Fiber lasers: flexible and functional solutions for today and the future

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ABSTRACT

Fiber lasers were demonstrated as early as in the 1960s, but they were hampered by the need for laser pumping for efficient operation. The mid 1980s saw the realization of rare-earth doped single-mode high silica fibers with low loss. In a symbiotic pairing with advances in semiconductor pump lasers, a rapid development of active fiber devices ensued. This led to the erbium-doped fiber amplifier (EDFA), which has revolutionized optical telecommunications.

Active optical fiber devices can ensure robust single-mode operation, which is necessary for many applications. Furthermore, a tight beam confinement leads to low laser thresholds and high gain efficiencies, despite the low cross-sections for stimulated emission and absorption in glass hosts because of a broad linewidth. This, on the other hand, is important for broadband amplification, tunable lasers, and for short pulses.

Cladding-pumping is used for power-scaling of fiber lasers. For this, a fiber that guides light in the inner cladding, typically a so-called double-clad fiber, must be used. The inner cladding is large enough for high-power multimode pump beams, even from diode stacks. Generally, the pumping scheme is critical for high-power fiber devices. While straightforward end-pumping is simple and efficient, several so-called side-pumping alternatives have been developed. Other important aspects include thermal management (much simplified by the long lengths possible with waveguiding), pump absorption (the core must be heavily doped to "compensate" for the undoped inner cladding), and damage. Damage and pump absorption are helped by a large core, which is a crucial design aspect.

Cladding-pumped ytterbium-doped fiber lasers are very efficient, and several hundred watts of output power has been obtained at ~1100 nm in a nearly diffraction-limited beam. Neodymium-doped fiber lasers are less efficient, but work with lower-brightness pumping schemes. Erbium-ytterbium co-doped fibers are also less efficient, but are still the best gain medium available in the important "eye-safe" 1530 – 1620 nm wavelength regime. Over 100 W of output power has been demonstrated. Thulium emits at ~2000 nm, which is an excellent starting-point for wavelength-conversion to the mid-IR. Also with thulium, power-scaling beyond 100 W seems feasible. Cladding-pumped Raman fiber lasers have recently been demonstrated. In MOPA configurations, single-frequency powers of ~100 W have been realized at both 1080 and 1560 nm. At 1560 nm, high-performing telecom components enable sophisticated signal processing at these power levels.

Pulsed fiber sources are more difficult than cw ones, but, for example, over 100 W of output power and nearly 10 mJ pulses have been obtained. Three-level systems are also challenging. Still, pulsed and cw lasers and amplifiers have been realized at 980 nm, with output powers of up to 4 W. This has been frequency-doubled to 488 nm.

Kilowatt-class devices seem possible with single-core Yb-doped fiber lasers. For higher powers, fiber lasers have been multiplexed in series as well as in parallel, with highly multi-mode output beams. More advanced configuration, including multi-core fiber designs, are considered for diffraction-limited multi-kW output at multi-kW levels.

We will discuss fundamentals of high-power fiber lasers and review recent results. Strengths of cladding-pumped fiber devices in areas such as high-power and broadband amplification, wavelength tuning, and operation at wavelengths where fiber lasers perform particularly well, will be highlighted.