Coherence measurement of a Ti:sapphire femtosecond pulsed laser

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The interference patterns produced by Gaussian-shaped broad-bandwidth femtosecond pulsed laser sources are derived. The interference pattern contains both spatial and temporal properties of laser beam. Interference intensity dependent on the bandwidth of femtosecond laser are given. We demonstrate experimentally both the spatial and the temporal coherence properties of a Ti:sapphire femtosecond pulse laser, as well as its power spectrum by using a pinhole pair.

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Over the past few years considerable progress has been made in femtosecond pulsed laser generation by Ti:sapphire lasers. The femtosecond laser is operated in the pulse mode with a broad linewidth, so both the temporal and the spatial coherences are different from that of monochromatic light. In classical coherence measurement the incident field is assumed to be quasi-monochromatic, so temporal coherence effects are isolated from spatial coherence effects[1]. But when broad bandwidth source illuminates a pinhole pair, the interference pattern will contain both temporal and spatial coherence information on the source as well as the power spectrum[2].

The degree of coherence is a function which refers to the correlation of two points of an arbitrary transverse plane in a given optical system, which is best explained with the help of Young's interference experiment. For monochromatic illumination, the interference intensity received at a point x on the observation plane is[3]

$$I(x) = 2I_0 1 + \cos[k(xd)/D]. \tag{1}$$

For broad-bandwidth with central frequency ω_0 and bandwidth $\mathrm{d}\omega$ illumination, the interference fringes at a point x can be written as

$$2I_1(\omega)1 + \cos[k(xd)/D]\mathrm{d}\omega. \tag{2}$$

The total intensity distribution is

$$\begin{aligned} I(x) &= 2\int I_1(\omega)[1+\cos(kxd/D)]\mathrm{d}\omega \\ &= 2\int I_1(\omega)\mathrm{d}\omega + 2\int I_1(\omega)\cos(\omega xd/cD)\mathrm{d}\omega, \end{aligned} \tag{3}$$

where $I_1(\omega)$ is the spectral distribution of femtosecond laser pulses, which represents the change of intensity dependent on the frequency.

For Gaussian-shaped femtosecond pulsed laser, the frequency spectrum $V(\omega)$ is

$$V(\omega) = \sqrt{\pi}T\exp\{-[T(\omega-\omega_0)/2]^2\} \tag{4}$$

where $\omega=\omega_0+\Delta\omega$, $\Delta\omega$ is variation of frequency. The spectral distribution $I_1(\omega)$ is

$$I_1(\omega) = \pi T^2\exp\{-2[T(\omega-\omega_0)/2]^2\}. \tag{5}$$

From Eqs. (3) and (5) we can derive that the total intensity distribution is

$$\begin{aligned} &I(x) \\ &= 2\sqrt{2}\pi^{3/2}T\{1+\exp[-(\mathrm{d}x/\sqrt{2}cDT)^2]\cos(\omega_0 xd/cD)\} \\ &= 2\sqrt{2}\pi^{3/2}T\{1+\gamma_{12}(x)\cos(\omega_0 xd/cD)\}, \end{aligned} \tag{6}$$

where $\gamma_{12}(x) = exp[-(dx/\sqrt{2}cDT)^2]$ is the complex degree of coherence, which characterizes the field correlations in the space-time domain[4], and here the time delay τ has been transformed to the spatial coordinate x=$Dc\tau/d$. The interference pattern produced by broad-bandwidth femtosecond laser contains both spatial and temporal coherence information as well as the power spectrum of the femtosecond laser source. The relationship between spatial coherence and the power spectrum is[4]

$$\gamma_{12}(\tau) = \int_0^\infty \sqrt{s_1(\omega)}\sqrt{s_2(\omega)}\mu_{12}(\omega)\exp(-i\omega\tau)\mathrm{d}\omega,$$

$$s_j(\omega) = S_j(\omega)/\int S_j(\omega)\mathrm{d}\omega, (j=1,2), \tag{7}$$

where s_j are the normalized spectrum of the field at the two points. μ_{12} is the spectral degree of coherence (also degree of spectral coherence or degree of spatial coherence), which characterizes field correlation in the space-frequency domain. We can conclude that the interference pattern depends on both the bandwidth and the intensity distribution of spectrum according to Eqs. (5)and (6).

Equation (6) can be analyzed in the spatial frequency domain. The Fourier transform of Eq. (6) is

$$\begin{aligned} F[I(x)] &= 2\sqrt{2}\pi^{3/2}T\{\delta(f_x) + (\sqrt{\pi}cDT/d)^2 \\ &\quad \exp[-\pi(\sqrt{2\pi}cDTf_x/d)^2] \\ &\quad *[\delta(f_x - d/\lambda_0 D) + \delta(f_x + d/\lambda_0 D)]\} \\ &= 2\sqrt{2}\pi^{3/2}T\{\delta(f_x) + \\ &\quad (\sqrt{\pi}cDT/d)^2[\exp(-\pi f_{x1}^2) + \exp(-\pi f_{x2}^2)]\}, \end{aligned}$$

$$\begin{aligned} f_{x1} &= \sqrt{2\pi}cDT(f_x - d/\lambda_0 D)/d, \\ f_{x2} &= \sqrt{2\pi}cDT(f_x + d/\lambda_0 D)/d, \end{aligned} \tag{8}$$

where $F[\cdot]$ represents the Fourier transform, and $*$ is the convolution operator, $\delta(f_x)$ is the Dirac delta function. The Fourier transform of the interferogram yields three terms: a dc term corresponding to a spike at zero frequency and two terms at $+d/\lambda_0 D$ and $-d/\lambda_0 D$ frequency containing information on the power spectrum convolved with the dc spike and weighted by the spatial coherence function at that frequency[5].

The experimental setup for measuring coherence of a Ti:sapphire femtosecond pulsed laser is illustrated in Fig. 1. The central wavelength of the Ti:sapphire femtosecond pulsed laser is about 805 nm. The pulse width is 56 fs, and the spectral bandwidth is 27 nm. The interference pattern is recorded by a charge coupled device (CCD) camera. The distance between the pinhole pair and the CCD camera is $D = 600$ mm, and this distance is sufficient to assure that the CCD camera can resolve the finest interference fringes.

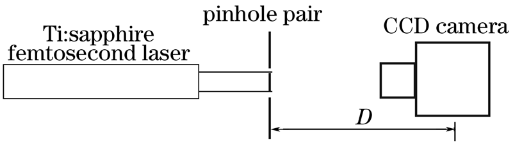

Fig. 1. Experimental setup for measuring coherence of a Ti:sapphire femtosecond pulsed laser.

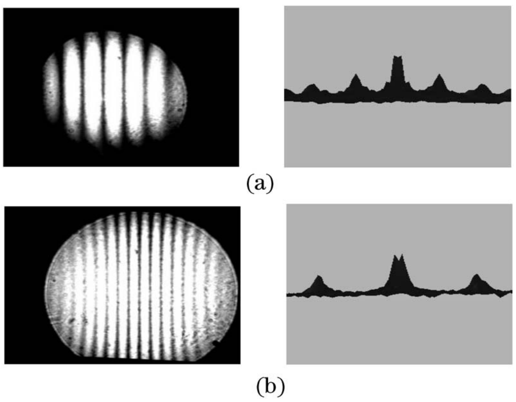

Fig. 2. Interference pattern (left) and their Fourier transform (right) produced by different pinhole separation of (a) 600 μm, (b) 2000 μm.

Figure 2 shows the interference pattern recorded by a CCD camera and their corresponding Fourier transform for different pinhole separations of (a) 600 μm, (b) 2000 μm, and the diameter of the pinholes is 200 μm. The intensity modulations are due to interference of the two pinholes. The depth of modulation is determined by the spatial coherence of the beam[5]. The Fourier transform of the interferogram yields three terms as described in Eq. (8). One zeroth order peak and two other symmetric first-order peaks that are modulated by the degree of spatial coherence. The path-length difference also introduces a time delay τ. If τ is sufficiently large, the spatial frequency components are well separated in time.

In summary, we demonstrate the coherence measurement of Gaussian-shaped broad-bandwidth femtosecond laser theoretically and experimentally. The interference intensity and the relationship between the coherence and bandwidth of femtosecond pulse laser are derived. The pinhole pair produces interference pattern containing both spatial and temporal coherence information as well as the power spectrum of the femtosecond laser source experimentally.

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