1 Introduction

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Nowadays fiber technology is a mature and vast sector of industry that has advanced remarkably during a few decades, firstly owing to the rapid development of optical communications. It is recognized that there are no alternatives to optical technologies in communication because non-optical methods cannot cope with the modern demand for information transfer.

A different situation exists in the field of fiber lasers. Based largely on the technology developed for optical communications, the practical value of fiber lasers should be critically examined before application to determine the actual impact of their implementation. This assessment is needed because alternative laser technologies, for example, solid-state and semiconductor, are well developed and could provide competitive solutions. Nevertheless, intensive R&D in fiber laser technology has radically changed the market situation in the scientific and industrial lasers sector. Nowadays, fiber lasers hold firmly the leading position in some applications by forcing out other laser systems. In particular, fiber lasers are starting to dominate in applications related to high-power lasers, sources with high brightness and several areas dealing with pulsed oscillators and spectral manipulation (http://www.ipgphotonics.com/) [1]. Combined with advances in glass technology and nonlinear optics, fiber systems are now available commercially over an extended spectral range.

Being a guided-wave system, fiber lasers allow us to use approaches that are not available with systems where the modes are determined firmly by the laser cavity, for example, solid state lasers. The guiding properties of the fiber establishing the mode structure allow us to prevent constraints induced by thermal lensing and implement specific methods of mode and dispersion control, for example, axially non-uniform waveguides and photonic crystal structures. The operation of an ordinary fiber system relies on the classical principle known as total internal reflection. Regardless of the significance of this physical mechanism, it imposes some limitations in the tailoring mode area, nonlinearity, and waveguide dispersion. Extensive efforts have been made in recent decades to improve the methods of light control. Among them, photonic crystal fibers (PCFs), which are rapidly developing the research field in optical science, represent a significant breakthrough both in research and

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applications [2–4]. The high potential of these waveguides in tailoring optical parameters permits diverse applications in various areas of photonics, particularly in nonlinear optics, ultrafast fiber oscillators, and high-power amplifiers. The correct structure of a PCF can guarantee that only the fundamental mode is guided, resulting in "endless single-mode" behavior. Photonic crystal fibers can be designed to have a large single-mode area essential for high-energy lasers. Very large mode-area PCFs have been demonstrated that reveal their superiority in high-power delivery, amplifiers, and lasers [5–7]. This development is discussed in Chapter 2.

PCFs with small glass cores and a high air-filling factor can generate peculiar chromatic dispersion and offer high optical density. The determined enhancement of different nonlinear processes in micro-structured optical fibers can be achieved through manipulation of the dispersion characteristics of the fiber [8, 9]. Chapter 3 is devoted to one of the most successful applications – supercontinuum generation, which takes advantage of the high nonlinearities and accurate control of chromatic dispersion provided by PCFs. Using PCFs and chirped fiber Bragg gratings contributes essentially to the dispersion management techniques that maintain the all-fiber format of ultrafast oscillators. In particular, exploiting PCFs that could generate anomalous dispersion over extended spectral band has resulted in all-fiber dispersion-managed soliton lasers operation around 1 μm [10–13]. With the net anomalous group-velocity dispersion (GVD), the nonlinearity balances GVD, resulting in a soliton-like pulse shaping, which implies that these fibers could support short pulse propagation with neither temporal nor spectral distortion as optical solitons. Net anomalous GVD compensates the accumulated pulse phase shift in a cavity consisting of segments with normal and anomalous GVD, representing a so-called dispersion map. With an increase in pulse energy, however, the excessive nonlinear phase shift cannot be eventually compensated by the dispersion, giving rise to the phenomenon known as pulse breaking. Though the strong dispersion map was shown to increase the threshold for multiple pulse operation, the wave-breaking instability still prevents energy scaling using this laser concept. Recent studies show that laser cavities with large normal dispersion tend to support highly-chirped pulses that can reach unprecedented energies and peak powers, while avoiding wave-breaking despite the accumulation of large nonlinear phase shifts [14–16]. The performance of such normal-dispersion lasers is presented in Chapter 4.

Chapter 5 is devoted to experimental and modeling aspects of ultrafast fiber systems. It overviews recent experimental results obtained for fiber lasers passively mode-locked with saturable absorbers and describes the methods for their modeling and computing. Various techniques used for dispersion compensation are discussed, including chirped fiber Bragg gratings and microstructure fibers.

As optically pumped devices, fiber lasers depend critically on the performance of the pumping sources. Progress in fiber lasers became possible owing to unprecedented development of optical pumping systems based on semiconductor lasers. The power available now commercially reaches the multi-kW level [17]. Fiber lasers and amplifiers as wave-guiding systems offer a unique opportunity to exploit pumping sources of low brightness. The so-called double clad pumping concept allows high-power, large numerical aperture, and large area sources to be efficiently used in cost-effective high-power fiber systems [18]. This approach exploits broad-area semiconductor lasers or bars usually coupled to multimode fibers that are optically matched with pumping cladding of double-clad fiber. Axially non-uniform, tapered (flared) amplifiers combined with a cladding pumping scheme can be utilized in high-power technology. Semiconductor [19] and fiber [20] gain media provide a practical solution for power scaling. This method, described in Chapter 6, is particularly valuable for all-fiber systems because it allows the achievement of high power while maintaining the diffraction-limited beam characteristics [21, 22].

Some fiber systems, however, require a core-pumping scheme. The most important example is Raman fiber devices, which represent one of the key technologies in modern optical communications. Although light generation covering a large wavelength range (895–1560 nm) has been reported using neodymium, ytterbium, bismuth, and erbium fiber systems, Raman fiber lasers and amplifiers offer an interesting opportunity for flexible wavelength tailoring [23]. Raman gain exists in every optical fiber and could provide amplification in every fiber optic link. Raman gain is available over the entire transparency region of the silica fiber, ranging from approximately 0.3 to 2 μm provided that an appropriate pump is used. The wavelength of the Raman peak gain is shifted from the pumping wavelength by the frequency of the optical phonons and therefore it can be tailored by tuning the pump wavelength. Another advantage of Raman amplification is that it has a relatively broad-band bandwidth of 5 THz, and the gain is reasonably flat over a wide wavelength range [23]. Mode-locked Raman fiber lasers with high-quality pulses are obtained both at normal and anomalous dispersion. Raman lasers and amplifiers are basically core-pumped devices since the cladding pumping scheme offers low gain efficiency. Consequently, a relatively large pump power launched into a single-mode fiber core is required to achieve noticeable gain. The relatively high pump power in a single-mode fiber required for Raman amplifiers is a serious challenge for communication technology. The development of high pump power sources has resulted in a broad deployment of Raman amplifiers in fiber-optic transmission systems, making them one of the first widely commercialized nonlinear optical devices in telecommunications [24]. Broadband non-resonant gain positioned by pump wavelength selection can be further extended by using multiple-wavelength pumping and improves the gain flatness. Distributed Raman amplifiers are demonstrated to improve the noise figures and reduce the nonlinear penalty of fiber systems, allowing for longer amplifier spans, higher bit rates, closer channel spacing, and operation near the zero-dispersion wavelength [25]. Available commercial laser diodes, however, produce single-mode fiber coupled power up to 1 W only and at very few wavelengths. Alternative pumping with powerful fiber lasers comes at a high cost and high power consumption. The fast response time of Raman gain could cause additional noise due to transfer of pump fluctuations to the signal. Pump–signal interaction in a long-length fiber exhibits an averaging effect of noise transfer dependent on the pumping direction. When a co-propagating pumping scheme is used, the averaging effect is low compared with counter-propagating geometry due to small walk-off between pump and signal and, consequently, tighter requirements on the noise level of pump lasers should be applied. Co-pumping pumping is, however, advantageous over the technique using only a counter-propagating scheme because the signal can be maintained at low level throughout each span of the transmission line. It is expected that co-propagating Raman pumping could improve system performance, significantly increasing the amplifier spacing under the condition that pumping sources have low-noise characteristics. The availability of low-noise pumping sources is critical for further improvement of the links using Raman amplification. Currently, due to a shortage of efficient low-noise pump sources, a counter-propagating pumping scheme for Raman amplifiers is preferred.

A promising pumping approach for Raman fiber amplifiers could utilize a semiconductor disk laser (SDL), which was demonstrated to offer low-noise and high power with diffraction-limited beam characteristics [26]. It has been shown that the relative intensity noise (RIN) of semiconductor lasers can reach an extremely low level, close to shot noise limit, provided that the laser operates in the so-called class-A regime. This regime is attained when the photon lifetime in the laser cavity becomes much longer than the carrier lifetime in the active medium. A laser operating under this condition exhibits a relaxation-oscillation-free flat spectral noise density. The emergence of low-noise, high-power disk lasers operating in the wavelength range 1.2–1.6 μm could radically change the conventional technology of Raman fiber amplifiers and lasers [27–30].

Extension of the operation wavelength towards the mid-infrared range has been triggered by numerous applications. Thulium- and thulium–holmium-doped fibers have been demonstrated to be a major candidate for high-power sources operating around 2 μm [31]. Silica-based fiber lasers producing outputs in the shortwave infrared (SWIR) region of the spectrum are fast becoming a mature technology [32]. Most of the important demonstrations of highly efficient and high-power SWIR fiber lasers involved the Tm^{3+} ion, because of the favorable ion interactions that produce high quantum efficiencies, and the compatibility of this laser with commercial diode laser excitation is presented in Chapter 7. Pushing the emission wavelength of silica-based fiber lasers further into the SWIR spectrum is of current interest for a range of applications, including atmospheric light transmission, Si photonics, and nonlinear optics. Thulium fiber has a broad amplification bandwidth, between 1.65 and 2.1 μm, and is, therefore, suitable for short pulse generation and wide spectral tuning [33]. A specific feature of optical fiber operating at 2 μm is a large anomalous dispersion that causes the operation in the soliton pulse regime. Using concept presented in Chapter 4, a 2-μm net normal-dispersion regime of the cavity consisting solely of anomalous-dispersion fiber has been demonstrated recently using dispersion offset set by the chirped fiber Bragg grating, which could be a practical solution for power scaling of long-wavelength lasers [34].

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