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Soliton Thulium-Doped Fiber Laser With Carbon Nanotube Saturable Absorber

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Abstract

We report stabilization of a thulium–holmium codoped fiber soliton laser with a saturable absorber based on carbon nanotubes. The laser generates transform-limited 750-fs pulses with 0.5-nJ energy.

Index Terms

Midinfrared; mode-locking; saturable absorber (SA); soliton pulse

I. Introduction

Fiber lasers currently attract great interest. High-power continuous-wave *Q*-switched and mode-locked fiber lasers at wavelengths around 1 and 1.5 μm have been developed [1]–[4]. High efficiency combined with the possibility of direct diode pumping make fiber lasers attractive for many applications.

Recent progress in thulium (Tm)- and holmium (Ho)-doped fiber lasers has enabled the demonstration of high-power fiber lasers in the midinfrared region. Average powers up to 100 W and 68% efficiency have been demonstrated in Tm- and Ho-doped fiber lasers [5]–[7]. The possibility of achieving quantum efficiency greater than one due to cross-relaxation energy transfer processes make this class of fiber lasers very attractive. Furthermore, for many applications in nonlinear optics, medicine, and sensing, integrated and robust laser sources around 2-μm wavelength are needed.

Tm-doped fiber is known to have a broad and smooth fluorescence spectrum, which is suitable for generating ultrashort pulses. However, only a few mode-locked oscillators based on Tm fiber have been reported. Nonlinear polarization evolution (NPE) was used by Nelson *et al.* to demonstrate a mode-locked thulium fiber laser that generated 500-fs pulses [8]. Sharp *et al.* used a semiconductor saturable absorber mirror (SESAM) in a Tm fiber laser to achieve 190-fs pulses [9]. Recently, Engelbrecht *et al.* reported a laser with grating-based dispersion compensation and double-clad thulium-doped fiber. The laser operates in the stretched pulse regime [10] with pulse energy as high as 4.3 nJ and dechirped pulse duration around 300 fs. NPE was used to initiate and stabilize the mode-locked pulses in this system, which offers excellent performance but sacrifices some of the benefits of fiber by its use of bulk optics. Regarding femtosecond amplification in Tm fiber, Imeshev *et al.* demonstrated a watt-level source operating around 2 μm, using a Raman-shifted Er-doped

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femtosecond laser as the seed [11]. Recently, Kivistö *et al.* also reported a tunable Raman soliton source using a Tm-Ho codoped seed laser [12].

In ultrafast fiber lasers, NPE and SESAMs are widely used to provide amplitude modulation. However, these two techniques have drawbacks. NPE requries additional elements in the cavity, including a polarizer and polarization controllers (PCs). Furthermore, fiber lasers mode-locked with NPE will generally not be environmentally stable. SESAMs have recently become readily available, but tend to damage in fiber lasers, perhaps owing to the large modulation depth that is needed. Recently, a new type of saturable absorber (SA) based on single-walled carbon nanotubes (SWCNTs) has been investigated [13]–[15]. SWCNTs possess subpicosecond recovery times, and broad absorption spectra. Solid-state and fiber lasers operating at 1- [16], 1.3- [17], and 1.5-μm [18] wavelengths have been mode-locked with SWCNT SAs. During the preparation of this manuscript, a report by Solodyankin *et al.* of a mode-locked Tm fiber laser that uses SWCNTs as the SA appeared [19]. The SWCNTs were deposited as a thin film on the end of a fiber segment. This laser generated only low-energy picosecond pulses due to the cavity design (a ring cavity without an isolator) and damage of the thin-film absorber. It is desirable to reach the excellent performance of the laser reported in [10], but in an all-fiber integrated format.

In this letter, we report a step toward that goal, by demonstrating a mode-locked Tm fiber laser that employs only fiber-format components, including a SA based on SWCNTs. In contrast to the approach reported in [19], the SA that we use is based on a fiber taper that is embedded in an SWCNT/polymer composite, following the design in [18]. In this geometry, the absorption is distributed, and so is the generated heat, which allows reliable operation at much higher power. The laser produces 750-fs solitons with 0.5-nJ pulse energy and 25-mW average power. The laser has been operated for many hours with no sign of degradation of the SA.

II. Experimental Setup and Results

The laser is shown schematically in Fig. 1. It contains ~70 cm of Tm–Ho codoped fiber with 9-μm core diameter and ~60-dB/m absorption at 1570 nm. The gain fiber is pumped in-core by an Er fiber laser that emits near 1570 nm, through a wavelength-division-multiplexing fiber coupler. The fluorescence spectrum of the gain fiber measured at low pump power covers the range 1.65 to 2.1 μm (Fig. 2). The cavity is formed between two loop mirrors based on 2×2 fused couplers. The reflectivities of the loop mirrors are ~40% and 5%. The fiber ends at the outputs have to be angle-cleaved to avoid feedback into the cavity, which would prevent or extinguish mode-locked operation. The SA is fabricated using the technique reported previously [18]. The only difference is that SWCNTs with larger average outer diameter (~1.5 nm) are used, to place the absorption band near 2 μm (Fig. 3). The total loss of the SA was measured to be 50%. The total dispersion of the cavity is estimated to be $\sim -0.2\ ps^2$.

Mode-locking occurs when the pump power is increased to 320 mW, without any adjustment of the laser cavity. However, the laser tends to start in a multiple-pulsing regime. Single-pulsing is then achieved by reducing the pump power to about 200 mW. The output power spectrum is shown in Fig. 4. The center wavelength is 1885 nm and the bandwidth is 6 nm. The spectrum shows the characteristic sidebands of soliton pulse shaping. Their locations agree with the positions expected from the estimated dispersion and pulse duration. Typical interferometric and intensity autocorrelations are shown in Fig. 5. The pulse duration is 750 fs assuming a sech pulse shape. The corresponding time-bandwidth product is 0.37, which is close to the theoretical value for transform-limited solitons.

At 200-mW pump power, the laser generates 25 mW from output 1 and 2 mW from output 2. The repetition rate of the laser is 45 MHz, so the pulse energy is ~0.5 nJ. We estimate the output (1) coupling to be 0.95, which explains why the energy of a soliton pulse can be so high. Mode-locking is maintained even when the fiber in the cavity is perturbed mechanically or moved, although the polarization state does change. The polarization state of the output is normally elliptical, with random orientation of the main axes. The polarization state is stable from pulse to pulse, and changes only when the fiber in the cavity is perturbed. We attribute this stability to the absence of polarization-sensitive components in the cavity. The output polarization can be controlled by including an inline PC in the cavity, but adjustment of the PC has little impact on the mode-locking. This indicates that the SA provides significant self-amplitude modulation, which dominates any residual NPE that arises from the lack of polarization control. A systematic description of this approach to stable mode-locking will be presented elsewhere.

III. Conclusion

We have demonstrated a soliton fiber laser based on Tm–Ho codoped fiber. An SA based on carbon nanotubes starts and stabilizes the mode-locking. The laser generates transform-limited 750-fs pulses with 0.5-nJ energy. This performance is encouraging, and we expect that the SA based on a fiber taper embedded in carbon nanotubes will find use stabilizing other pulse evolutions in 2-μm fiber lasers.

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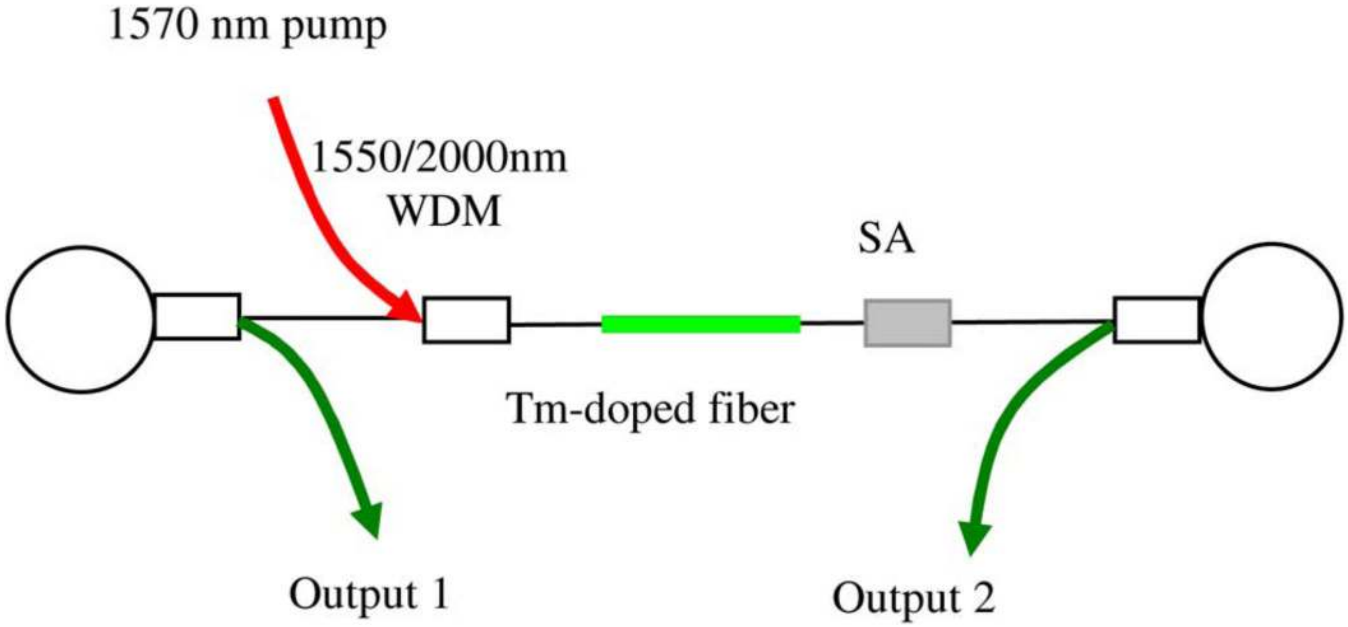

Fig. 1.
Experimental setup. SA: SWCNT saturable absorber. WDM: wavelength-division-multiplexing coupler.

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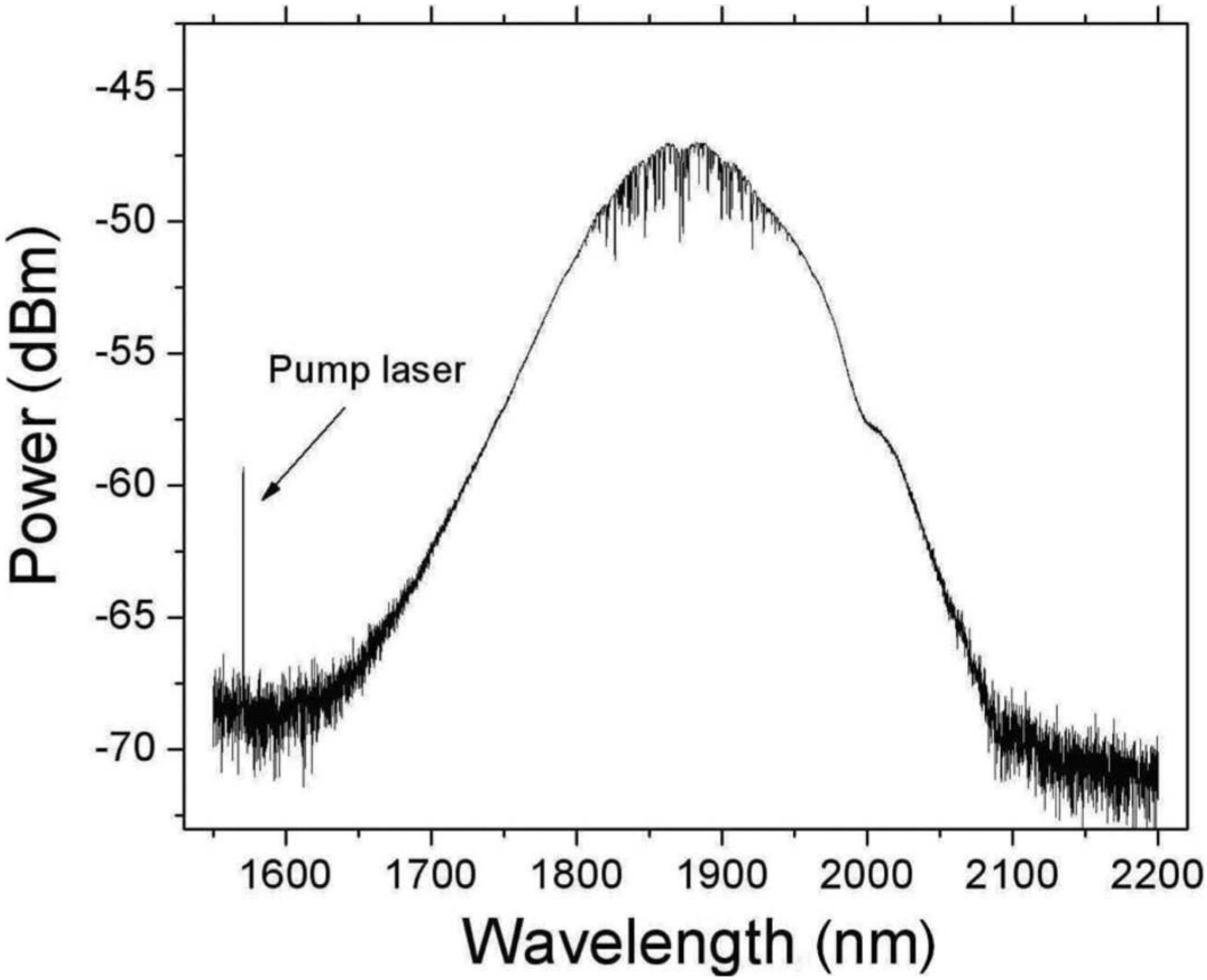

Fig. 2.
Fluorescence spectrum of the Tm–Ho codoped fiber pumped at 1570 nm.

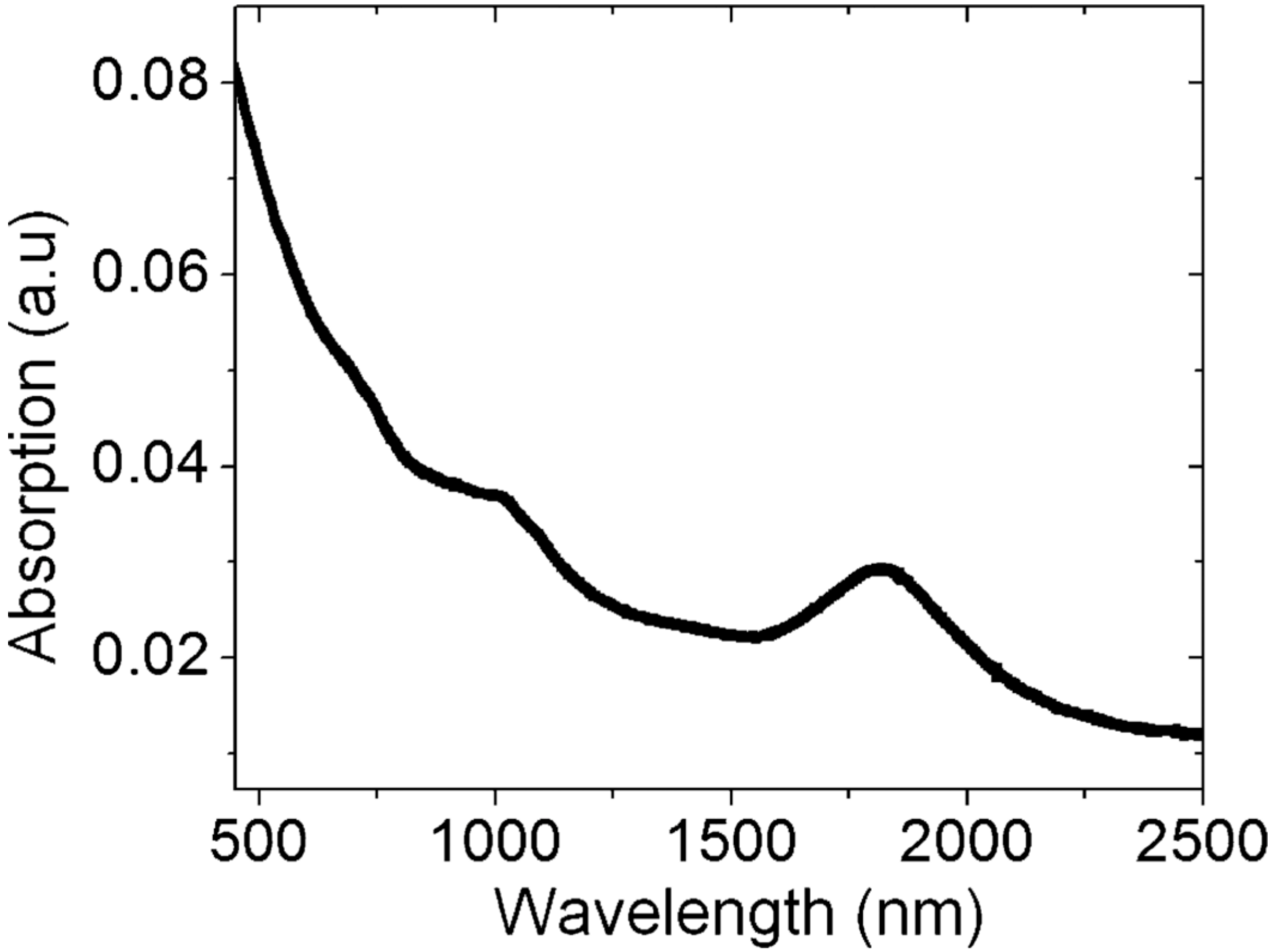

Fig. 3.
Absorption spectrum of the SA.

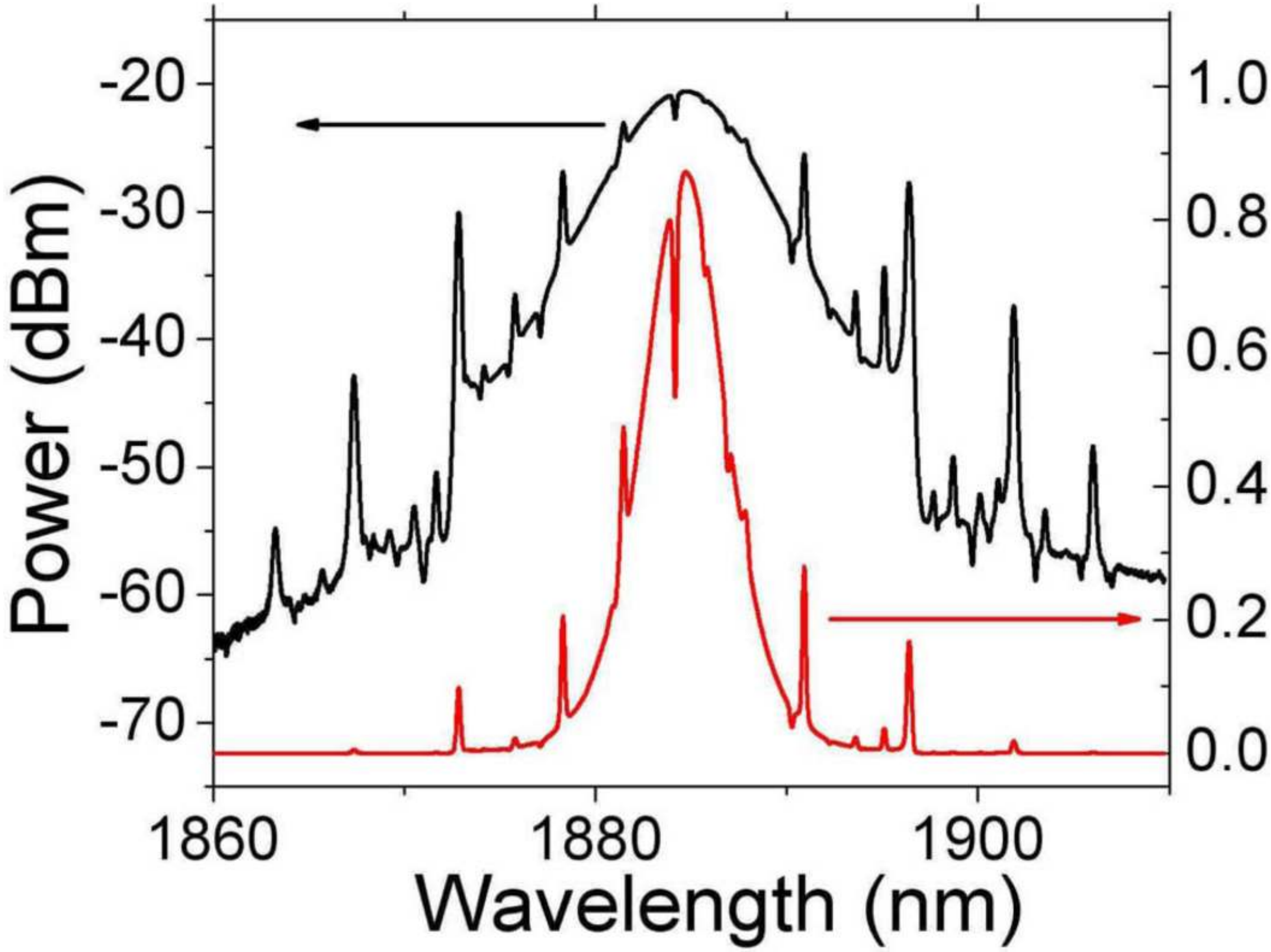

Fig. 4.
Output spectrum on linear (red) and logarithmic (black) scales.

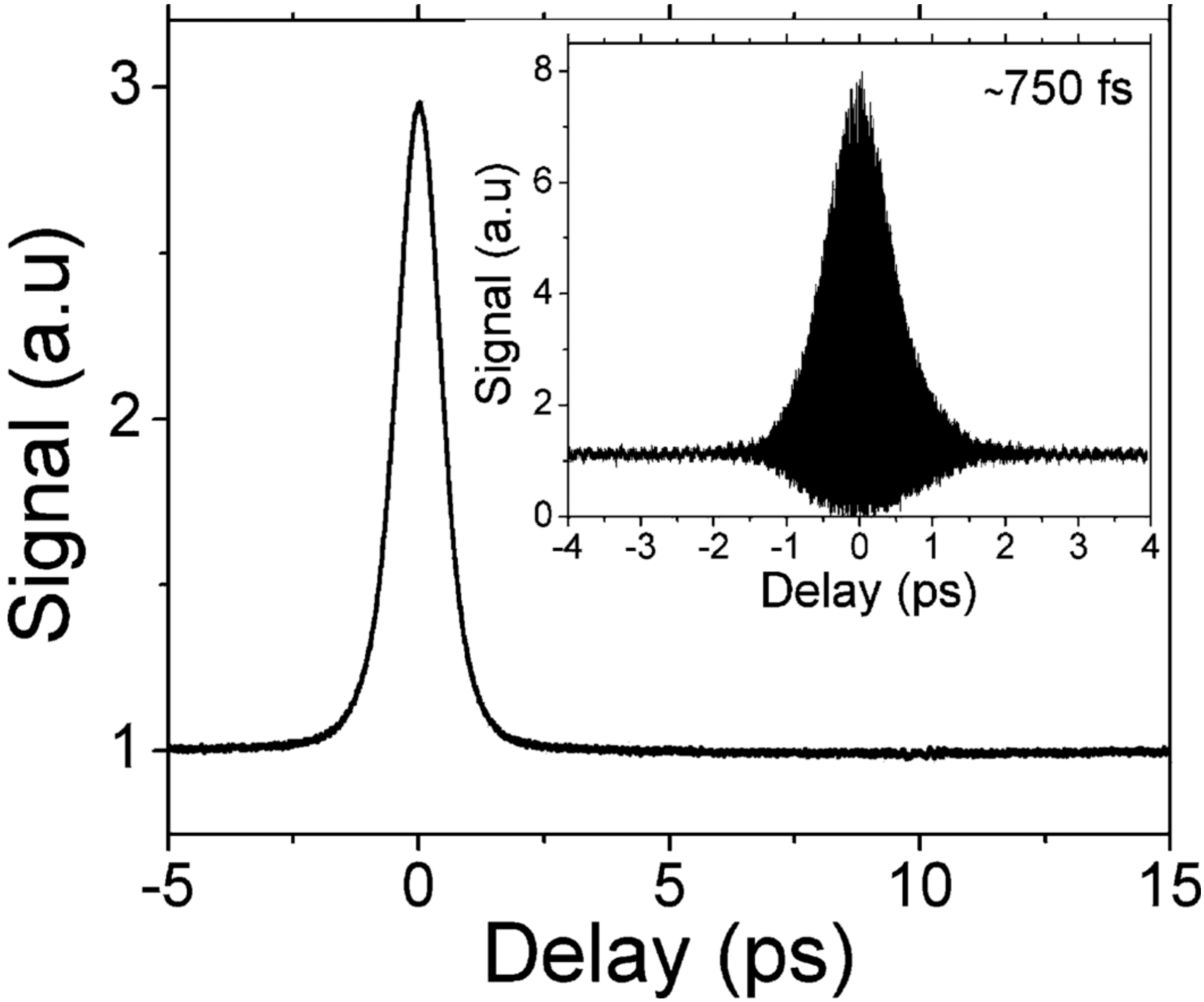

Fig. 5.
Pulse intensity autocorrelation. Inset: interferometric autocorrelation.