Abstract. The current state of the art in mid-infrared fiber laser research is reviewed. The relevant glass and ceramic fiber host materials and the fiber, pump, and resonator geometries are introduced. Lasers operating on transitions ranging from 1.9 to 4 µm occurring in the rare-earth ions Tm$^{3+}$, Ho$^{3+}$, Er$^{3+}$, and Dy$^{3+}$ and their population mechanisms are discussed on the basis of the fundamental spectroscopic properties of these ions. Continuous-wave fundamental-mode power levels ranging from a few mW near 4 µm up to 85 W near 2 µm have been demonstrated in recent years. Power-scaling methods and their limitations, the possibilities to optimize the population mechanisms and increase the efficiencies of these lasers, novel concepts, as well as the prospects of future mid-infrared fiber lasers at transitions in the wavelength range beyond 3 µm and extending to 5 µm are described.

1. Introduction

Since the introduction of the double-clad fiber more than two decades ago and with the recent technological advances in the fields of fiber fabrication and beam-shaped high-power diode lasers, the performance of diode-pumped fiber lasers has dramatically improved. Today, fiber lasers can compete with their corresponding
bulk crystalline systems in certain applications, especially when fundamental-transverse-mode, continuous-wave (CW) laser operation at output powers in the milliwatt to the kilowatt range is required. The increased recent interest in fiber lasers emitting at mid-infrared wavelengths between 2 and 3 µm primarily relates to the high application potential in laser micro-surgery. Due to the high absorption of water in the spectral region at 2.7–3.0 µm, high-quality laser cutting or ablation has been demonstrated in biological tissues. In addition, laser wavelengths near 2 µm could be suitable for tissue welding and lithotripsy. A number of other potential laser applications in the mid-infrared spectral region, e.g. environmental trace-gas detection, are becoming increasingly important. In all these applications fiber lasers may find their niches.

The high costs of fabricating fibers with sufficiently low losses in the mid-infrared region of the spectrum has impeded the necessary research efforts in the field of mid-infrared fiber lasers. The currently available fiber materials that are suitable as host materials for specific rare-earth-doped fiber lasers in the spectral region 2–5 µm will be introduced in Sect. 2. The invention of the double-clad fiber geometry and the holey fiber concept has accelerated the scaling of the output power and hence the success of high power fiber lasers. The various aspects of the fiber, pump, and resonator geometries will be described in Sect. 3. An overview of mid-infrared fiber lasers will be given in Sect. 4.

Equipped with this general information, the performance of the most important mid-infrared fiber laser transitions in the wavelength range 2–3 µm will be discussed in detail. Sect. 5 will be devoted to the Tm³⁺ fiber lasers at 1.9 and 2.3 µm, whereas the Ho³⁺ fiber lasers at 2.1 and 2.9 µm will be discussed in Sect. 6. An impressive example of the variety of population mechanisms and operational regimes in a single system is the Er³⁺ 2.7-µm fiber laser transition, which will be investigated in Sect. 7. The latest member of the mid-infrared fiber laser group, the Dy³⁺-doped fluoride fiber laser will be discussed in Sect. 8. At wavelengths beyond 3 µm, it becomes increasingly difficult to find suitable host materials for actively doped laser systems. This statement holds true for glass fibers in the same way as for crystalline materials. The prospects of future mid-infrared fiber lasers in this wavelength range and novel concepts for mid-infrared fiber lasers will be discussed in Sect. 9.

Besides general introductions to the different topics of lasers [1, 2] that include many aspects relevant also to mid-infrared fiber lasers, a comprehensive introduction to the field of rare-earth-doped fiber lasers can be found in [3].

2. Fiber materials

The choice of the fiber material involves a number of considerations: the maximum phonon energy, the environmental durability, the draw ability, the rare-earth solubility, and the purity of the starting materials. The maximum phonon energy