High-power fiber sources: fundamental properties

J. Nilsson
Optoelectronic Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom
Tel: +44 23 8059 3101, Fax: +44 23 8059 3142, email: jn@orc.soton.ac.uk
Also with Southampton Photonics, Inc., 3 Wellington Park, Hedge End, SO30 2QJ, United Kingdom

Rare-earth (RE) doped fiber lasers form a compelling combination of the attractive laser-optical properties of rare-earth ions and optical fibers. Optically pumped rare-earth ions have many attractive laser properties such as a high efficiency (with in-band pumping it can exceed 80%) and a relative immunity to the environment. This means, for example, that even a potentially high temperature does not significantly change the spectroscopy. Rare-earth ions (when triply ionized) also have a relatively weak oscillator strength (typical value $10^{-5} - 10^{-3}$), because the normally dominant electrical dipole transitions are forbidden. As a result, a relatively high stored energy is required to reach a given level of gain. This is good for Q-switched lasers and other pulsed devices, in which the energy acts as a reservoir and counteracts distortions of the pulse shape. The downside is that a relatively large number of ions (or more accurately, concentration - length product) is required to reach a specific gain. Since concentration-quenching limits the concentration, the device has to be relatively long to reach a significant gain. In a bulk (non-waveguiding) gain medium this is impossible because of diffraction. With the development of low-loss rare-earth doped fibers [1], the diffraction could be counteracted so that tight beam confinement could be maintained over arbitrary lengths. Thus, gains of many tens of decibels became possible, even in glass hosts in which the emission lines are much broader, with lower peak emission cross-sections. In addition, the long length of fiber lasers (10 m is a typical value) simplifies heat-sinking and, with cladding-pumping, opens up for kW-level output power [2].

Uniquely, cladding-pumped fibers can combine a high, broadband gain with high power, high efficiency, and single-mode operation. The latter is a result of the transverse control of the beam that the use of a waveguide (i.e., the fiber core) offers. For high-power operation, however, conventional-size single-mode cores are inappropriate because of the high power densities that would result. To reduce the power density, large cores are used. At the same time, the numerical aperture (NA) is reduced to maintain single-mode guidance. At some point, however (beyond core diameters of 15 μm for a wavelength of 1.1 μm), it becomes increasingly difficult to achieve robust guidance with the very low core-NAs that would be required. Because of the many benefits, cores larger than this are still used. Despite supporting multiple modes, single-mode operation is still possible, if some mode-selecting mechanism is employed. Furthermore, mode-coupling must be suppressed, through careful fiber fabrication and layout of the fiber device. At present, core areas of up to ~1000 μm² have been used in fiber devices with single-mode output. Such large cores help to suppress (unwanted) nonlinear effects. These are generally considered to be a weak point of fibers because of the long interaction length and tight beam confinement. However, nonlinear effects are effectively counteracted by various design strategies such as the large core, but also, for example, through the use of chirped-pulse amplification and reduction of the effective nonlinear coefficients through the use of temperature broadening in stimulated Brillouin scattering [3].

The fiber core can also be used for spectral filtering [4] as well as for dispersion tailoring (in particular in case of micro-structured fibers).

The properties of rare-earth doped fibers allows for high-power sources with narrow linewidths (including "single-frequency" beams), wideband tunability and wavelength selection. These properties make fiber sources ideal for beam-combination to ultra-high, potentially diffraction-limited power levels. Both incoherent (Spectral) and coherent beam-combination is possible. Ultrashort (femtosecond) pulses can also be generated and amplified because of the large bandwidths. Master oscillator – power amplifier configurations allow for precise, adaptive, control of the output characteristics. Thus, fibers enable a host of new sources with properties with which a range of applications can be addressed.