High power fiber lasers

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Abstract

We discuss fundamental aspects of high-power fiber lasers and describe their recent dramatic advances and prospects including our up-to-date experimental results with particular attention to kilowatt-class, refined power amplifier regimes.

Summary

Fiber lasers are thin, light-guiding strands of glass only a few times the thickness of a hair. They have a tiny core doped with rare-earth materials that absorb optical pump power and release it through the process of stimulated emission at the signal wavelength.

The first rare-earth-doped fiber laser was demonstrated in the early-1960s [1, 2] following the original suggestion for an optical maser [3]. Following remarkable advances in fiber technology based on the modified chemical vapor deposit method (MCVD) and in pump diode technology, the initial demonstrations of single-mode fiber lasers and amplifiers were realized in the mid-1980s at the University of Southampton [4, 5], and they went on to revolutionize the optical telecommunications industry. Furthermore, in recognition of their potential as versatile tools in the altogether-different industrial manufacturing market, academia and industry have in recent years driven the fiber laser technology to the stage of kilowatt-level output powers [6–9]. These advances herald a revolution in material processing and micro-machining, as well as in a wide range of science and technology areas, such as medicine, free-space satellite communications, range finding, and guide star (astronomy). Fiber lasers are now competing with and replacing conventional, bulk solid-state lasers in many application areas.

Fiber lasers adopt technologies from solid-state physics and optical telecoms. Most common types of fiber lasers have a core doped with a rare earth, e.g., neodymium, ytterbium, erbium, or thulium. Typically, the core has a diameter in the range of a few to a few tens of micrometers, preferably small enough to maintain operation on a single transverse mode, whilst large enough to avoid damage and nonlinear scattering and to obtain sufficient pump absorption. This fiber circuitry combined with pump-diode technology provides a unique high-gain environment for robust designs, which is also all-solid state, compact, stable, reliable, and reproducible. Moreover, like in optical telecoms, the optical power generated by fiber lasers can readily be transferred from one place to another which is at a distance as well as having a variety of opportunities for add/drop multiplexed regimes.

Remarkably, fiber lasers based on such a tiny strand have proven themselves to be capable of generating and delivering over 1 kW of output power in a conventional laser configuration with high beam quality. A demonstration of an ytterbium-doped fiber laser in a kilowatt regime showed that a maximum output power of 1.36 kW was reached and limited only by available pump power [8]. The laser operated with near diffraction-limited beam quality (M^2 = 1.4) despite its relatively large multi-mode core. The excellent slope efficiency of 83% (quantum efficiency close to 95%) leads to a relatively low thermal load, which suggests that significantly higher powers should be possible when higher pump power becomes available. Kilowatt fiber lasers (or even higher-power fiber sources) are now commercially available [9].

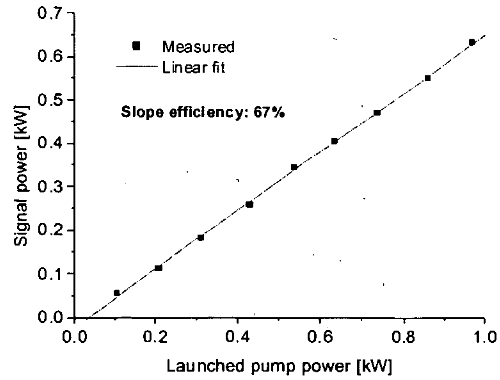

Fig. 1. Laser characteristics of a plane-polarized ytterbium-doped fiber laser with output power of 0.63 kW [10].

Even more refined fiber sources operating in a range of regimes are also approaching the kilowatt level. An illustration of the record-power characteristic curve of a plane-polarized ytterbium-doped fiber laser is shown in Fig. 1 [10]. The maximum power was 0.63 kW with near diffraction-limited beam quality ($M^2 = 1.2$) and a polarization extinction ratio (PER) better than 16 dB. When this type of polarization- maintaining birefringent fiber was further exploited in a master-oscillator power amplifier (MOPA) configuration, it could generate 264 W of single-frequency radiation of which linewidth was less than 60 kHz (resolution limited).

More recently, a single-frequency, single-mode ytterbium-sensitized erbium-doped fiber master-oscillator power-amplifier with 150 W (51.8 dBm) of continuous-wave output power at 1563 nm with 33% slope efficiency was demonstrated [11]. This was also tunable in the range of 1546 to 1566 nm at >125 W. In a pulsed regime, 321 W average-power, 1 GHz, 20 ps, 1060 nm pulsed fiber MOPA source was demonstrated [12]. The estimated peak power was 13 kW.

Indeed, the MOPA configurations can provide highly-controllable single-frequency radiation with opportunities for tunable, frequency-swept, and pulsed operation. Because of the cavity-free traveling-wave nature of the amplifiers, they can maintain the spectral purity of the seed source with a minimum of phase noise added. Furthermore, this configuration allows additional opportunity for beam combination which is a flexible way to further power scaling beyond the limit of an individual fiber source, up to hundreds of kilowatt or even an arbitrary power level. Thus, their potentials cannot be underestimated.

Here we review the current state of the art of kilowatt-level fiber laser sources including fundamental aspects and recent results. We will discuss power-scaling prospects of fiber sources, and analyze our up-to-date experimental results, leading to an outlook for the future. The focus will be on refined fiber sources based on ytterbium-doped fibers operating at 1.1 μm and erbium/ytterbium-doped fibers at 1.5 μm, in a multitude of regimes including both continuous-wave and pulsed operation.

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References

1. E. Snitzer, "Optical maser action of Nd3+ in a barium crown glass," Phys. Rev. Lett. **7**, 444, (1961).
2. C. J. Koester and E. Snitzer, "Amplification in a fiber laser," Appl. Opt. **3**, 1182 (1964).
3. A. L. Schawlow and C. H. Townes, Phys. Rev. **112**, 1940 (1958).
4. S. B. Poole, D. N. Payne, and M. E. Fermann, "Fabrication of low loss optical fibres containing rare earth ions," Electron. Lett. **21**, 737 (1985).
5. R. J. Mears, L. Reekie, S. B. Poole, and D. N. Payne, "Neodymium-doped silica single-mode fibre lasers," Electron. Lett. 21, 738 (1985).
6. Y. Jeong, J. K. Sahu, D. N. Payne, and J. Nilsson, "Ytterbium-doped large-core fibre laser with 1 kW of continuous-wave output power," Electron. Lett. **40**, 470 (2004).
7. A. Liem, J. Limpert, H. Zellmer, A. Tünnermann, V. Reichel, K. Mörl, S. Jetschke, S. Unger, H.-R. Müller, J. Kirchhof, T. Sandrock, A. Harschak, "1.3 kW Yb-doped fiber laser with excellent beam quality," CLEO 2004, San Francisco, USA, May. 16-21, 2004, postdeadline paper CPDD2.
8. Y. Jeong, J. K. Sahu, D. N. Payne, and J. Nilsson, "Ytterbium-doped large-core fiber laser with 1.36 kW continuous-wave output power," Opt. Express **12**, 6088 (2004).
9. Information available: http://www.ipgphotonics.com, http://www.spioptics.com.
10. Y. Jeong, J. Nilsson, J. K. Sahu, D. B. S. Soh, P. Dupriez, C. A. Codemard, S. Baek, D. N. Payne, R. Horley, J. A. Alvarez-Chavez and P. W. Turner, "Single-mode plane-polarized ytterbium-doped large-core fibre laser with 633 W continuous-wave output power," Opt. Lett. **30**, 459 (2005).
11. Y. Jeong, J. K. Sahu, D. B. S. Soh, C. A. Codemard, and J. Nilsson, "Tunable single-frequency ytterbium-sensitized erbium-doped fiber MOPA source with 150W (51.8 dBm) of output power at 1563 nm," OFC 2005 Anaheim, 6-11, Mar., 2005, postdeadline paper PDP1.
12. P. Dupriez, A. Piper, A. Malinowski, J. K. Sahu, M. Ibsen, Y. Jeong, L. M. B. Hickey, M. N. Zervas, J. Nilsson, D. J. Richardson, "321 W average power 1 GHz 20 ps 1060nm pulsed fiber MOPA source," OFC 2005 Anaheim, 6-11, Mar., 2005, postdeadline paper PDP3.