Compact and high-power broadband terahertz source based on femtosecond photonic crystal fiber amplifier

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We present a review of the development of a compact and high-power broadband terahertz (THz) source optically excited by a femtosecond photonic crystal fiber (PCF) amplifier. The large mode area of the PCF and the stretcher-free configuration make the pump source compact and very efficient. Broadband THz pulses of 150 μW extending from 0.1 to 3.5 THz are generated from a 3-mm-thick GaP crystal through optical rectification of 12-W pump pulses with duration of 66 fs and a repetition rate of 52 MHz. A strong saturation effect is observed, which is attributed to pump pulse absorption; a Z-scan measurement shows that three-photon absorption dominates the nonlinear absorption when the crystal is pumped by femtosecond pulses at 1 040 nm. A further scale-up of the THz source power is expected to find important applications in THz nonlinear optics and nonlinear THz spectroscopy.

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Terahertz (THz) waves, generally defined in the 0.1–10 THz range, are finding growing applications in various important fields[1−4] such as imaging, food and pharmaceutical quality control, security screening, and standoff detection of bio-threat species, among which THz time-domain spectroscopy (THz-TDS)[5] is particularly appealing. However, the low conversion efficiency and low power of typical broadband THz sources severely hinder the utility and realization of the full potential of THz-TDS. Recently, there have been efforts to generate THz pulses using compact pump sources in fiber format[6,7].

In this letter, we review the development of a compact and high-power broadband THz source based on an all-photonic crystal fiber (PCF) amplifier[8]. Based on optical rectification, 150-μW THz pulses could be generated from a 3-mm-thick GaP crystal by 66-fs, 12-W pump pulses at 52 MHz[9]. A Z-scan measurement showed that the three-photon absorption effect dominated the nonlinear pump absorption in the bulk GaP[10], which could help explain the observed saturation of the THz output. A further scaling of the power of the THz-TDS system is visualized.

Unlike conventional optical fibers (COFs), PCFs are typically made from a single material while having wavelength-scale air holes running down the entire fiber length[11]. A typical scanning electron microscopy (SEM) image of the PCF (crystal fiber A/S, Denmark) is shown in Fig. 1.

A PCF can be endlessly single mode[12], that is, the fiber is single mode irrespective of the wavelength when the ratio of the air hole diameter to the air hole pitch is below 0.4. Being endlessly single mode implies that PCFs of extremely large mode areas (LMAs) can be obtained. Furthermore, the commonly used stack-and-draw fabrication process makes it easy to fabricate highly birefringent, double-cladding, and multicore structures. These novel properties make PCF ideally suited for high-power and ultrafast laser/amplifier applications. PCF-based light sources have now become the ideal sources for the generation of broadband THz waves, as demonstrated in Refs. [9,13]

As shown in Fig. 2, the pump source for the THz-TDS system includes a fiber oscillator and a fiber amplifier, both based on the same Yb-doped LMA PCF with a mode diameter of 29 μm (corresponding to a mode area of 660 μm^2). Stress-applying parts are introduced into the cladding to preserve single-polarization single-mode operation. The gain PCF (1.5 m) for the oscillator generates 300–500-fs seed pulses of 1 040 nm with up to 400-mW average power at a repetition rate of 52 MHz, as shown by the dotted line in Fig. 3(a). For compactness, the

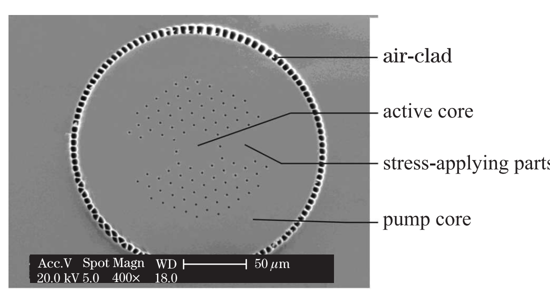

Fig. 1. SEM image of a Yb-doped polarization-maintaining double-cladding PCF.

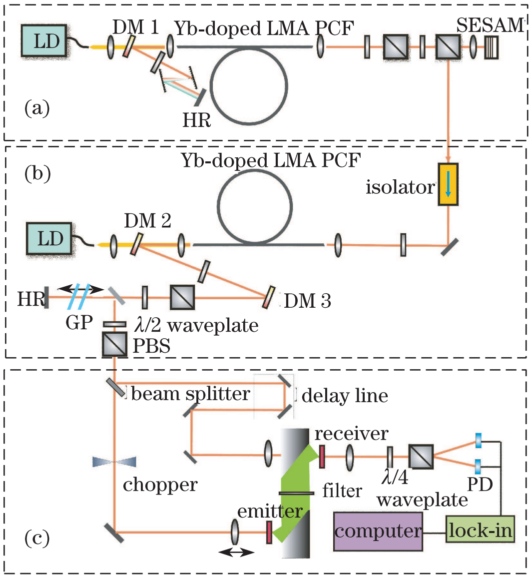

Fig. 2. Schematic of the THz-TDS system used in the experiment. LD: laser diode; DM: dichroic mirror; HR: high-reflection mirror; GP: grating pair; PBS: polarization beam splitter; PD: photodiode; SESAM: semiconductor saturable absorber mirror.

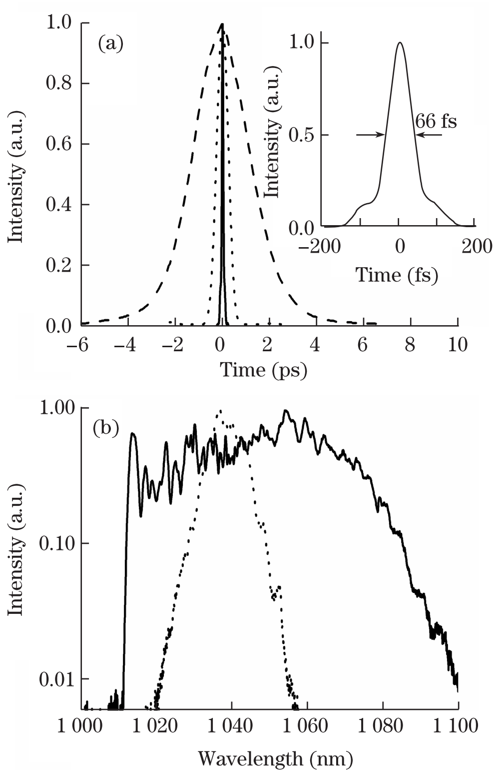

Fig. 3. (a) Intensity autocorrelation traces measured for pulses from the PCF oscillator (dotted line), PCF amplifier before compression (dashed line), and PCF amplifier output upon compression (solid line and the inset), with the input laser pulses having an average power of 300 mW and a pulse width of 414 fs, while the pulse width from the PCF amplifier being 2 ps and the compressed pulse width being 66 fs with a power of 21 W; (b) spectra of the pulse from the oscillator (dotted line) and the amplifier (solid line).

fiber amplifier works in a stretcher-free configuration[14], where pulse stretching is achieved by the normal dispersion in the 3.5-m PCF. Thus, the seed pulses from the oscillator can be stretched to 2 ps (dashed line in Fig. 3(a)). Excited with a 976-nm, 47-W laser diode, the amplifier can deliver pulses as short as 66 fs with a power of 21 W. Short pulse duration is possible because the amplification of laser pulses in the PCF is accompanied by spectral broadening and nonlinear phase shift accumulation mainly due to self-phase modulation[14]. The spectrally broadened pulses (see Fig. 3(b) for comparison) can be compressed by the grating pair to as short as 66 fs (solid line in Fig. 3(a) and also the inset), which is much shorter than that in commonly used fiber systems. The LMAs offered by the PCFs can sustain higher power without a breakdown of the medium in the nonlinear amplification scheme; hence, the single-stage and stretcher-free amplifier is ideally suited for a compact and high-power THz-TDS system.

The optical rectification-based THz-TDS unit of the whole system is shown in Fig. 2, where a 3-mm <110>-cut bulk GaP crystal is used as the emitter for pump pulses at 1 040 nm to fulfill the collinear phase matching condition. The power of the pump pulses from the PCF amplifier is varied by a combination of a $\lambda/2$ waveplate and polarization beam splitter. The position of the lens in front of the emitter is controlled by a translation stage to obtain the best pump beam area on the crystal to let the emitter work just under the damage threshold. The THz radiation generation is optimized by the THz-TDS unit, and the THz pulse power is then measured by a Golay cell detector (TYDEX GC-1P) used in place of the balance detection part of THz-TDS.

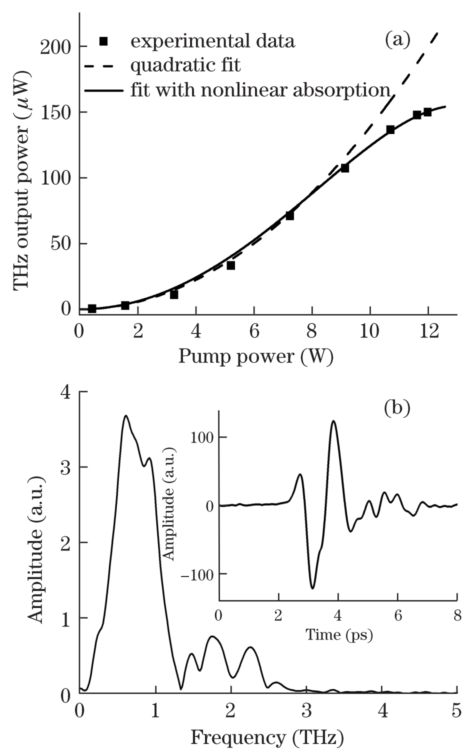

Fig. 4. (a) THz output power as a function of pump power within the 3-mm-thick GaP crystal, with the pump pulse duration being 66 fs, and fits with and without nonlinear absorption terms are also shown; (b) spectra and temporal profile (shown in the inset) of the 150-μW THz pulse measured by THz-TDS.

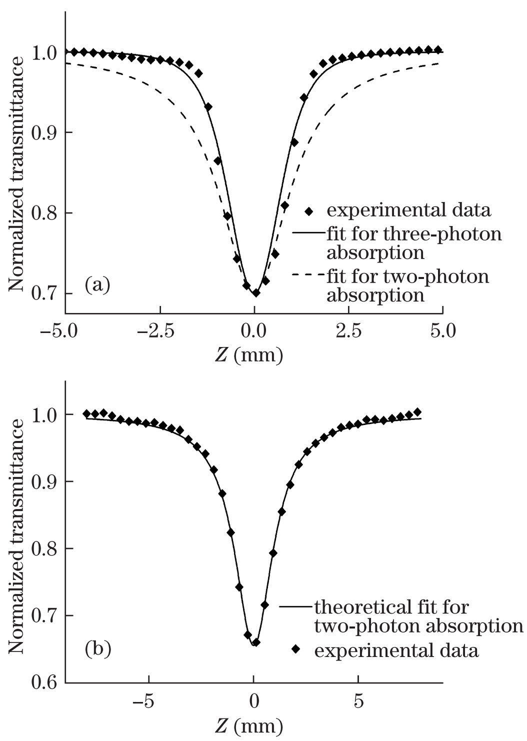

Fig. 5. (a) Normalized experimental transmittance for 1 040-nm pump light; (b) normalized experimental transmittance for 800-nm pump light, both for <110>-cut GaP crystal.

The dependence of the THz output on the pump power within the 3-mm-thick crystal is shown in Fig. 4(a), where a saturation effect is seen for pump power of above 9 W. Systematic optimization of the system allows 150-μW THz pulses to be generated by 66-fs, 12-W pump pulses from the 3-mm-thick GaP emitter. The pulse spectrum extends from 0.1 to 3.5 THz (Fig. 4(b)); the pulse waveform is shown in the inset with a signal-to-noise ratio larger than 200.

An analysis of the pulse and crystal parameters used in similar fiber amplifier systems[6,9] shows that our system could have been more efficient considering the much shorter pulse duration. The limitation imposed on the system efficiency can be explained by the observed saturation of the THz generation caused by the nonlinear absorption of the pump pulses and the associated free-carrier absorption of the THz radiation in the THz emitter. We used a modified Z-scan technique to achieve polarization-resolved measurement of the nonlinear properties of the bulk GaP excited by the PCF amplifier working at 1 040 nm[10]. It is demonstrated that the three-photon absorption effect dominates the nonlinear absorption processes, as shown by the experimental transmittance for 1 040 nm and its fits in Fig. 5(a). In contrast, femtosecond laser pulses at 800 nm can satisfy the condition of direct-gap two-photon absorption in GaP (Fig. 5(b)). Because the weight factor for the three-photon absorption coefficient is orders of magnitude smaller than that for the two-photon absorption, the PCF amplifier is a better candidate to be the pump source for GaP.

In conclusion, a broadband THz source for high-power TDS is presented. The use of a high-power PCF amplifier enables the generation of 150-μW THz pulses extending to 3.5 THz from a 3-mm-thick GaP crystal at a pump power of 12 W. The power of the THz-TDS system is potentially scalable with a further increase in the pump power, e.g., by using an amplifier that is based on a multicore PCF concept[15].

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