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Fibre Lasers

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Fibre Lasers

Wei Shi, Shijie Fu, and Qiang Fang

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36.1 Introduction
Fibre laser is one of the lasers using fibre as the gain medium. So far, laser emissions have been successfully demonstrated with glass fibres, polymer fibres, single-crystal fibres and even gas-filled hollow-core fibres. The rare-earth (RE)-doped glass fibre laser is the main form of the fibre lasers.

Since the birth of the first glass fibre laser demonstrated by Snitzer and co-workers in 1964 [1], fibre lasers have seen progressive developments in all aspects of the laser performance and their application range has expanded significantly. Nowadays, the emission wavelengths of fibre lasers range from ultraviolet to visible/near-infrared and even to mid-infrared. Because of the excellent heat dissipation capability and the inherent long gain length of optical fibre, continuous wave (CW) output power as high as 100 kW has been generated with a single multimode fibre [2] and 10 kW diffraction-limited output has been obtained from a single large-mode area fibre [3]. In pulsed fibre lasers, tens of multi-joule nanosecond pulses [4–6], femtosecond pulses with multi-joule pulse energy, gigawatt (GW) peak power, and over 800 W average power [7,8], and ultrashort pulses as short as sub-10fs [9] have been achieved. Due to the high gain of highly doped optical fibres and their compatibility to fibre Bragg gratings, stable and robust single-frequency operation can be achieved with short-fibre-cavity lasers. Low-noise single-frequency fibre lasers with linewidth as narrow as several kilohertz or even sub-kilohertz have been demonstrated [10]. Single-frequency multi-joule -level laser pulses have been recently obtained in an all-fibre master oscillator and power amplifier (MOPA)

laser system [11]. These outstanding performances of fibre lasers and their inherent attractive advantages, including compactness, robust operation, easy thermal management, excellent beam quality, free alignment and convenient maintenances, have facilitated extensive applications of fibre lasers in the industry (material welding, cutting, soldering, marking, cleaning), medicine, research, defence and security [12].

Among fibre lasers there is a wide variety of fibre geometries, resonator designs and pumping arrangements. Some of these variants will be described later in this chapter and in companion chapters. First, we describe the canonical fibre laser design since this illustrates the salient characteristics of fibre lasers in general.

This basic structure (see Figure 36.1) is essentially the same as that of a conventional optical fibre as used in telecom applications, i.e. with a central glass core surrounded by a glass
cladding, whose refractive index, $n_{cl}$, is less than that of the core, $n_{co}$, thus ensuring guidance of light within the core. Unlike in conventional fibres, the core contains laser-active dopant ions which, when suitably pumped, provide amplification at wavelengths corresponding to the transition of the dopant ion. So far, laser action has been confined to the RE. Pumping is achieved optically, e.g. by launching the pump light directly into the exposed core at the end of the fibre (see Figure 36.4). Thus, the core not only guides the amplified laser light but also the pump light. The final ingredient, needed to complete the laser, is provision of a resonator for feedback, thus converting the amplifier to an oscillator. In its simplest form, relying on the very high gains that can be achieved in active fibres, this feedback can be provided by Fresnel reflections from the fibre ends. Often a more sophisticated feedback arrangement is used, with the laser light emerging from a fibre end and then passing through a region of free space before being fed back, (see Figure 36.1). This then allows a range of different components, such as filters and modulators, to be inserted into the resonator for control of the spectral and temporal characteristics of the laser output.

The core-pumping scheme is adopted in the fibre laser, as shown in Figure 36.1. It is difficult to couple much low-brightness pump power into the highly restrictive fibre active core to get high-power fibre lasers. The cladding-pumping scheme (see Figure 36.2) promotes the revolutionary development of fibre lasers in terms of output power and pulse energy [13]. In this pumping scheme, the high-power low-brightness pump light is launched into the fibre inner-cladding with a larger size and larger numerical aperture (NA). The pump light could be gradually absorbed by the active fibre core and transformed to the much brighter laser when they propagate in the fibre inner-cladding and cross the active core.

We now briefly survey some of the main features of fibre lasers, before elaborating on these and giving them a quantitative basis in Section 36.3.

### 36.2 Features of Fibre Lasers

#### 36.2.1 High Gain and Low Threshold

The basis for these two connected features is the small cross-sectional area of the core, typically in the range $10^{-11}$–$10^{-10}$ m$^2$, corresponding to core diameters in the range 4–10 µm. This area is a factor of 2–3 orders of magnitude smaller than the typical pumped area involved in an end-pumped bulk laser. Hence, this same factor increases the gain for a given pump power, or conversely decreases the threshold for a given resonator loss. Submilliwatt threshold pump powers and gains of 10dB mW$^{-1}$ are not uncommon for the active-fibre devices.

![FIGURE 36.2 Schematic of cladding-pumping principle of operation.](image)

These high gains led to a number of important possibilities, of which high-gain amplifiers for telecom have been the most prominent [14–16], while more generally it provides very convenient MOPA schemes for power scaling of a wide variety of laser sources, including diode lasers and fibre lasers [17]. Related to the fact that modest pump powers can lead to high pump intensities in the core, is the result of very strong saturation (or ‘bleaching’) of the absorbing ions, i.e. most of the ions can be pumped out of the ground state into an excited state. This population of excited ions can then easily be subjected to a second or even a third pumping stage that takes them to yet higher excited states. Laser action can then take place from these highly excited states with the emission of photons that are more energetic than the pump photons (see Figure 36.3). This is referred to as an upconversion laser, and while upconversion lasers were first demonstrated in a bulk laser geometry, a dramatic improvement in performance and practicality resulted when a fibre laser geometry was adopted, leading to CW visible lasers directly pumped by near-infrared diode lasers [18].

#### 36.2.2 High Efficiency

The excellent modal overlap between pump and laser modes over the entire length of the laser medium contributes to the typically very high efficiencies. Also, the high gains and the low background losses of the host (for silica, a few dB km$^{-1}$) allow one to ensure that the output coupling is the dominant loss, i.e. essentially no laser photons are wasted. The ability to use a three-level laser effectively, by virtue of the high pump intensity in the core, has given prominence to the ytterbium (Yb$^{3+}$) ion. This ion offers no significant channels for parasitic loss of excitation from the upper laser level, and essentially 100% quantum efficiency (~80% power efficiency) can be achieved [19].

#### 36.2.3 Broad Gain-Linewidth

In a fibre, the host medium being glass (silica is commonly used), the dopant ions occupy a wider range of environments than in the ordered lattice of a crystal host. This results in a significant broadening of the transition linewidths, including that of the amplifying transition. As an example, Figure 36.4 shows a typical spontaneous-emission spectrum of an erbium-doped

![FIGURE 36.3 An upconversion laser. Sequential absorption of two pump photons of energy $h\nu_1, h\nu_2$ (these may be identical for a suitable energy-level scheme) takes ions to the excited level 4, and subsequent laser emission to level 2 produces laser photons that are more energetic than the pump photons.](image)
silica fibre in the 1.5 µm spectral region, indicating a bandwidth of ~4 THz or 25 nm. This is more than an order of magnitude broader than the same transition would exhibit in a typical crystalline host. Other REs show similarly broad, and in the case of the important ions Yb\textsuperscript{3+} and Tm\textsuperscript{3+} even broader, typical crystalline host. Other REs show similarly broad, and in the case of the important ions Yb\textsuperscript{3+} and Tm\textsuperscript{3+} even broader, and magnitude broader than the same transition would exhibit in a (usually silica) and can serve as a mirror or filter. Not only does it have superior characteristics of stability and robustness compared to bulk counterparts but also have much greater functionality, e.g. allowing it to fulfil sophisticated pulse-shaping functions that enhance the fibre laser’s role as a source of ultrashort pulses. The grating can be made to extend over the full length of the gain medium, thus resulting in a distributed feedback (DFB) laser [25,26], a very convenient source with an output that is robustly single-frequency (single-longitudinal mode). Another example of a simple and stable component is the fibre-coupler, obviating the need for bulk beam splitters. Figure 36.5 shows a typical example of how fibre lasers can have an all-fibre construction by incorporating various fibre components.

36.2.6 Capability of Generating High-Power High-Brightness Laser Beam

RE-doped glass fibre is an outstanding laser gain medium to achieve a high-power laser with high brightness [28–30] because, first, the geometry of the glass fibre enables very high surface-to-volume ratio, which facilitates the heat dissipation to the surroundings (air, coolant, heat sinks); second, because of the inherent long action length, glass fibres can provide very large single-pass gain, offering the option of MOPA scheme for the effective power scaling; third, the waveguide nature of the fibre provides significant freedom to well control the beam quality of a fibre laser and strong immunity from the thermally induced spatial mode distortion. Other factors include the developments of high-brightness semiconductor diode lasers (pump sources), novel fibre designs, new pumping schemes and high-power fibre components.

36.3 Basic Principles and Formulae

For simplicity we assume that the fibre has a so-called step-index profile (uniform refractive index, value $n_\text{co}$ in the core and $n_\text{cl}$ in the cladding). The NA of the fibre defines the
maximum incidence angle \( \theta_m \) (‘acceptance-angle’) at the end-face of the fibre core, for subsequent guidance to take place in the core, with \( \theta_m \) given by, \( \sin \theta_m = NA \). The NA is given by \[ NA = \left( n_{o}^2 - n_{i}^2 \right)^{1/2}. \] (36.1)

It is customary to define a quantity referred to as the \( V \) value, given by
\[ V = 2\pi a (NA)/\lambda \] (36.2)

where \( a \) is the core-radius and \( \lambda \) is the (vacuum) wavelength of the guided wave. For the fibre to be monomode at wavelength \( \lambda \), (i.e. for the LP\(_{01} \) and higher-order modes to be cut off, allowing only the LP\(_{01} \) mode to propagate), \( V \) must be less than 2.4. Thus, substituting in Equation (36.2), a wavelength of 1 \( \mu \)m and a typical NA of 0.15, one finds that for \( V=2.4, a \) has the value 2.5 \( \mu \)m, implying a maximum diameter of 5 \( \mu \)m for monomode propagation at this wavelength. One can see from Equation (36.2) that monomode operation can be maintained at larger diameters provided the NA is appropriately reduced to keep \( V \) below 2.4. There are however, practical limits to this procedure since, e.g., the reduced index difference, \( n_{o} - n_{i} \), makes the fibre more liable to bending losses.

Conversely, to increase gain for a given pump power, or equivalently to reduce the threshold power, one needs to minimize the mode areas for pump and laser modes. This can be achieved, up to a point, by reducing the core size. However, it is important to note that, while it is a reasonable approximation to identify the LP\(_{01} \) mode area with core area for \( V \) values around 2.4, this is not in general true and, for small \( V \) values, \( (V<2) \) the mode size increases as \( V \) is further reduced. Hence, reduction in core size must be accompanied by a corresponding increase in NA (to keep \( V \) from decreasing below \( \sim 2 \)) if reduced mode volume is to result. Thus, assuming \( V=2.4 \), so that mode-area\( \equiv \)core-area, then Equation (36.2) implies that gain is proportional to \((NA)^2\).

If one now considers a four-level laser, i.e. with an empty lower-laser level (see Figure 36.6a), assuming \( V=2.4 \) and equating core area to the mode area, then the gain, expressed in dB \( \text{mW}^{-1} \) of absorbed pump power, is given by
\[ \text{Gain} = (NA)^2 \phi / \left( 10^4 \Delta \nu h \nu_p \right) \] (36.3)

Here, \( \Delta \nu \) is the linewidth (FWHM) of the amplifying transition, \( \nu_p \) is the pump frequency and \( \phi \) is the product of \( \phi_p \), the pump-quantum efficiency, i.e. the fraction of absorbed pump photons that produce an ion in the upper-laser level, and \( \phi_r \), the radiative quantum efficiency, i.e. the fraction of spontaneous decays of ions in the upper-laser level that occur as radiative emission via the amplifying transition. Insertion of typical numbers for the case of Nd\(^{3+} \) ions [0.8 \( \mu \)m pump, \( \lambda_p = 1 \mu \)m, \( \phi_p = 1 \), \( \phi_r = 0.5 \) (radiative decay also occurs via the 0.94 \( \mu \)m, and 1.3 \( \mu \)m, channels), \( \Delta \nu = 3 \text{THz} \) and assuming an NA of 0.15, gives a gain of 1.5 dB \( \text{mW}^{-1} \). A somewhat higher figure has been achieved in Er-doped fibre at \( \sim 1.5 \mu \)m, where \( \phi \sim 1 \), and by deliberately using a larger NA, a gain of 11 dB \( \text{mW}^{-1} \) has been achieved [32]. The expression of Equation (36.3) cannot be applied directly to the case of the Er\(^{3+} \) ion, however, as this exhibits a three-level scheme, i.e. the lower-laser level is also the ground level (see Figure 36.6b). An approximate analytical treatment of the three-level case leads to Equation (36.3) being modified by insertion of the factor \((I/I_s - 1)/(I/I_s + 1)\) into the right-hand side, where \( I_s \) is the saturation intensity of the pump transition, \( I_s = h \nu / \sigma \tau \). Here, \( \sigma \) is the pump-absorption cross-section and \( \tau \) is the lifetime of the upper-laser level. When \( I \gg I_s \), a condition that is easily achieved in a fibre since it may typically need only \( \sim \text{milliwatt} \) power levels, then the three-level case approaches that of the four level, as expected, since this corresponds to most of the ground-state population having been promoted to the upper-laser level. In general, however, the treatment of the three-level case is more complicated analytically than that of the four level since the ratio \( I/I_s \) decreases progressively along the fibre as the pump intensity is decreased by absorption (for \( I < I_s \), this factor indicates that the medium has negative gain, i.e. is absorbing). Furthermore, a number of laser transitions involve a lower-laser level that is somewhat above the ground level, although still containing a significant thermally-excited population. This is often referred to as a quasi-three-level transition. Further complications arise from the fact that the nature of a transition may in fact be continuously graded from effectively three level at the short-wavelength end of the emission spectrum, to the four level at the long-wavelength end since the longer emission wavelengths correspond to emission into higher-lying sublevels of the ground manifold (see Figure 36.6b).

To complete this brief survey of basic principles, an indication is given of the role played by amplified spontaneous emission via the amplifying transition. Insertion of typical numbers for the case of Nd\(^{3+} \) ions [0.8 \( \mu \)m pump, \( \lambda_p = 1 \mu \)m, \( \phi_p = 1 \), \( \phi_r = 0.5 \) (radiative decay also occurs via the 0.94 \( \mu \)m, and 1.3 \( \mu \)m, channels), \( \Delta \nu = 3 \text{THz} \) and assuming an NA of 0.15, gives a gain of 1.5 dB \( \text{mW}^{-1} \). A somewhat higher figure has been achieved in Er-doped fibre at \( \sim 1.5 \mu \)m, where \( \phi \sim 1 \), and by deliberately using a larger NA, a gain of 11 dB \( \text{mW}^{-1} \) has been achieved [32]. The expression of Equation (36.3) cannot be applied directly to the case of the Er\(^{3+} \) ion, however, as this exhibits a three-level scheme, i.e. the lower-laser level is also the ground level (see Figure 36.6b). An approximate analytical treatment of the three-level case leads to Equation (36.3) being modified by insertion of the factor \((I/I_s - 1)/(I/I_s + 1)\) into the right-hand side, where \( I_s \) is the saturation intensity of the pump transition, \( I_s = h \nu / \sigma \tau \). Here, \( \sigma \) is the pump-absorption cross-section and \( \tau \) is the lifetime of the upper-laser level. When \( I \gg I_s \), a condition that is easily achieved in a fibre since it may typically need only \( \sim \text{milliwatt} \) power levels, then the three-level case approaches that of the four level, as expected, since this corresponds to most of the ground-state population having been promoted to the upper-laser level. In general, however, the treatment of the three-level case is more complicated analytically than that of the four level since the ratio \( I/I_s \) decreases progressively along the fibre as the pump intensity is decreased by absorption (for \( I < I_s \), this factor indicates that the medium has negative gain, i.e. is absorbing). Furthermore, a number of laser transitions involve a lower-laser level that is somewhat above the ground level, although still containing a significant thermally-excited population. This is often referred to as a quasi-three-level transition. Further complications arise from the fact that the nature of a transition may in fact be continuously graded from effectively three level at the short-wavelength end of the emission spectrum, to the four level at the long-wavelength end since the longer emission wavelengths correspond to emission into higher-lying sublevels of the ground manifold (see Figure 36.6b).

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emission (ASE) in limiting the maximum achievable gain and thus also limiting the maximum energy that can be stored (and subsequently extracted, e.g. in the form of a Q-switched pulse). Photons created by spontaneous emission at one end of the fibre and then guided over the fibre’s length will be amplified, thereby causing some reduction of the population inversion and hence of the gain. This ASE process therefore acts as a limiter, reducing the achievable gain even in the absence of any feedback, to a level that, in practice, is typically 40 dB over a single pass. ASE for example, provides the ultimate limit on tuning range achievable from a fibre laser. Thus, when tuning to the extreme wings of a transition, where the gain is low, while one can, in principle, compensate the low gain by pumping harder, this can raise the gain at line-centre to a level that induces strong ASE. This therefore limits the tuning range that can be covered. ASE also limits the energy stored in the population inversion. The relation between gain and stored energy is

\[
\text{Gain [dB]} = \frac{4.34}{\text{E}_{\text{sat}}} \cdot \frac{\text{E}_{\text{sat}}}{\text{E}_{\text{stored}}}
\]

where \( E_{\text{sat}} \) is the saturation energy, for a given gain, is proportional to \( A_{\text{core}} \). Typical values for Nd\(^{3+}\) for a 5 \( \mu \text{m} \) core diameter are \( -3 \text{ dB} \ \mu\text{m}^{-1} \), thus the ASE-limited energy is \( -10 \ \mu\text{J} \). For Er\(^{3+}\), with a much smaller \( \sigma_{\text{r}} \), corresponding to the much longer \( \tau_{\text{r}} \) than for Nd\(^{3+}\) (-30x), there is a correspondingly greater energy-storage capability. Further increases in the energy storage are achievable by scaling up the core area.

**36.4 Energy Level and Optical Spectra Properties of Rare-Earth Ions in Optical Fibre**

As the main luminescent elements, RE ions play an important role in the development of fibre laser. In periodic table of elements, the RE ions employed in active fibre are mainly focused on lanthanides, which are characterized by the filling of the 4f shell. The Ionization process to RE ions removes the electrons on the 6s and 5d shell preferentially, and the corresponding electronic configuration can be taken as the xenon structure plus a certain number of electrons on the 4f shell. Since the trivalent level of ionization is the most stable state for lanthanide ions, most of RE ions in active fibres are trivalent. Stark splitting of the energy level is generally formed due to the interactions including electron–electron and electron–host.

In addition to laser transitions accompanied with emission of photons, an excited RE ion can decay nonradiatively by means of phonon emission, resulting from the interaction with vibrations of host material. If the energy levels are separated in one or two phonon energy, nonradiative transition to lower electronic state occurs rapidly through emission of phonons. For energy gaps much larger than the phonon energy, the nonradiative decay rate is inversely proportional to the exponential of energy gaps [33]. Moreover, due to the large variation of vibrational spectra for different materials, the nonradiative decay is extremely host-dependent. For silica host, which obtains a phonon energy around 1100 cm\(^{-1}\), the infrared transparency is limited by absorption loss due to the excitation of phonons in the glass lattice to \( \sim 2 \ \mu\text{m} \). This forms the multiphonon edge of silica glass. Wavelength transparency to longer wavelength can be obtained under glass host with lower phonon energy, such as fluoride and chalcogenide glass. Especially, the heavy metal fluoride glass, ZBLAN (ZrF\(_4\)-BaF\(_2\)-LaF\(_3\)-AlF\(_3\)-NaF), with phonon energy of 600 cm\(^{-1}\), has been studied with more efforts on lasing wavelength extended to mid-IR because of the benefits including high allowable doping levels, relatively high strength and low background loss.

The RE ions in glasses possess spectroscopic parameters similar to that in crystals. But, unlike crystal, in which the RE ions exhibit absorption and emission transitions with discrete lines, the glass is a disordered material that the inhomogeneous broadening of spectral lines results in broadband spectra of absorption and emission transitions.

In the following section, we provide the major energy levels and spectroscopic parameters of the most used RE ions in the development of fibre lasers.

**Neodymium.** Since the first demonstration of fibre laser with Nd-doped glass fibre in 1964 [1], Nd\(^{3+}\) has attracted intense attention for the development of fibre lasers in the early stage. Figure 36.7 shows the main energy levels of Nd\(^{3+}\) for most important laser transitions. Strong absorption around 800 nm has been employed as the main pump scheme with an energy-level transition from \( \mathbf{I}_{\text{5/2}} \rightarrow \mathbf{F}_{\text{5/2}} \). While the laser transitions between energy levels: \( \mathbf{F}_{\text{5/2}} \rightarrow \mathbf{I}_{\text{5/2}} \), \( \mathbf{F}_{\text{3/2}} \rightarrow \mathbf{I}_{\text{11/2}} \) and \( \mathbf{F}_{\text{3/2}} \rightarrow \mathbf{I}_{\text{13/2}} \) correspond to the three emission peaks of Nd\(^{3+}\) at 930, 1060 and 1340 nm, respectively, among them, the four-level transition around 1060 nm has been well exploited for both glass and crystalline hosts, especially to achieve high-power and high-energy laser due to the large emission cross-section. Afterwards, the Nd\(^{3+}\) is gradually replaced by a more powerful RE ion, Yb\(^{3+}\) for the development of high-power fibre laser around 1 \( \mu\text{m} \), which will be introduced in the next part.

**FIGURE 36.7** The energy-level diagram of regular laser transitions of Nd\(^{3+}\).
For $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{13/2}$ transition, within the optical communications window around 1300 nm, it had been investigated for fibre amplifiers to fill in this window. Except for the low emission intensity, the excited-state absorption (ESA) between energy levels $^4\text{F}_{9/2}$ and $^4\text{G}_{7/2}$ limits the lasing performance in this band. Another transition of Nd$^{3+}$, $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{9/2}$, corresponds to the three-energy-level lasing for wavelength between 900 and 950 nm, which provides the possibility to achieve blue laser through non-linear frequency conversion. The main challenge for this laser transition comes from the gain competition with the other two four-energy-level transitions.

Ytterbium energy-level diagram of Yb$^{3+}$ is illustrated in Figure 36.8a, which consists of simple two Stark manifolds (ground $^2\text{F}_{7/2}$ state and excited $^2\text{F}_{5/2}$ state). Compared with traditional Nd$^{3+}$, the Yb$^{3+}$ exhibits the advantages on longer upper-energy-level lifetime (~1 ms), small quantum defect, and absence of ESA. Figure 36.8b shows the typical absorption and emission spectra of Yb$^{3+}$ in silica fibre. The strong and wide absorption bands near 915 and 976 nm, corresponding to the transition from the lowest Stark sublevel of the ground $^2\text{F}_{7/2}$ state to the second and the first Stark sublevels of excited $^2\text{F}_{5/2}$ state, facilitate efficient pump with InGaAs laser diodes for high-power operation. Furthermore, Yb-doped silica fibre possesses a broad emission band, from 950 to 1200 nm, which offers a convenient way to achieve versatile laser source in this broad emission range [19].

All the features mentioned earlier, together with the advantages of fibre laser scheme, make the Yb$^{3+}$ become the most powerful RE ion for the high-power and high-efficiency fibre laser system. Since the first Yb$^{3+}$-doped fibre laser demonstrated by Hanna et al. in 1988 [34], significantly progress in scientific research, and commercialization have been made with this ion in fibre lasers. One of remarkable results is reported by IPG Photonics Inc. in 2009 in which single-mode 1070 nm Yb-doped fibre laser with a record power of 10 kW has been developed in all-fibre scheme using a number of hundred-watts 1018 nm fibre lasers as pump laser [3].

Erbium. Because of the broad applications in the area of optical communication, Er-doped fibre lasers and amplifiers have been extensively investigated in the past few decades. The energy-level diagram of Er$^{3+}$ is shown in Figure 36.9a with typical energy transition for both pump and laser. Similar to Yb$^{3+}$, Er$^{3+}$ can be pumped with a laser diode at 980 nm, but the corresponding absorption cross-section is much smaller, as shown in Figure 36.9b. In addition, Er$^{3+}$ can also be directly in-band pumped to the upper levels of $^4\text{I}_{13/2}$ at a wavelength around 1480 nm, through which the quantum defect can be significantly alleviated compared to pump at 980 nm. The emission spectrum of Er$^{3+}$ covers the whole C-band, which motivates its applications in optical signal transmission, whereas power scaling of the Er-doped fibre laser is constrained by low doping concentration due to pair-induced quenching, which lowers the laser efficiency and deteriorates the output stability [35]. Co-doping of Er$^{3+}$ with Yb$^{3+}$, which has a higher doping concentration (generally more than 10 times higher than that of Er$^{3+}$), provides an effective solution. The operating mechanism can be understood with Figure 36.10: Yb$^{3+}$ in ground state $^2\text{F}_{7/2}$ absorbs a pump photon at 980 nm to transit to upper state $^2\text{F}_{5/2}$ and then transfers the energy to Er$^{3+}$, raising it to the excited state $^4\text{I}_{13/2}$. Since output power for the co-doping system is still limited by the parasitic lasing of Yb$^{3+}$ at a wavelength of ~1.1 µm, optimization of co-doping concentration ratio between Er$^{3+}$ and Yb$^{3+}$ should be addressed for efficient energy transfer [37].

Thulium. A Tm-doped fibre laser has become the most mature fibre laser system around 2 µm after broad investigation and development in recent 10 years. Figure 36.11 shows the relevant energy-level transitions for lasing around 1.9 µm. For pump at 793 nm, corresponding to energy-level transition from ground-state $^3\text{H}_6$ to excited-state $^3\text{H}_4$, Tm$^{3+}$ has the highest absorption cross-section. Efficient pump can be realized with high-power commercially available diode laser at 0.8 µm. In addition, a cross relaxation process occurs when the doping concentration of Tm$^{3+}$ reaches 3–5 wt% [38]. It means that two excited Tm$^{3+}$ can be obtained at the upper level with only one pump photon at 793 nm absorbed, which may double the quantum efficiency in theory. Additionally, Tm-doped fibre can be in-band pumped by the laser at 1570 nm, which can be provided by the well-developed high-power Er-doped fibre laser. The majority of works on Tm-doped fibre lasers are focused on lasing a wavelength around 1.9 µm, where Tm$^{3+}$ has the largest emission cross-section, as shown in Figure 36.11b. As the wavelength increases, emission intensity of Tm$^{3+}$ drops

The energy-level diagram of Er$^{3+}$ is shown in Figure 36.9a with typical energy transition for both pump and laser. Similar to Yb$^{3+}$, Er$^{3+}$ can be pumped with a laser diode at 980 nm, but the corresponding absorption cross-section is much smaller, as shown in Figure 36.9b. In addition, Er$^{3+}$ can also be directly in-band pumped to the upper levels of $^4\text{I}_{13/2}$ at a wavelength around 1480 nm, through which the quantum defect can be significantly alleviated compared to pump at 980 nm. The emission spectrum of Er$^{3+}$ covers the whole C-band, which motivates its applications in optical signal transmission, whereas power scaling of the Er-doped fibre laser is constrained by low doping concentration due to pair-induced quenching, which lowers the laser efficiency and deteriorates the output stability [35]. Co-doping of Er$^{3+}$ with Yb$^{3+}$, which has a higher doping concentration (generally more than 10 times higher than that of Er$^{3+}$), provides an effective solution. The operating mechanism can be understood with Figure 36.10: Yb$^{3+}$ in ground state $^2\text{F}_{7/2}$ absorbs a pump photon at 980 nm to transit to upper state $^2\text{F}_{5/2}$ and then transfers the energy to Er$^{3+}$, raising it to the excited state $^4\text{I}_{13/2}$. Since output power for the co-doping system is still limited by the parasitic lasing of Yb$^{3+}$ at a wavelength of ~1.1 µm, optimization of co-doping concentration ratio between Er$^{3+}$ and Yb$^{3+}$ should be addressed for efficient energy transfer [37].

Thulium. A Tm-doped fibre laser has become the most mature fibre laser system around 2 µm after broad investigation and development in recent 10 years. Figure 36.11 shows the relevant energy-level transitions for lasing around 1.9 µm. For pump at 793 nm, corresponding to energy-level transition from ground-state $^3\text{H}_6$ to excited-state $^3\text{H}_4$, Tm$^{3+}$ has the highest absorption cross-section. Efficient pump can be realized with high-power commercially available diode laser at 0.8 µm. In addition, a cross relaxation process occurs when the doping concentration of Tm$^{3+}$ reaches 3–5 wt% [38]. It means that two excited Tm$^{3+}$ can be obtained at the upper level with only one pump photon at 793 nm absorbed, which may double the quantum efficiency in theory. Additionally, Tm-doped fibre can be in-band pumped by the laser at 1570 nm, which can be provided by the well-developed high-power Er-doped fibre laser. The majority of works on Tm-doped fibre lasers are focused on lasing a wavelength around 1.9 µm, where Tm$^{3+}$ has the largest emission cross-section, as shown in Figure 36.11b. As the wavelength increases, emission intensity of Tm$^{3+}$ drops
**FIGURE 36.9** (a) The energy levels of Er\(^{3+}\). Pump at 980 nm and In-band pump at 1480 nm correspond to the energy transition from ground state \(^{4}I_{15/2}\) to excited state \(^{4}I_{11/2}\) and \(^{4}I_{13/2}\). (b) Up: Absorption and emission cross-section of Yb\(^{3+}\) as well as absorption cross-section of Er\(^{3+}\) at the wavelength from 875 to 1125 nm; Bottom: Absorption and emission cross-section of Er\(^{3+}\) at wavelength from 1450 to 1650 nm in Er-Yb co-doped fibre [36].

**FIGURE 36.10** Energy-level diagram of Er-Yb co-doped fibre. The Er\(^{3+}\) is excited by the following two steps: the Yb\(^{3+}\) is excited to upper level under pump at 980 nm, and then the excited Yb\(^{3+}\) transfers energy to an Er\(^{3+}\) in ground-state \(^{4}I_{15/2}\), raising it to excited-state \(^{4}I_{13/2}\).

**FIGURE 36.11** (a) Lower-energy levels of Tm\(^{3+}\). Process of cross relaxation occurs under the pump at 793 nm, which can double the quantum efficiency in theory. (b) Absorption and emission cross-section of Tm-doped silica fibre. Dashed lines indicate common pumping regions for Tm-doped fibres. (Reprinted with permission from Ref. [39], OSA.)
gradually. Recently, with the development of fabrication techniques on high-quality Tm-doped fibre and fibre devices around 2 µm, various demonstrations in Tm-doped fibre lasers, including high-power CW laser to kilowatt [40], single-frequency operation with linewidth in kilohertz [41], and ultrafast operation with pulse duration shorter to 27 fs [42], have been presented by the researchers.

Holmium. Extending operating wavelength of fibre laser to >2.1 µm with Ho-doped fibre has attracted more attention for its distinctive applications involving atmospheric transmission window in this wavelength region. The energy levels of Ho$^{3+}$ are shown in Figure 36.12a. The Ho$^{3+}$ can be pumped to upper level $^5I_6$ with a high-power diode laser or Yb-doped fibre laser at 1.12 µm for three-level lasing at 2.1 µm. While the small absorption cross-section requires long active fibre for efficient lasing, which introduces more background loss for silica fibre. As shown in Figure 36.12b, the absorption loss due to silica and hydroxyl contamination becomes significant for the wavelength region >2.1 µm. The other option of the pump scheme is in-band pump at 1.95 µm, where much higher absorption avoids serious background loss with long fibre. This has been realized with well-developed Tm-doped fibre laser as a high-power pump source. Furthermore, similar to Er-Yb co-doped fibre, Tm-Ho co-doped fibre is employed to exploit the favourable absorption properties of Tm$^{3+}$. The resonant energy transfer from Tm$^{3+}$ to Ho$^{3+}$ motivates the performance improvement of Ho$^{3+}$ on laser emission at 2.1 µm.

RE ions in ZBLAN Fiber. The main discussion of energy levels and spectra properties above is based on the RE ions in silica host. As we mentioned at the beginning of the section, although the silica host has outstanding properties on low loss, strong mechanical strength and mature fibre devices fabrication techniques, the high phonon energy limits the lasing wavelength to ~2 µm. With nearly half of the phonon energy, ZBLAN fibre attracts intense attention for the development of mid-IR as well as upconversion ultraviolet and visible fibre laser [44]. For mid-IR lasing with Er$^{3+}$, through ground-state absorption and ESA, energy-level transition $^4I_{11/2} \rightarrow ^4I_{13/2}$ can

**FIGURE 36.12** (a) The energy-level diagram, as well as common pump and lasing transitions of Ho$^{3+}$ in silica host. (b) Absorption and emission cross-section of Ho-doped silica fibre in the wavelength range of 1.7–2.2 µm. The silica and hydroxyl absorptions in this wavelength region are also shown. (Reprinted with permission from Ref. [43], OSA.)
produce an emission of 2.7 µm, and \(^{2}F_{sg} \rightarrow \ ^{4}I_{sg}\) can produce an emission of 3.45 µm. For Ho-doped ZBLAN fibre, 2.9, 3.2, and 3.9 µm emissions can be achieved from the transitions, \(^{1}I_{6} \rightarrow \ ^{3}I_{6}, \ ^{3}F_{1} \rightarrow \ ^{3}F_{3},\) and \(^{1}I_{6} \rightarrow \ ^{3}I_{4},\) respectively. Furthermore, RE ions such as Er\(^{3+}\), Tm\(^{3+}\), Ho\(^{3+}\) and Nd\(^{3+}\) have also been employed in the upconversion fibre laser [43]. Among them, an impressive result on CW ultraviolet laser operating at 284 nm has been achieved with Tm-doped ZBLAN fibre for transition between energy level \(^{1}I_{6}\) and \(^{3}H_{6}\) [45]. An output power of 42 µW was obtained at the pump power of 590 mW.

### 36.5 Laser Performance

Fibre lasers have built up a fruitful system with operating regimes including CW, Q-switched, mode-locked, single-frequency and wavelength-tunable. Some of these will be introduced in detail in companion chapters of this handbook. Here, to emphasize the unique properties of fibre lasers, a brief discussion of laser performance on three aspects of fibre laser operation is addressed, involving high-power fibre laser with MOPA configuration, mode-locked fibre laser, and single-frequency fibre laser with DBR structure.

RE-ion-doped glass fibre provides an outstanding gain medium for high-power lasers, due to the unique geometry of optical fibre, whose high surface-to-volume ratio allows for superior capability of heat dissipation under high-power condition. To achieve high laser power, fibre sources are generally realized with MOPA configuration as the bulk lasers in which a high-performance, low-power oscillator is served as the seed and followed by a series of amplifier stages to realized power scaling. The MOPA configuration provides an excellent solution for power amplification while preserving the desirable characteristics obtained from the seed. With the development of high-brightness semiconductor diode lasers, novel high-gain active fibres and high-power fibre components, output power of fibre lasers has reached 100 kW in multimode and 10 kW in single mode. As we mentioned above, the first 10-kW single-mode fibre amplifier was realized with MOPA configuration. The master oscillator provides an output power of 1 kW and then amplified under one stage of amplifier with 15 m of Yb-doped fibre. By using several hundred-watts fibre lasers at 1018 nm as the pump source, 10 kW output power in a single mode was demonstrated eventually.

Mode-locked fibre lasers capable of producing ultrafast laser pulses (picosecond and femtosecond pulses) with compact fibre configuration provide the peak powers several orders of magnitude higher than that in the CW mode. Development with robust and compact designs motivates the applications in the areas such as ophthalmology, micromachining, medical imaging and precision metrology [46]. As the commercially available fibre components allow for all-fibre mode-locked laser constructed via simple fibre splicing routines, nowadays commercialization of mode-locked fibre laser is gradually mature in the wavelength regimes of 1, 1.5 and even 2 µm.

Single-frequency fibre laser, which maintains the laser running with a single-longitudinal mode, has become an ideal laser source for the applications such as high-resolution spectroscopy, coherent lidar, and interferometric sensing due to the outstanding properties on low noise, narrow linewidth, and the resulting long coherence length [47]. Among the different configurations, distributed Bragg reflector (DBR) fibre laser, which combines a pair of narrowband FBGs with a short piece of RE-doped fibre, shows attractive properties on simplicity and compactness. With the development of soft glass fibres, which possess high RE-ion solubility, high optical gain coefficient of several decibels per centimetre can be achieved. This facilitates efficient operation of compact single-frequency DBR fibre lasers, where output power up to hundreds of milliwatts can be realized with ~2-cm long active fibre. With the DBR fibre laser as high-performance single-frequency seed, output power of hundreds of watt in a single-longitudinal mode has been presented in 1–2 µm with all-fibre MOPA configurations. Moreover, to meet the need of practical applications, such as coherent lidar, pulsed single-frequency fibre amplifiers have been demonstrated with pulse energy in the multi-joule level.

### 36.6 Future Prospects

Fibre laser technology has developed over 50 years with the laser performance improved significantly. In the family of lasers, fibre laser attracts great attention in recent years due to the unique properties on compactness, robustness and free of maintenance, which allows for it to displace some of the laser systems gradually. New operating wavelengths, higher power/energy, narrower linewidth (single-frequency), shorter pulse duration, and wider tunable wavelength range, have become the eternal pursuit for the development of fibre lasers.

Silica fibre has been maintaining the dominant place due to the superior mechanical and optical characteristics. High-power operation of fibre lasers still relies on silica glass host, while further power scaling requires to deal well with the photodarkening and mode instability effect. The former one is focused on the material itself in which optimization of glass component needs to be addressed. The later one can be taken as a result of the combination of photodarkening and waveguide structure. Therefore, strategies can also be directed to waveguide structure design and operating environment adjustment under high-power operation. Novel fibre-based functional devices, such as filter, multiplexer/demultiplexer, and saturable absorber, are deserved to be developed with the exploration of fibre structures to enrich the performance of fibre lasers. Furthermore, as the research in wavelength regime of 1–2 µm is maturing gradually, wavelength extension to mid-IR, visible and UV for fibre lasers are required to meet the need for practical applications. Alternative hosts with desirable mechanical and spectroscopic properties and corresponding fibre devices are anticipated to develop.

### REFERENCES


FURTHER READING


Covers a range of non-linear optical processes that occur in fibres. It formats the foundation of the development of fiber lasers, such as mode-locked fiber lasers, Raman fibre lasers and Brillouin fibre lasers.


The most comprehensive treatment of fiber lasers, comprising a multiauthor collection of chapters each written by acknowledged experts, covering fabrication, spectroscopy, fiber components, silica and fluoride fiber lasers in various modes of operation and amplifiers.


The advanced progress in the area of fiber lasers is reviewed systematically with various regimes. Corresponding applications for different kinds of fiber lasers are addressed in detail.


Covers the basic principles of lasers. While not explicitly dealing with fiber lasers, it gives good coverage of material needed for an understanding of fiber lasers, such as the principles of optically pumped solid-state lasers and mode-locking of lasers.


More detail about different glass hosts and challenge for rare-earth-doped fiber lasers are introduced. High-power fiber laser and their industrial applications are also included.