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Measuring temporal fluctuation on femtosecond scale in a random medium

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Abstract

We report an observation of femtosecond optical fluctuations of transmitted light when a coherent femtosecond pulse propagates through a random medium. They are a result of random interference among scattered waves coming from different trajectories in the time domain. Temporal fluctuations are measured by using cross-correlated frequency optical gating. It is shown that a femtosecond pulse will be broadened and distorted in pulse shape while it is propagating in random medium. The real and imaginary components of transmitted electric field are also distorted severely. The average of the fluctuated transmission pulses yields a smooth profile, probability functions show good agreement with Gaussian distribution.

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Keywords: Femtosecond laser pulse; Random medium; Cross-correlated frequency-resolved optical gating

1. Introduction

The interaction between optical field and random media is an area that has attracted much attention from scientific research because of its important applications in various disciplines such as aerosphere analysis, medical imaging. Propagation and scattering of optical field in random media will be fluctuated due to interference of the multiply scattered waves. When a coherent light propagates through a random scattering medium, it will be resulted in two components in the transmitted wave: one is the unscattered wave; the other is the multiply scattered wave [1]. The scattered and unscattered wave can be used to image objects embedded in the scattering medium or to characterize the random medium itself [2–11]. These researches are helpful to determine the optical properties of biological and medical tissues. And all of these works is to study photon migration and light scattering in random media by a time resolved technique using continuous wave laser or picosecond laser. In this paper, the propagation and transmission of an ultrafast laser pulse in a random medium were measured by frequency resolved technology using femtosecond laser.

When femtosecond pulses propagate through a random scattering medium, the output field is time-fluctuating multiply scattered waves, and random variation will occur in each of the space, time and frequency domain since the amplitude and the phase are changed by scattering [12]. We report an observation of femtosecond optical fluctuations of transmitted light when a coherent femtosecond pulse propagates through a random medium, and the temporal fluctuations are characterized by using the cross-correlated frequency-resolved optical gating (XFROG). XFROG is one of the most sensitive and robust technique to characterize femtosecond pulse; and it is especially suitable for characterization the weak and complex femtosecond pulse [13–16].

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2. Experiments

The experimental setup is illustrated in Fig. 1. The femtosecond laser pulse is generated by a Ti:sapphire oscillator. Central wavelength is about 820 nm. The input femtosecond pulse is split into two by a beam splitter; one is probe pulse, the other is reference pulse. Reference pulse travels along the delay arm; probe pulse propagates through a random optical medium in the other arm and the medium is mounted on a translation stage. A variable delay stage in the delay arm provides control of the relative delay time between the reference and probe pulses, and the increment of delay time is 6.7 fs. After propagating through the random optical medium, the probe pulse is recombined with the reference pulse by a converging lens in a 100 μm thick β-barium borate (BBO) crystal, where the two beams mixed together to form a sum frequency signal. The crossing angle between the probe and reference pulse in BBO is about 10°. An aperture placed behind the BBO crystal allows only the sum signal to be collected by a spectrometer, and the spectrum of the signal field is recorded.

We firstly use second-harmonic generation frequency-resolved optical gating (SHG-FROG) technique to characterize the reference pulse, which is identical to the input pulse impinge on the random medium. The measured trace, retrieved temporal intensity and phase, the real and imaginary components of complex electric field in time domain are shown in Fig. 2. The pixel grid size of measured trace is 1024×100. The temporal full width half maximum (FWHM) of the reference pulse is 64 fs; time bandwidth products of input pulse is 0.8839, which is a dimensionless number given by multiplying the FWHM and the spectral width of femtosecond pulse [17,18]; the minimum FROG error is 0.0097013, and FROG error is defined as [13,16]

$$G = \sqrt{\frac{1}{N^2}\sum_{i,j=1}^{N}\left|I_{\mathrm{FROG}}(\omega_i,\tau_j) - \alpha I_{\mathrm{FROG}}^{\mathrm{meas}}(\omega_i,\tau_j)\right|^2} \quad (1)$$

where $I_{\mathrm{FROG}}^{\mathrm{meas}}(\omega,\tau)$ denotes the measured FROG data, $I_{\mathrm{FROG}}(\omega,\tau)$ is the FROG trace calculated from the retrieved or reconstructed pulse, and α is a real normalized scaling factor. The scaling factor is chosen to minimize G. G is generally referred to as the FROG error. For experimental data free of systematic errors and proper convergence of the algorithm, the lowest attainable FROG error depends on the grid size N.

In our experiment, the random sample is made by using a piece of transparent silica glass with thickness 1 mm, and it is frosted one side by sand blaster in order to obtain random surface roughness. The standard deviation of the surface roughness of the sample is measured with Taylor–Hobson Form Talysurf Series2-50i as σ_C =1257.1 nm and surface profile obeys circular complex Gaussian field statistics [12,19]. Taylor–Hobson Form Talysurf Series2-50i instrument measures dimension, form, and texture simultaneously. It measures all elements of surface geometry, such as curvature, inclination, roughness, waviness and so on. Talysurf Series2-50i contacting stylus profilometer is with a 2 mm/60 degree diamond tip, which detects and evaluates all elements with just a single traverse across the component. The linear surface profiles can then be used to quantify the 2D surface roughness characteristics of almost all geomaterial surfaces.

XFROG is applied to a pulse that propagated through the random medium. After the probe pulse propagated through the random optical medium, XFROG measures the cross-correlation between the weak transmitted probe pulse and the reference pulse; the cross-correlation signal is achieved in the BBO crystal and recorded by spectrometer. Measured XFROG trace in one experiment is shown in Fig. 3a. We can retrieve the temporal fluctuation of transmitted pulse by using XFROG algorithm. In order to estimate the ensemble average statistics of the output pulse and the transmitted complex electric field, we performed five measurements, moving the sample laterally with a small step size of 10 μm between each measurement. The retrieved output pulse, the real and imaginary components of electric field from five independent measured XFROG traces are illustrated in Fig. 3b–d, respectively. We observe that the transmitted femtosecond pulse profiles through random medium have inherently temporal fluctuation on the order of femtosecond, and Fig. 3b shows the average of the five independent measured profile yields a temporally smooth transmitted profile. Furthermore, the temporal response in Fig. 3 is almost symmetric; the reason is that the temporal support of the response in Fig. 3 is about 400 fs, not much more than the reference pulse in Fig. 2.

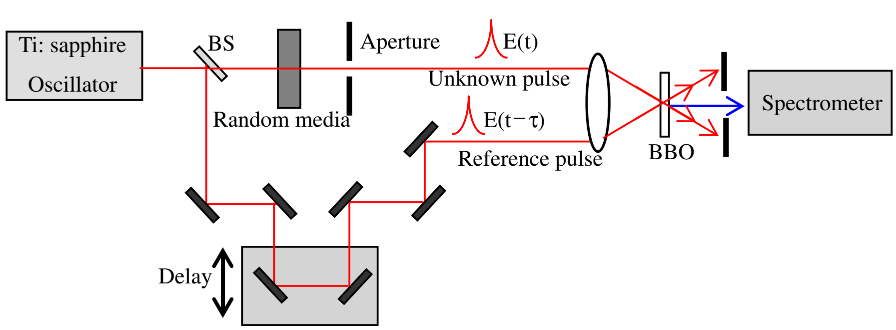

Fig. 1. Experimental setup for measuring temporal fluctuation on femtosecond scale by the use of cross-correlated frequency-resolved optical gating.