hundreds-of-terahertz range and acts as an optical frequency "ruler" when a cesium atomic clock is used to stabilize the spacing. Optical frequency measurement is one application of this ruler.

2. Detection of the offset frequency and control of pulse-to-pulse CEP slip $\Delta\phi$

When a laser pulse propagates through a dispersive material, the CEP ϕ evolves because the phase and group velocities differ. The carrier propagates at the phase velocity, while the envelope propagates at the group velocity. As a result, a pulse-to-pulse CEP slip $\Delta\phi$ occurs. Techniques for controlling $\Delta\phi$ can be best understood in the frequency domain. Generally, pulses generated from a laser cavity have a random $\Delta\phi$. **Figure 2(b)** shows three pulses from an infinite pulse train that has a constant $\Delta\phi$ when the CEP slip is controlled. The frequency domain representation of this pulse train (Fig. 2(a)) is a frequency comb with tooth spacing equal to the pulse repetition rate (f_{rep}). The

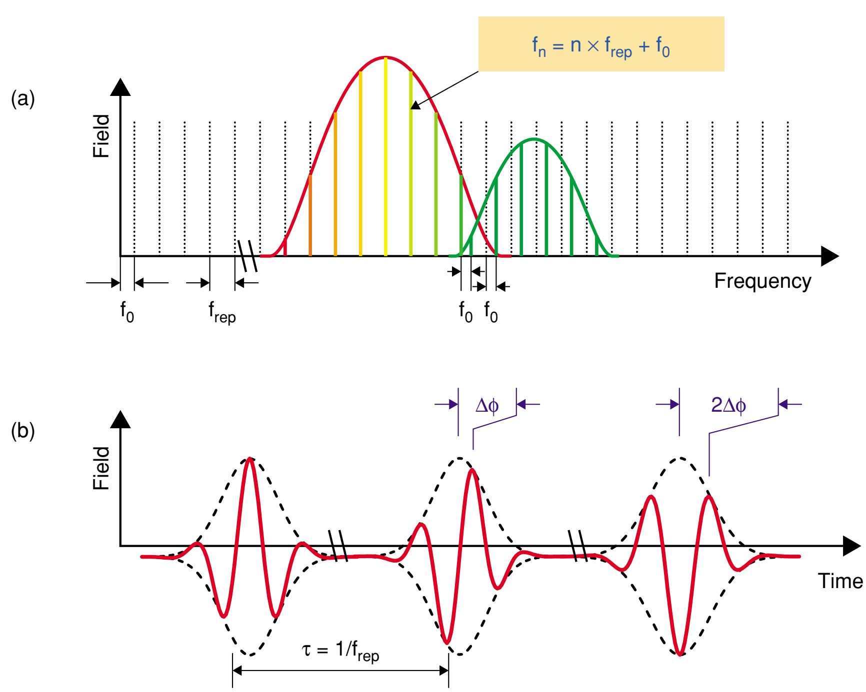

Fig. 2. Time-frequency correspondence and relationship between $\Delta\phi$ and f_o. (a) In the frequency domain, the elements of the frequency comb of a mode-locked pulse train have a spacing of f_{rep}. (b) In the time domain, the three pulses are part of an infinite train with a constant $\Delta\phi$ when the pulse-to-pulse CEP slips are controlled.

entire comb is offset from the exact harmonics of f_{rep} by an offset frequency (f_o). Without active control, f_o is a dynamic quantity that is sensitive to perturbations of the laser. The relationship between f_o and $\Delta\phi$ can be expressed as

$$\Delta\phi = 2\pi f_o/f_{rep}. \quad (2)$$

Thus, the task of controlling $\Delta\phi$ is reduced to controlling f_o. When both f_o and f_{rep} are controlled, the laser frequency to be measured can be determined by monitoring the beat signal between the frequency comb and the laser [10], [11].

The spectrum emitted by the oscillator is broadened by a photonic-crystal fiber [12] to span more than an octave (factor of 2 in frequency) (**Fig. 3**). A nonlinear interferometer (f-to-2f interferometer) (**Fig. 4**) generates the CEP-slip beat signal. A dichroic mirror transmits infrared components at 1040 nm. These components are then frequency-doubled in a β-barium borate crystal and recombined at the beam splitter with the 520-nm beam propagating through the other arm of the Mach–Zehnder interferometer. From the photodiode signal, the heterodyne beat between them yields a frequency difference f_o. Interference between the orthogonally polarized 520-nm beam is enforced by a polarizer aligned to produce a maximum beat signal at f_o. We previously reported phase-locking the CEP slip beat note to f_o = 20 MHz (synthesized by a

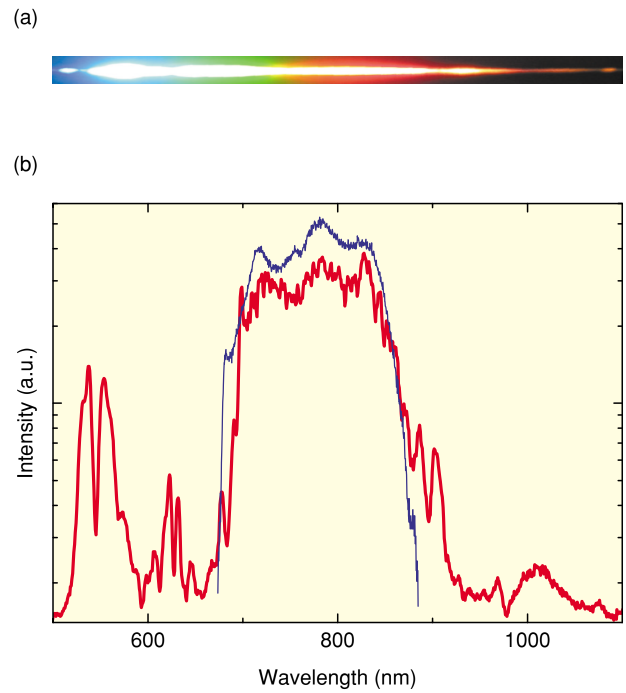

Fig. 3. Propagation in the photonic-crystal fiber broadens the spectrum to more than one octave by self-phase modulation. (a) Photograph and (b) spectrograph before (blue line) and after (red line) the photonic-crystal fiber.

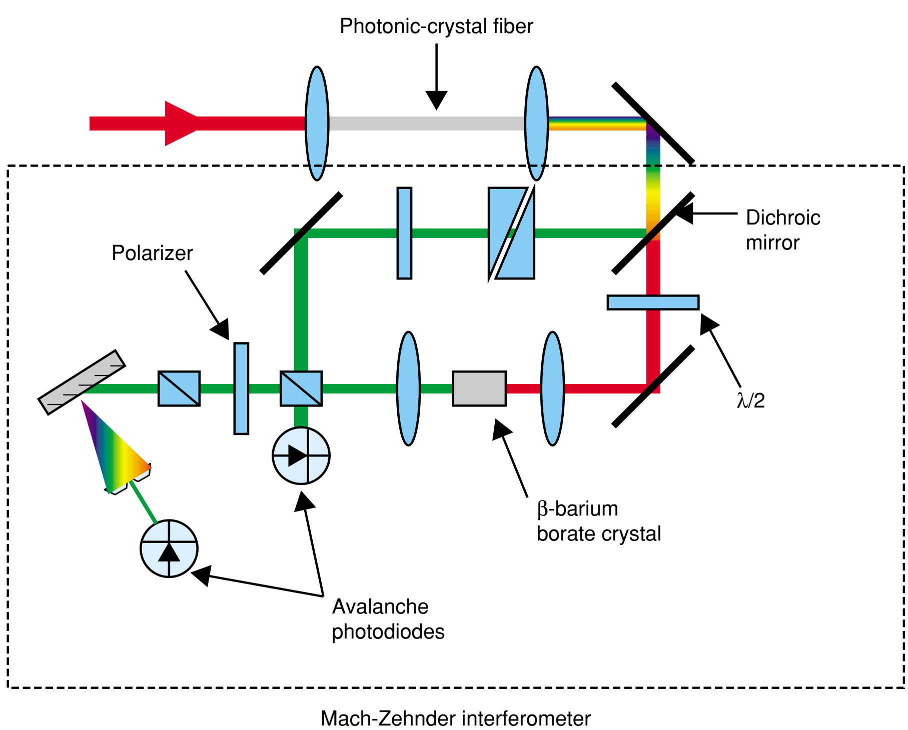

Fig. 4. The *f*-to-2*f* interferometer used in the measurement of f_o.

quarter of the laser frequency) [13]. The repetition frequency (f_{rep}) of our Ti:S laser is 80 MHz. Therefore, from Eq. 2, the CEP of our Ti:S oscillator is set such that every fourth pulse exhibits the same optical field waveform.

3. Control of CEP variations and direct measurement of CEP of a few-cycle laser pulse

The CEP of a few-cycle laser pulse influences nonlinear phenomena. The higher the laser intensity is, the larger the nonlinear effect becomes. It is easy to observe such phenomena in an intense few-cycle laser pulse. However, even if the pulse-to-pulse CEP slips of the oscillator are controlled, amplification gives rise to variations in the CEP of the amplified pulses [14]. This section describes experiments we performed on controlling the CEP variations of an amplifier and directly measuring the CEP. A schematic diagram of the setup used in the experiments is shown in **Fig. 5**. A pair of glass wedges (apex angle: 2.8°) was placed in front of the off-axis parabolic mirror. One was fixed in position; the other was movable in the horizontal direction. The wedges were used to optimize dispersion and adjust the CEP.

First, the pulse generation method is explained in Section 3.1. Then, the control of CEP variations of an amplifier is described in Section 3.2. Although CEP-sensitive phenomena have recently been measured using a few-cycle oscillator [7], [8], almost all previous direct measurements of the CEP have relied on strong-field processes in an intense few-cycle laser pulse [15], [16]. In contrast, our direct measurement of the CEP, described in Section 3.3, used low energy.

3.1 Generation of a few-cycle Ti:S amplified laser pulse using a pulse-to-pulse CEP-slip-controlled oscillator

In this experiment, we used a multipass Ti:S chirped-pulse amplification (CPA) system. CPA, with the laser pulse being stretched out temporally prior to amplification, can boost an ultrafast laser pulse up to the terawatt level and above. The amplifier delivers 1 mJ of energy in a 25-fs pulse. The CEP slip of the pulses delivered by the Ti:S oscillator was controlled as described in Section 2. We amplified the pulses with the same CEP of the oscillator. The bandwidth of the amplified pulse had to be expanded to compress the pulse width. A spectrally broadened amplified laser pulse is shown in **Fig. 6(a)**. The broadening occurred due to self-phase modulation (SPM) in the hollow-core waveguide filled with neon gas. SPM is a nonlinear optic effect of light-matter interaction and can be induced by focusing light into a nonlinear medium. The amplified pulses were finally compressed by reflecting them off chirped mirrors to compensate for the pulse broadening (**Fig. 6(b)**). Our

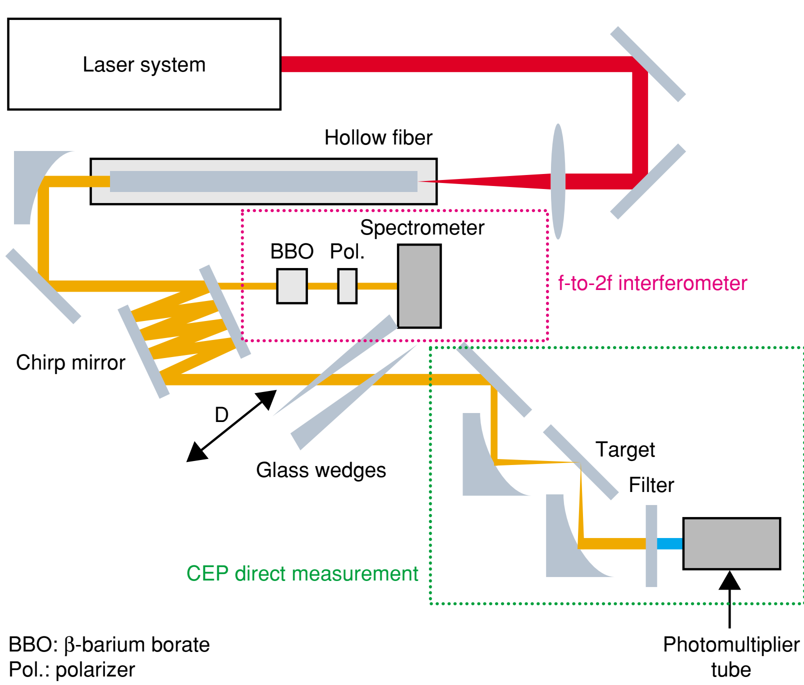

Fig. 5. Schematic diagram of the experimental setup.

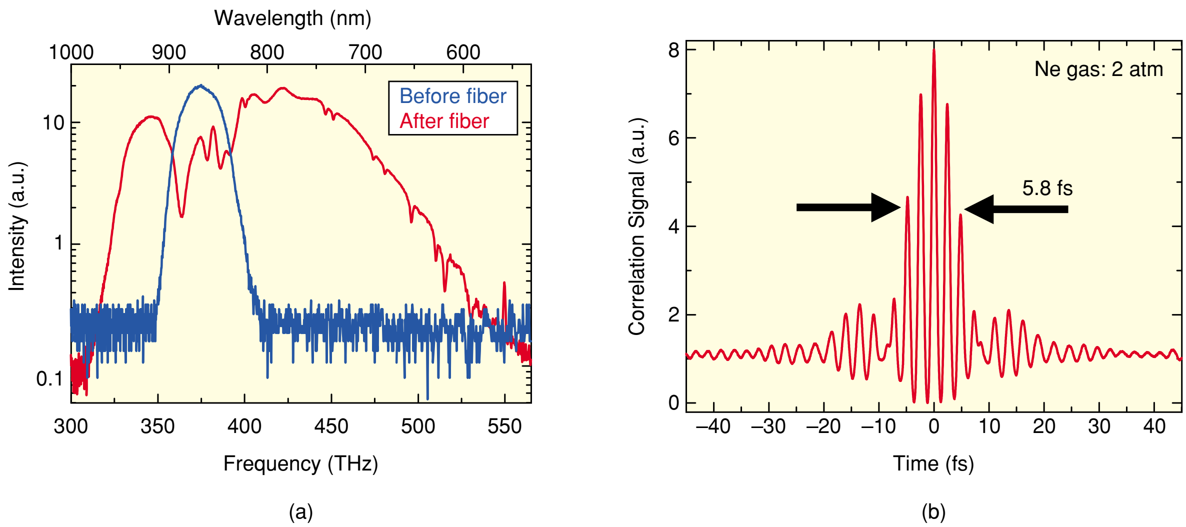

Fig. 6. A few-cycle laser pulse under gas pressure of 2 atm in a hollow fiber. (a) Laser spectra before and after the hollow fiber. (b) Autocorrelation signal.

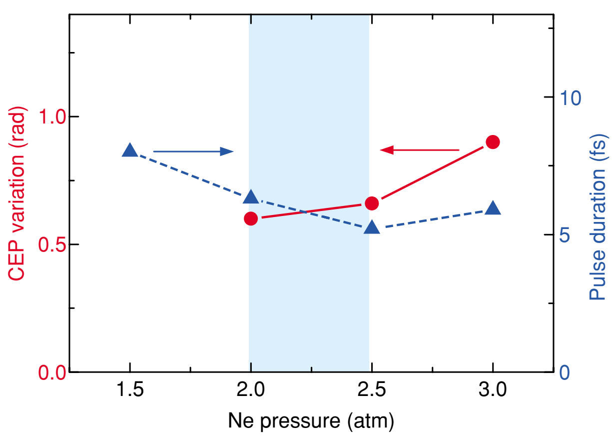

Fig. 7. Relationship between the laser pulse width and the CEP variations in the experiment.

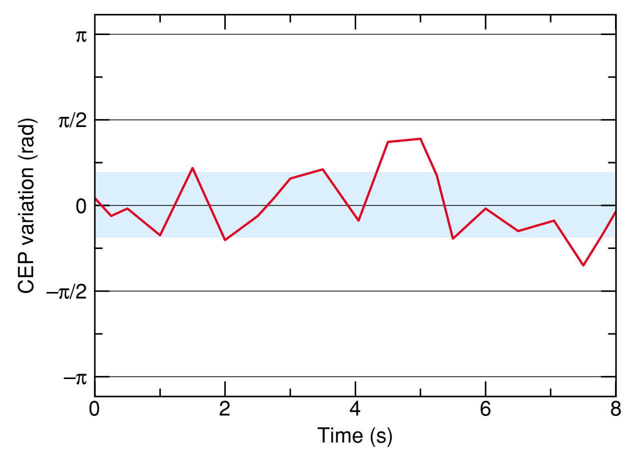

Fig. 8. CEP variations after the hollow fiber using a multi-pass amplifier with the CEP-slip-controlled oscillator. The gas pressure in the hollow fiber was 2 atm. The width of the blue zone shows the standard deviation of the CEP drifts.

amplified laser system delivered 0.3 mJ of energy in a pulse 5.8 fs wide, which corresponds to about two optical cycles at a center wavelength of 716 nm.

3.2 Control of CEP variations

We experimentally confirmed that additional CEP variations induced in the hollow fiber increased with increasing gas pressure and we determined the gas pressure where the CEP variations were smallest. The spectral width of the amplified laser pulse covered more than a one-octave bandwidth. The phase difference between the second harmonic produced by the β-barium borate crystal and the blue components of the white light provided information about the CEP. The CEP slip of the amplified laser pulse was measured with an interferometer using the second harmonic produced by the β-barium borate crystal; the blue components of the white light were measured with a spectrometer [17]. As shown in **Fig. 7**, in the gas pressure region between 2 and 2.5 atm in the hollow fiber, short pulses were generated and the CEP variation was small. We also measured the CEP variations of intense spectrally broadened pulses that passed through a hollow fiber. An additional CEP variation of 0.12 rad was induced in white light generated in the hollow fiber under the optimum gas pressure. As shown in **Fig. 8**, at the optimum gas pressure, the CEP variation was within $\pm\pi/8$ rad for

20 s [18].

3.3 Direct measurement of CEP of a few-cycle laser pulse

The stable CEP of an oscillator is expected to reveal new phenomena in nonlinear optics. Our new method uses pulses whose energy is almost two orders of magnitude lower than in previous CEP measurements using amplifiers [15], [16]. The method is based on the interference between the second and third harmonics and provides direct information about the CEP of a few-cycle laser pulse. When a laser pulse is focused on a solid target at an oblique angle, even and odd harmonics are generated due to the broken symmetry of the solid-air interface. Since the spectrum of a few-cycle laser pulse covers more than one octave, the second- and third-harmonic spectra overlap in the ultraviolet region. We performed a measurement using the technique and obtained the series interference signals of different phases shown in **Fig. 9**. The interference signals were detected using a photomultiplier tube. The intensity of the interference was very sensitive to the CEP. The pulse energy was 1 μJ, which is one order of magnitude larger than that of a recently reported 220-nJ Ti:S oscillator [19]. Since even and odd harmonics up to the fifth order with efficiencies of 10^{-10}–10^{-13} have been generated by focusing a laser on a gold surface at the laser intensity of 5 GW/cm^2 [20], which can be achieved using a standard Ti:S oscillator, our method should enable direct detection of the CEP using an oscillator. We expect that it will lead to the observation of various phenomena related to CEP-sensitive interactions in solids using an oscillator. We hope that this simple method using a low-energy pulse will widen the range of CEP-sensitive applications.

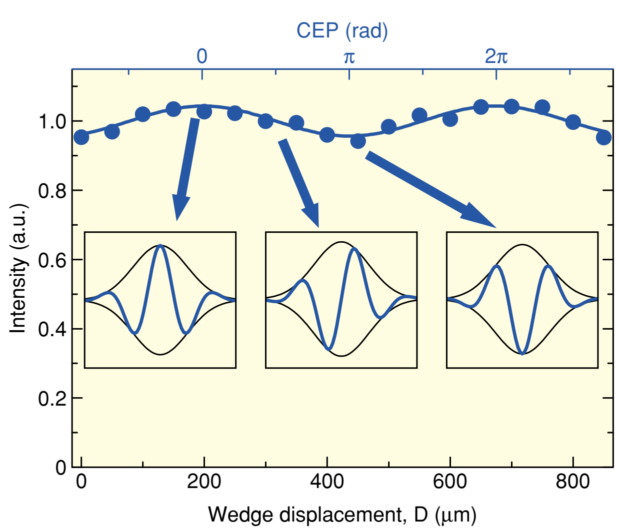

Fig. 9. Interference intensity as a function of the change in path length through the fused silica glass wedges (Fig. 5).

4. Summary

CEP control is becoming important in experiments on nonlinear phenomena. We described a method of controlling the pulse-to-pulse CEP slip of an oscillator. In addition, we showed that CEP variations due to amplification can be reduced by controlling the gas pressure in a hollow fiber. Various phenomena, such as the recently reported quantum interference control in injected photocurrents in low-temperature-grown gallium arsenide and rapid Rabi flopping in gallium arsenide using an oscillator of few-cycle laser pulses, are sensitive to the CEP. We described a measurement that provides direct information about the CEP of a few-cycle laser pulse. This method will let us directly measure the CEP of low-energy laser pulses, such as those generated from an oscillator. Therefore, we expect new phenomena in nonlinear optics to be observed in the near future using the stable CEP of an oscillator. We are seeking a direct method of accessing and controlling the rapidly oscillating optical field in the laser pulse envelope using a few-cycle laser pulse. Success in these endeavors will contribute to the development of new techniques for optical signal processing.

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