Ultrashort Pulse Amplification in Fibers: Challenges, Status and Potential

J. Limpert
Institute of Applied Physics, Friedrich-Schiller-University Jena, Albert-Einstein-Str. 15, 07745 Jena, Germany
Helmholtz-Institute Jena, Helmholtzweg 4, 07743 Jena, Germany

Abstract: The recent demonstration of rare-earth-doped fiber lasers with a continuous-wave output power approaching the 10 kW-level with diffraction-limited beam quality has proven that fiber lasers constitute a power-scalable solid-state laser concept. To generate intense pulses from a fiber several fundamental limitations have to be overcome. Nevertheless, novel experimental strategies and fiber designs offer an enormous potential towards ultrafast laser systems with high average powers (>kW) and high peak power (>GW). The challenges, achievements and perspectives of ultrashort pulse generation and amplification in fibers will be reviewed.

Sources of ultrashort and high peak power optical pulses have become extremely important for numerous applications such as spectroscopy, remote sensing or high field physics. In fact, considerable progress has been made over the last decade to obtain high peak power femtosecond sources based on Ti:Sapphire lasers and amplifiers. Such systems are the work-horse of ultra-fast science and have proven to be a very reliable option at low repetition rates. Ultra-short and intense laser sources are used in high field physics to probe processes which often have very small probabilities of occurrence. For instance, attoscience uses weak XUV pulses produced with such IR ultra-short pulses. As a consequence of this low probability of occurrence, detection of the XUV induced processes requires very sophisticated and sensitive apparatus. An increase of few orders of magnitude in the repetition rate will clearly provide a tool that would allow breaking the actual limits and that would open the way to in-depth investigation of such phenomena. The same holds true for other application of ultra-short laser pulses such as laser micro-machining.

Having a gain medium that is both long and thin, which constitute the fiber concept, not only leads to outstanding thermo-optical properties, but also to a very high single pass gain. Fiber-based laser systems have the reputation to be immune against any thermo-optical problems due to their special geometry. Their excellent heat dissipation is due to the large ratio of surface-to-active volume. The beam quality of the guided mode is determined by the fiber core design and is, therefore, largely power-independent. In continuous-wave operation powers as high as 10 kW in a diffraction-limited beam quality have already been demonstrated. Overall, ytterbium-doped double-clad fibers appear to be an ideal candidate for compact high performance lasers and amplifiers in the 1 µm wavelength range. However, the same geometry is also enhancing nonlinear effects by making the light propagate under tight confinement over considerable long interaction lengths. As a matter of fact, in the context of ultra-short pulse amplification nonlinearity is mostly harmful and imposes performance limitations in fiber laser systems.

Hence, to reduce the impact of nonlinearity, a temporal and spatial scaling is needed. Temporal scaling can be achieved by the well-known technique of chirped-pulse amplification (CPA). On the other hand, spatial scaling requires advanced fiber designs that present a large mode area of the actively doped core and an as short as possible absorption length, thus reducing the nonlinear interaction length. Consequently, there has been a pursuit of novel fiber designs with increased core dimensions, which are still able to emit a stable fundamental mode quality. State-of-the-art fibers possess actively doped cores with diameter up to 100 µm. Such fibers allow for the realization of femtosecond fiber laser systems with mJ pulse energy, GW peak power and average powers as high as 830 W in a compact and directly diode pumped architecture.

The presentation will cover the basics of the fiber concept, fundamental limitation and how to overcome them, high performance experiments, the future scaling potential and selected applications.

The following articles provide further insight to ultrafast fiber laser systems:

J. Limpert, et.al. “High Repetition Rate Gigawatt Peak Power Fiber Laser-Systems: Challenges, Design, and Experiment” IEEE JSTQE 15, 1, 159 (2009).

J. Limpert et.al. “High-power ultrafast fiber laser systems,” IEEE JSTQE 12, 2, 233 (2006).

T. Eidam, "Femtosecond fiber CPA system emitting 830 W average output power," Opt. Lett. **35**, 94-96 (2010).

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