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Hollow-core photonic crystal fibers for high-power, ultrafast lasers

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Combining Kagome lattice hollow-core photonic crystal fibers with ultrafast lasers enables transmission and pulse compression with high energy and high average power.

Industry and science require ever faster laser systems with high repetition (MHz) rates and peak powers. As an example, fast specialized micromachining requires ultrafast lasers with average power ranging from hundreds of watts to kilowatts[1]. The past decade has seen dramatic progress in the development of hollow-core photonic crystal fibers (HC-PCF)[2] and ultrafast lasers[2–5], and we can now combine the two to enable laser systems of unsurpassed ultra-high average power with short pulse durations. Several groundbreaking laser technologies, namely slab-[2], fiber-[3], and thin-disk amplifiers and oscillators[4,5] have exponentially increased the available average- and peak power and pulse energy. Ultrafast sources have exceeded the milestone of kilowatt average power, and they reach pulse peak powers of tens- to hundreds of megawatts in sub-picosecond pulses (see Figure 1). For scientific applications, the same parameter range is desirable for experiments with higher average photon flux and the accompanying higher signal-to-noise ratio and shorter measurement durations[6,7].

However, there are few robust solutions for fiber-based beam delivery at this very high peak power, creating a hindrance for some applications. In industry there are practical challenges, such as the degradation of beam quality and limits on pulse duration and power available on target after transmission in standard silica fibers. For scientific applications, one difficulty is the relatively long pulse durations of a few hundred femtoseconds to a few picoseconds. Most targeted experiments, such as undertaken in strong-field laser physics, would benefit from efficient fiber-based solutions for simple pulse compression schemes,

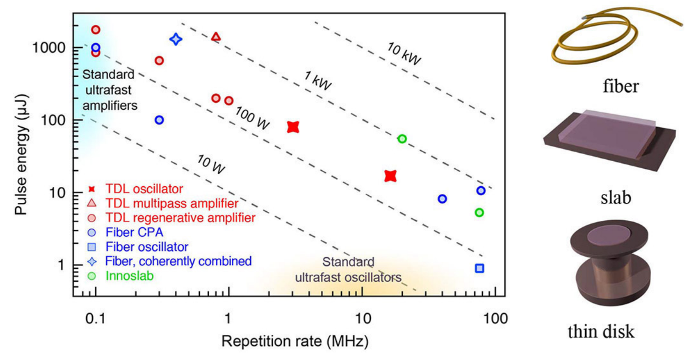

Figure 1. *Overview of ultrafast laser sources combining high pulse energy and repetition rate, and illustration of different laser architectures. These optimize heat removal to support very high average power in the kW regime. TDL: Thin disk laser. CPA: Chirped pulse amplification.*

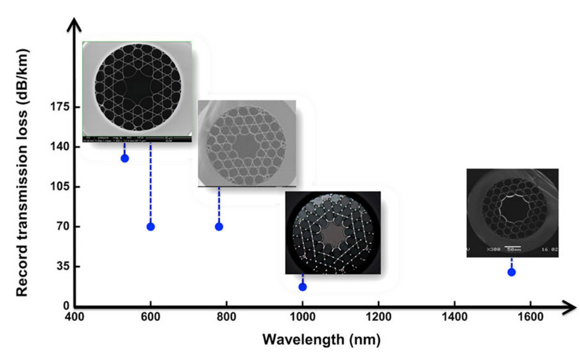

Figure 2. *Inhibited coupling (IC) Kagome-type hypocycloid hollow-core photonic crystal fibers (HC-PCF). This type of fiber exhibits extremely low loss in the near-IR–visible spectral range. Record values are 17 decibels (dB)/km at around 1μm, and 70dB/km at 780nm and 500–600nm. IC Kagome HC-PCFs exhibit outstanding guidance and delivery properties, low waveguide dispersion, and anomalous group velocity dispersion over a large portion of the transmission bandwidth, making them excellent candidates for pulse compression applications.*

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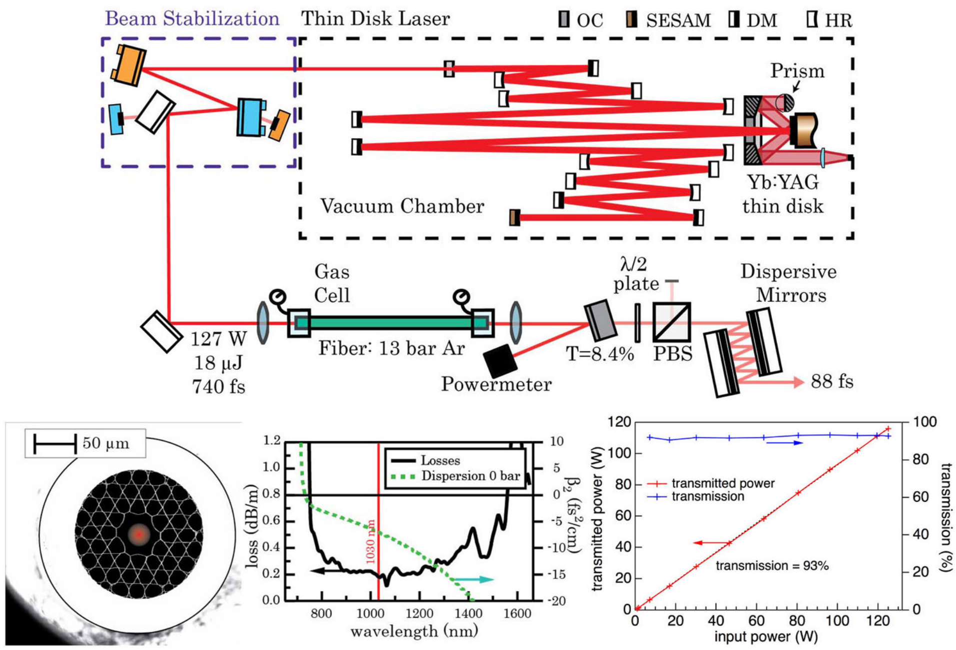

Figure 3. *Experimental setup for high-average power transmission and compression of mode-locked ytterbium: yttrium aluminum garnet (Yb:YAG) TDL. The 7-cell, 3-ring IC Kagome-type hypocycloid core HC-PCF used in high-power pulse compression has a mode-field diameter of* $\approx 30\mu m$*. This fiber is an excellent candidate for efficient pulse compression with low loss of 180dB/km and negligible dispersion* $\approx -5fs^2/cm^2$ *at a center wavelength of 1030nm. Over the entire range of input power up to 127W, we achieved >90% transmission through the 66cm-long fiber filled with 13bar of argon (Ar). The resulting spectral broadening due to self-phase modulation supported pulse compression to well below 100fs. OC: Output coupler. SESAM: Semiconductor saturable absorber mirror. DM: Dispersive mirror. HR: Highly reflective (mirror). PBS: Polarizing beam splitter. T: Transmission.*

which would reduce the pulse duration to the sub-100 fs range.

Alongside the progress achieved in ultrafast lasers, the field of HC-PCFs has also seen the emergence of gas photonics[8] (nonlinear effects in gaseous media). In particular, the development of inhibited coupling (IC) guidance[9], the photonic manifestation of a quasi-bound state in a continuum, represents a conceptual departure from photonic bandgap guiding (PBG) HC-PCF[10]. This has enabled new fiber designs, such as the seminal hypocycloid-shaped-core Kagome-type HC-PCFs, with negative radius of curvature[9] (see Figure 2). These novel IC fibers exhibit broadband transmission, ultra-low dispersion, and a strongly reduced optical overlap with the surrounding silica. They also offer improved single-mode guidance and extremely low transmission loss, which surpasses those of PBG HC-PCFs with record-low loss of 17dB/km at $1\mu m$.[11] Remarkably, this unique combination of optical properties lends itself beautifully to ultrafast pulse handling (high energy pulse delivery) and conditioning (spectral broadening and pulse compression). We have shown the fiber technology's potential in the transmission of femtosecond pulses with millijoule pulse energies and intensities of tens of gigawatts per square centimeter, with low-loss and in single-mode operation.[10] Our recent experiments demonstrated low-loss transmission and pulse compression of ultrafast lasers in the 100W average power regime (see Figure 3)[12].

For our investigation, we used a laser source based on a semiconductor saturable absorber mirror mode-locked thin-disk laser (SESAM-TDL)[12,13]. This technology has reached the highest average powers (up to 275W[3]) and pulse energies (up to $80\mu J$[14]) of any ultrafast oscillator, leading to compact multi-MHz sources suitable for the applications described above.

Our passively mode-locked ytterbium: yttrium aluminum garnet (Yb:YAG) TDL operates at 1030nm with 127W available average power in the compression setup. At a repetition rate of 7MHz, the resulting pulse energy was $18\mu J$ and the pulse duration was 740fs. We spatially stabilized the oscillator beam before focusing it to the IC Kagome-type HC-PCF. We placed the

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66cm-long fiber in a water-cooled sealed holder, where we could inject different gases with pressures of 0–15 bar. We achieved ≈93% of transmission when the fiber was filled with 13bar of argon over the entire range of input average power, reaching up to 118W at the output. At the maximum power, the initial spectrum broadened to 26nm of full width at half maximum spectrum due to self-phase modulation, supporting sub-100fs pulses. For compression of the spectrally broadened pulses, we used 20 bounces on dispersive mirrors centered at 1030nm and providing -550fs^2 per bounce (total -11000fs^2), achieving 95% of transmission through the dispersive mirror pair. The complete compression system had an efficiency of >85% in terms of power.

In summary, we have shown that IC Kagome-type HC-PCFs are well suited for transmission and pulse compression with high energy and high average power using novel ultrafast lasers. We demonstrated outstanding transmission of more than 90% for a 66cm fiber at an average power exceeding 100W. This is a new record for any fiber in the sub-picosecond regime.

We expect that IC Kagome-type HC-PCFs will support transmission of both kilowatt average power and millijoule pulse energy in the near future, and our work now will focus on realizing that aim.

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