# High power fiber sources: more than kilowatts

Johan Nilsson
Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, England
jn@orc.soton.ac.uk

**Abstract** *Fiber lasers and amplifiers have reached several kilowatts of output power, and offer many attractions beyond raw power. This tutorial discusses basic scientific and practical issues of fiber sources, and advantages and limitations that derive from them.*

## Introduction

The huge investment made by the telecommunications community in photonics over the last three decades brings a considerable opportunity to disrupt also other areas with new optical technology. The extraordinary level of optical control coupled with the extended reliability that is routine in telecoms is regarded as revolutionary in, e.g., lasers for industrial processing or the life sciences. Remarkably, the mW of telecommunications can be scaled with near-perfect beam quality to the kilowatt level using fiber amplifiers. These attributes and the ability to control high power through modulation of a small seed laser, or **M**aster **O**scillator, followed by a **P**ower **A**mplifier make these so-called MOPAs revolutionary light sources that can enable and dominate a range of application areas.

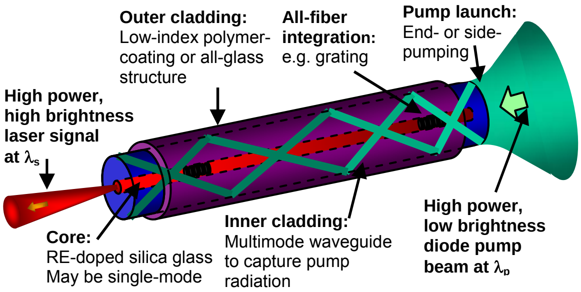


*Figure 1. Schematic of cladding-pumped fiber laser.*

This tutorial will cover the basics of lasers and amplifiers based on cladding-pumped silica fibers, as exemplified in Fig. 1. This includes the fundamental advantages and limitations of the fiber geometry and guided-wave operation, key properties of the fiber material, and important practical issues such as pump coupling. Thermal considerations, nonlinearities, and spectroscopy are examples of important issues, with different impact for different types of fiber sources made with different active dopants (Yb, Er, Tm, Nd) in different modes of operation.

## Ytterbium-doped fiber lasers at 1.1 μm

Ytterbium-doped fiber lasers (YDFLs) exhibit a host of attractive features that make them superior for scaling to the highest powers. These features allowed them to be scaled beyond 1 kW and now up to 3 kW with (nearly) diffraction-limited output [1], [2], [3]. The key features behind this power scalability are the thermal management that the fiber geometry facilitates, the low quantum defect of $Yb^{3+}$, the high efficiency that can be achieved even at high Yb-concentrations, the high damage threshold and low loss of the silica host, and the excellent properties of suitable pump diodes in the 915 – 975 nm wavelength range.

The high Yb-concentration and the high pump absorption it enables bring many performance advantages. It allows the fibers to be shorter, which mitigates nonlinear effects, and it also facilitates the use of fibers with the large inner claddings that are required for kilowatt-level operation. An important aspect of cladding-pumped fiber lasers is that they convert diode pump beams of relatively low brightness into a much brighter, even diffraction-limited, beam from the fiber laser. The high Yb-concentration is crucial also for this. Ytterbium-doped fibers pumped at the absorption peak at around 975 nm allow a pump beam of relatively low intensity launched into the inner cladding to be converted into a signal of roughly three orders of magnitude higher intensity, as averaged over the core. This is limited, roughly, to one order of magnitude less than the ratio of the pump absorption to the background loss. If we try to enhance the intensity conversion further, the efficiency will suffer as the background loss through the length of fiber increases. In addition, the pump-NA can be up towards one order of magnitude larger than the signal-NA (say, 0.5 vs. 0.05). Thus, as the brightness is approximately proportional to the inverse of the square of the NA, an YDFL can improve the brightness by five orders of magnitude in total, with current fiber technology.

**Er:Yb co-doped fiber lasers at 1.6 μm**

Erbium:ytterbium co-doped fiber lasers (EYDFLs) are the preferred choice for high-power sources in the important 1.5 – 1.6 μm wavelength range. This range is attractive because of its “eye-safer” nature and for its compatibility with telecom components. Ytterbium sensitization increases the pump absorption, which is quite low in Yb-free Er-doped fibers. While power levels as high as 0.3 kW have been reached with EYDFLs [4], this is still an order of magnitude below that from YDFLs. The primary reason for this is the much more complex spectroscopy of EYDFLs. It involves energy transfer from Yb-ions to the lasing ions, and this constitutes a bottle-neck which hinders power-scaling. Figure 2 shows a measurement of the Yb fluorescence decay time of an EYDFL, which is closely related to the energy transfer time.

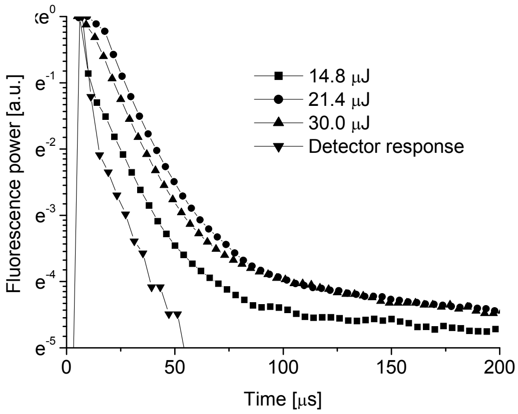


*Figure 2. Yb fluorescence decay curves following excitation with 100 ns, 920 nm pulses of different energies. From [4].*

It is difficult to reach transfer rates as high as those of Fig. 2, and further improvements would require very challenging developments of the Er:Yb gain medium. The thermal load can also be troublesome in high-power EYDFLs, but the fiber geometry helps in this respect, and if necessary additional fiber and device-level engineering can be used to further improve the thermal management.

**Neodymium-doped fiber lasers at 0.9 μm**

Neodymium-doped fiber lasers (NDFLs) typically emit at around 1060 nm, but because of factors such as a much lower permissible concentration and therefore pump absorption, they are out-performed by YDFLs at that wavelength. However, NDFLs can also emit at 0.9 μm, but this only works if the normally dominant 1060 nm emission is suppressed. In fibers, this is possible with a core that guides at 0.9 μm but not at 1060 nm. Such so-called waveguide filters can be realized with W-type fibers [5], [6] and hollow optical fibers [7]], both of which have a cut-off wavelength for the fundamental mode, as well as with photonic bandgap fibers, which only guide over a restricted wavelength range [8]. Figure 3 shows the transmission characteristics of a W-type fiber at different wavelengths with a clear loss difference between 920 nm and 1060 nm. Figure 4 illustrates the near complete suppression of the 1060 nm emission.

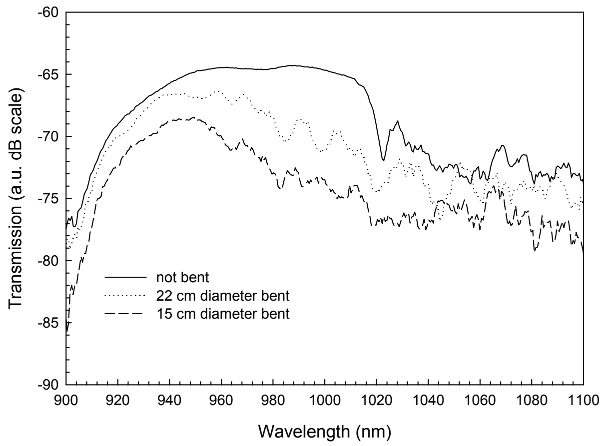


*Figure 3. Core transmission of W-profile Nd-doped fiber at different bend radii. From [6].*

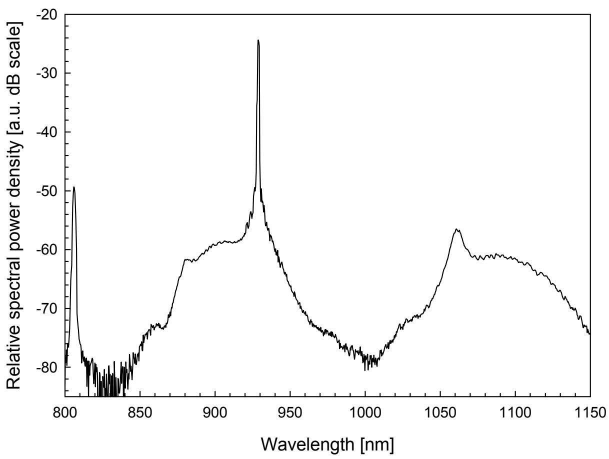


*Figure 4. Spectrum of a 0.9 μm Nd-doped fiber laser. Resolution 1 nm. From [6].*

This type of engineerability greatly adds to the attraction of fibers as laser gain media.

## Single-frequency MOPAs

Fibers are attractive for high-power MOPAs because of their unique capability of high gain, high power, and high efficiency, all at the same time. Single frequency fiber MOPAs take advantage of this, and amplify a well-controlled but low-power seed source to high powers in a cascade of amplifiers providing 40 – 50 dB of gain. However, stimulated Brillouin scattering (SBS) limits the power that can be reached. SBS is a nonlinear effect, so it can be mitigated by a shorter effective length and a larger mode area. Broadening of the signal linewidth as well as the Brillouin gain bandwidth helps, too. In the absence of broadening, the Brillouin-limited output power is given by

$$\sqrt{\frac{I_p A_{dop} A_{eff} G_B^{\max} \alpha_p^{core}}{g_B}}$$

where $I_p$ is the pump intensity that can be launched into the fiber amplifier, $A_{dop}$ is the doped area (typically the core area), $A_{eff}$ the effective area of the mode, $G_B^{max}$ the maximum allowable Brillouin gain, $\alpha_p^{core}$ the core pump absorption, and $g_B$ is the unbroadened Brillouin gain coefficient. According to this, it is difficult to reach output powers of more than around 100 W in single-frequency Yb-doped fiber MOPAs. However, with thermal broadening of the Brillouin gain we have reached over 0.4 kW of output power with SBS-free linearly polarized operation. Other means of Brillouin suppression have also been demonstrated recently.

Many other types of sources, including pulsed ones, also benefit from the high level of control that fiber MOPAs provide.

## Summary

These examples of devices illustrate some important issues for high-power fiber systems, as well as their potential. Other important issues include the pump launch and the pump brightness, and in particular the core size. It is hugely beneficial to use a large core. Many interesting concepts have been proposed, as will be discussed in the tutorial.

## References


1 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**, 6088-6092 (2004)

2 V. Reichel, K. W. Moerl, S. Unger, S. Jetschke, H.-R. Mueller, J. Kirchof, T. Sandrock, A. Harschack, A. Liem, J. Limpert, H. Zellmer, and A. Tünnermann, "Fiber-laser power scaling beyond the 1-kilowatt level by Nd:Yb co-doping," Proc. SPIE **5777**, 404-407 (2005)

3 www.ipgphotonics.com (2007)

4 Y. Jeong, S. Yoo, C. A. Codemard, J. Nilsson, J. K. Sahu, D. N. Payne, R. Horley, R. Horley, P. W. Turner, L. M. B. Hickey, A. Harker, M. J. Lovelady, and A. N. Piper, "Erbium:ytterbium co-doped large-core fiber laser with 297 W continuous-wave output power", IEEE J. Sel. Top. Quantum Electron. **13**, 573-579 (2007)

5 T. J. Kane, G. Keaton, M. A. Arbore, D. R. Balsley, J. F. Black, J. L. Brooks, M. Byer, L. A. Eyres, M. Leonardo, J. J. Morehead, C. Rich, D. J. Richard, L. A. Smoliar, and Y. Zhou, "3-Watt blue source based on 914-nm Nd:YVO4 passively-Q-switched laser amplified in cladding-pumped Nd:fiber", presented at Advanced Solid-State Photonics, Santa Fe, NM, USA, February 2-5, 2004, paper MD7.

6 D. B S. Soh, S. W. Yoo, J. Nilsson, J. K. Sahu, K. Oh, S. Baek, Y. Jeong, C. A. Codemard, J. Kim, and V. N. Philippov, "Neodymium-doped cladding pumped aluminosilicate fiber laser tunable in the 0.9 µm wavelength range", IEEE J. Quantum Electron. **40**, 1275-1282 (2004)

7 J. Kim, P. Dupriez, D. B. S. Soh, J. Nilsson, and J. K. Sahu, "Core area scaling of Nd:Al-doped silica depressed clad hollow optical fiber and Q-switched laser operation at 0.9 µm", Opt. Lett. **31**, 2833-2835 (2006)

8 A. Wang A, A. K. George, and J. C. Knight, "Three-level neodymium fiber laser incorporating photonic bandgap fiber", Opt. Lett. **31**, 1388-1390 (2006)

9 Y. Jeong, J. Nilsson, J. K. Sahu, D. N. Payne, R. Horley, L. M. B. Hickey, and P. W. Turner, "Power scaling of single-frequency ytterbium-doped fiber master oscillator power amplifier sources up to 500 W", IEEE J. Sel. Top. Quantum Electron. **13**, 546-551 (2007)