Advances in high power, short pulse, fiber laser systems and technology

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Abstract: We review recent advances in Yb fiber lasers and amplifiers for high power short pulse systems. We go on to describe associated recent developments in fiber components for use in such systems. Examples include microstructured optical fibers for pulse compression and supercontinuum generation, and advanced fiber grating technology for chirped-pulse amplifier systems.

1. Introduction

There is an increasing demand for high-power ultrashort-pulse laser systems for industrial and scientific applications. Fiber laser technology is emerging as an attractive option for pulsed systems – not least due to the fact that during the past few years, the favourable heat-dissipation geometry of fibers has enabled tremendous increases in the average continuous wave output powers that can be reached. Powers of up to 1.4kW in a single transverse mode have now been achieved [1], and multi-mode systems are now approaching the 10kW regime. Furthermore, the broad gain bandwidths of Er and Yb doped fibers can support ultrashort ~100 fs pulses. However, due to nonlinear effects, the creation of practical high power pulsed fiber systems still requires new amplification techniques and the development of new fiber components.

Nonlinear effects in the fiber core, the most important being self-phase modulation, stimulated Raman and Brillouin scattering, quickly become significant with ultrashort pulses due to the high peak powers. In order to overcome the nonlinear limits, and hence increase the pulse energies and powers that can be achieved, it is necessary to employ more complex amplification schemes, which enable reducing the nonlinearity of the gain medium, and controlled temporal stretching of the pulses during amplification. The technique of chirped pulse amplification (CPA) [2] is commonly used, in which ultrashort pulses from an oscillator are stretched to several hundred picoseconds duration before amplification, and recompressed at the output of the amplifier by a matching compressor. This reduces the peak powers in the amplifier below the threshold for nonlinear pulse distortion, allowing for amplification to much higher pulse energies. However CPA systems incorporate many separate components in order to stretch and recompress the pulses, and due to the large temporal stretching ratios, the compressor gratings have ~1 m separation, and do allow for a truly compact system. As a consequence, the application of such systems has so far been limited, but recently demonstrated fiber technology should lead to practical future systems.

This paper is structured as follows. To highlight the improvements in large mode area fibers, we first consider a high average power parabolic pulse system that we demonstrated recently [3]. We also show our compact gain-switched laser diode source. We then report the development of a CFBG pulse stretcher with both 2^{nd} and 3^{rd} order dispersion to match the bulk grating compressor demonstrated in an Yb fiber CPA system. Finally, the unique dispersion and nonlinear properties of microstructured optical fibers (MOF) are reviewed, and illustrations given of new applications, such as supercontinuum generation, and how MOF can replace bulk gratings in mode-locked oscillators and CPA compressors. We conclude with a summary, and consider the future challenges.

2. High power pulsed systems based on large core fibers

Since the main performance limitation of rare-earth-doped fibers is nonlinearity in the fiber core, by applying fibers with large-core-area and short absorption lengths, higher pulse energies can be achieved. Another aspect is that the energy storage capability of a doped fiber scales as well with the core area. The first system considered is a femtosecond source delivering high average power. The fiber used for the final amplifier had a 40 micron core, with low NA to enable higher power and pulse energy than had previously been achieved from such a system. Furthermore, by careful launching of the seed, single mode output was obtained from this multi-mode amplifier.

When moderate energy pulses are required, a parabolic amplifier scheme can be used, which omits the stretcher typically found in a CPA system, and thereby enables a much more compact compressor to be used. It has been shown that high power pulses in a fiber amplifier with normal dispersion evolve towards parabolic pulses with a linear chirp, which enables recompression to short durations despite significant self-phase modulation in the fiber [4]. Parabolic pulses from Yb fiber amplifiers have previously been demonstrated with average powers up to 17 W (pulse energy 230 nJ) using a bulk glass seed laser [5], and up to 13 W (pulse energy 260 nJ) using a fiber based seed laser [6]. Here we review our demonstration showing high average power of >25 W, and high pulse energies of 410 nJ from an all Yb fiber system. A conventional bulk-grating compressor was used to remove the linear chirp, resulting in 100 fs pulses [3]. The setup is shown in Fig. 1.

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Fig. 1. Schematic of parabolic amplification system.

Our femtosecond mode-locked Yb fiber oscillator (developed in-house) [7] produces ~30pJ pulses with a 50 MHz repetition rate. The pulses are centered at 1055 nm with a spectral FWHM of 18.6nm with an autocorrelation FWHM of ~110fs.

The output of the amplifier system is shown in Fig. 2. It can be seen that the spectrum of the pulses broadens at higher energies. The spectral bandwidth of the high energy pulses was ~20 nm. The measured autocorrelations correspond to pulse durations of ~160 fs at low energy and ~110 fs at 410 nJ. The autocorrelations demonstrate that the pulses did not have large pedestals and that the pulse quality was good ($\Delta\nu\Delta\tau$ ~0.6) for pulses with energies up to 410 nJ. The system also produced pulses at higher average powers of up to 40 W without the onset of significant Raman scattering, but for these higher energy pulses the nonlinear spectral broadening exceeded the amplifier bandwidth, and the quality of the recompressed pulses was reduced.

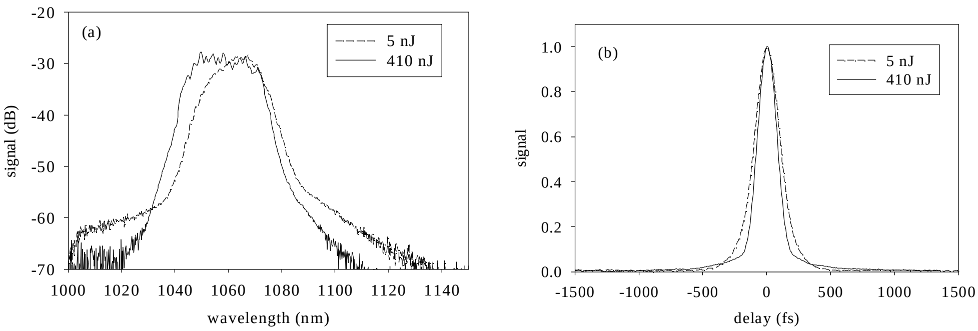

Fig. 2. (a) spectra and (b) autocorrelations of low (5 nJ) and high (410 nJ) energy pulses from parabolic amplifier system.

The second system considered again uses a large mode amplifier, operating at 1550nm using Er/Yb co-doped fiber. The system incorporates a novel pulse source based on a low power pulsed semiconductor laser, and which shows the compatibility of high power fiber technology with compact, low cost sources. Using this setup, we demonstrated a 60 W average power, 4.5 ps pulses, at a repetition rate of 10 GHz [8]. The 1.5 µm region is attractive for such applications as free space, space-based communications, or LIDAR because it is relatively eye-safe, compatible with existing telecommunications hardware, and suitable for detecting aerosols, clouds and pollution.

The short pulse amplification scheme is shown in Fig. 3(a). A 1555 nm DFB laser in a high-speed fiber pigtailed package is gain-switched by driving with a 10 GHz sinusoid at 30 dBm RF power and a DC bias current of 54 mA. The linear chirp of the pulses was compensated in 120 m of dispersion compensating fiber (DCF) to produce 4.5 ps duration pulses with an average power of 3 dBm. The pulses are launched into a preamplifier, consisting of a commercial Erbium doped fiber amplifier to amplify the average power up to 33 dBm. This signal is then launched into the power amplifier. The power amplifier is pumped by a diode stack at 975 nm that is free space coupled into the double-clad gain fiber pumped in a counter-propagating configuration [9]. The gain fiber has a 30-

µm diameter Er/Yb co-doped phosphosilicate core with a numerical aperture (NA) of 0.20. The D-shaped inner cladding has a 400/360 µm diameter for the longer/shorter axis and is coated with a low-refractive-index polymer outer cladding which provides a nominal inner-cladding NA of 0.48. The fiber length is ~3 m which leads to ~10 dB pump absorption. The signal is launched into the gain fiber using a tapered splice that provides efficient mode matching between the single mode fiber (SMF-28) and the core of the gain fiber. The power amplifier efficiency is shown in Fig. 3(b). The output power increases linearly with launched pump power and the overall slope efficiency is 22%.

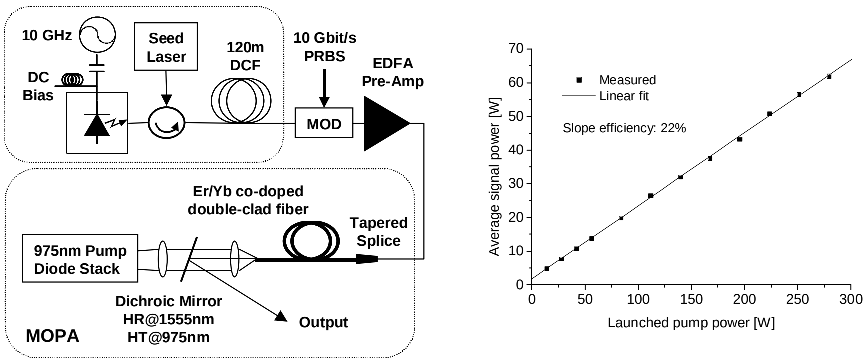

Fig. 3. (a) Experimental setup. (b) Power amplifier efficiency.

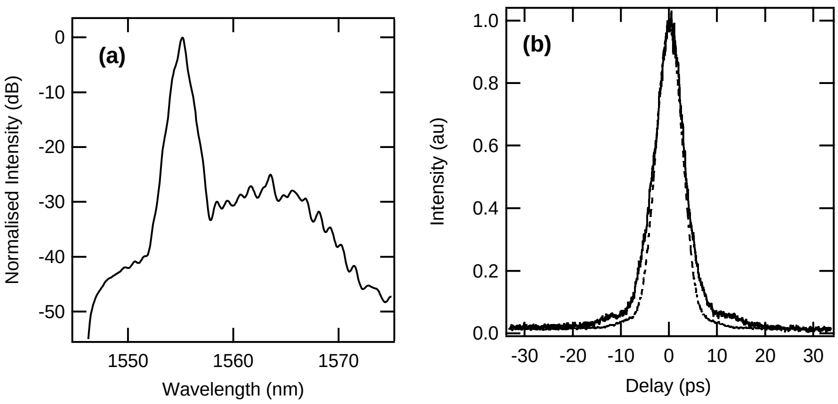

Fig. 4. (a) Optical spectrum after the high power amplifier at an average power of 60 W and a pulse repetition rate of 10 GHz. (b) Autocorrelation traces of the 10 GHz pulses before (dashed line) and after high power amplification (solid line).

The optical spectrum at the output of the MOPA is shown in Fig. 4(a). At 60 W average output power the signal peak is 25 dB above the peak of the background ASE. There was no spectral broadening observed confirming that the nonlinear effects are minimized in the large core amplifier fiber of the MOPA. The pulse quality after amplification was verified using autocorrelation measurements shown in fig. 4(b). The input pulse duration of 4.5 ps, determined from the input autocorrelation trace, is maintained after amplification to 60 W. The low level pedestal observed on the output autocorrelation trace is from a small coupling of the first-order mode into higher-order modes within the amplifier fiber. We have also used the modulator to reduce the repetition rate of the pulses from 10 GHz down to 10 MHz to investigate the peak power scaling effects in this amplifier system. Peak powers of 1.3 MW have been obtained, however further work is required to optimize the preamplifiers to improve the OSNR for lower repetition rates.

3. CFBG with both 2nd and 3rd order dispersion compensation

In a typical femto-second CPA system, pulse stretching is done with bulk gratings, but in the interests of moving as close as possible to an all-fiber system, we use a chirped fiber Bragg grating (CFBG). Due to the high pulse energies bulk gratings must still be used for the compressor. The bulk grating compressor inevitably has a large 3rd order phase term in addition to the 2nd order dispersion. In order to achieve femtosecond pulse durations both these terms must be matched in the pulse stretcher.

Here, we present for the first time, to our knowledge, an Yb fiber CPA system using a CFBG with both 2nd and 3rd order dispersion. The CFBGs presented here have acceptance bandwidths of up to 18nm and were produced using a scanning technique previously developed to produce precision gratings for telecommunication applications [10, 11]. A CFBG with 2nd and 3rd order dispersion matched to a bulk grating has previously been demonstrated in a CPA system at 1550nm [12], but the maximum energy and minimum pulse duration will be limited using Er compared to Yb amplifiers. A CFBG that matched the diffraction grating compressor dispersion was presented recently operating at a wavelength of 1.05μm [13]. However, in that study no amplification was implemented and the recompressed pulses had poor contrast.

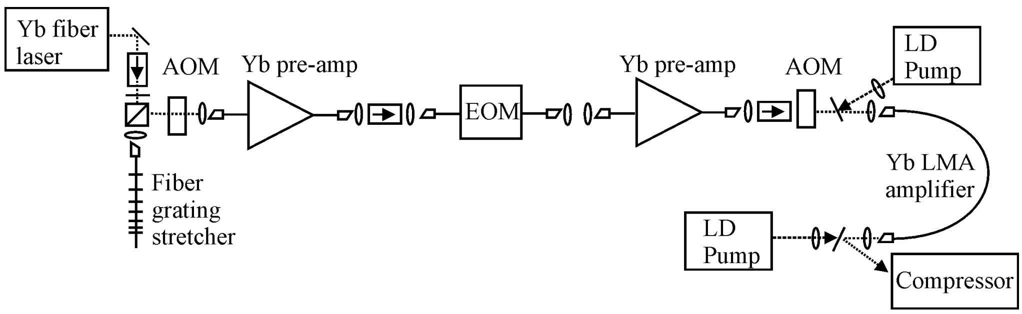

Fig 5. Schematic of CPA system. (AOM,EOM=Accousto/Electro-optic modulator, LD=laser diode, LMA=large mode area fiber.)

Fig. 5 shows the schematic of our CPA system. Pulses from our femtosecond mode-locked Yb fiber oscillator [7] were stretched with the CFBG and then passed through two single-mode (5μm core) core-pumped Yb doped fiber amplifiers. Electro-optic and acousto-optic modulators were used to reduce the repetition rate and filter ASE between amplifier stages. Power amplification took place in a 9m length, cladding pumped Large Mode Area, fiber with a core diameter 16.5μm, doped with 7000 ppm Yb^{3+} ions, and a cladding diameter of 200μm. The fiber, which was effectively single mode in operation, was pumped from opposite ends with 915nm and 975nm pump diodes. Fig. 6a) shows the power output of the final stage amplifier as a function of pump power - the slope efficiency was ~70%. The maximum average power achieved before compression was 17 W. Fiberised and free-space polarization controllers were distributed through the system as necessary.

The group delay response of the gratings reported in this paper was measured by an RF phase-delay measurement technique. Fig. 6b) shows the reflection spectrum and delay as a function of wavelength for a CFBG centered at 1053nm with an acceptance bandwidth of 18nm. The solid curve through the delay data is a fit to 2nd and 3rd order dispersion, giving values of D x length = 44.65±0.4 ps/nm ($\beta_2 = \left(\partial^2\phi/\partial\omega^2\right) = -26.4$ ps^2/rad), and dD/dλ x length = 1.48±0.2 ps/nm^2 ($\beta_3 = \left(\partial^3\phi/\partial\omega^3\right) =$ 0.545 ps^3/rad^2) closely matching the values for our 1500 lines/mm reflection grating compressor.

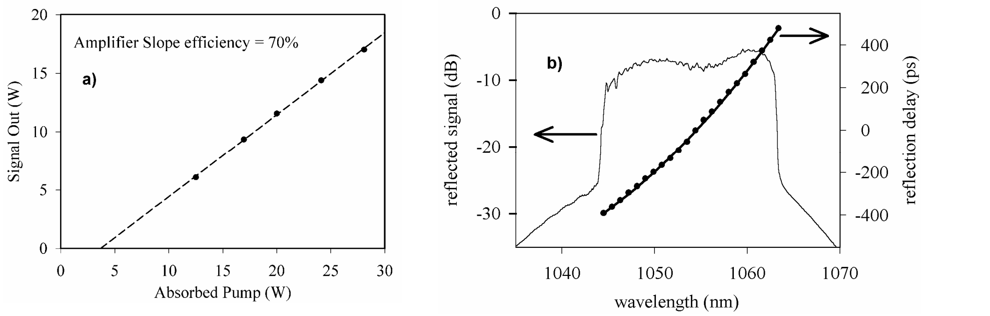

Fig 6. a) Power performance of CPA system LMA amplifier. b) Reflection spectrum and measured delay as a function of wavelength for an 18nm CFBG. The solid curve through delay data is a fit to 2nd and 3rd order terms.

The bandwidth of the amplifiers was considerably less than the spectral bandwidth of the seed laser, and in the CPA system we stretched the pulses with a relatively narrow band grating (7 nm) in order to avoid distortions due to gain narrowing effects. The 2nd and 3rd order dispersion of the 7 nm CFBG were approximately the same as for the 18 nm CFBG described above.Fig. 7a) shows the autocorrelation of the recompressed output pulses.

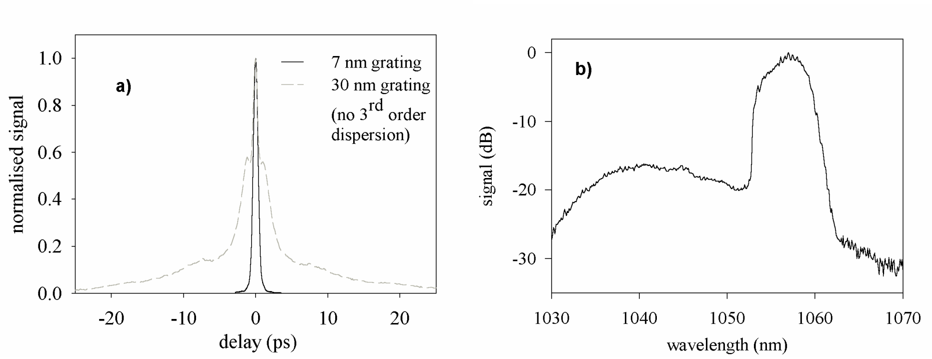

Fig 7. a) Autocorrelation after recompression (demonstrates importance of higher order dispersion compensation), and b) the spectrum of the pulses from CPA system.

The output pulse width is estimated at ~500 fs. Fig. 7a) also includes an autocorrelation of a pulse through the same system which was stretched with a 30 nm bandwidth grating which had only 2nd order dispersion. It can be seen that uncompensated 3rd order dispersion has resulted in a substantially broader autocorrelation (~3 ps) with a broad pedestal. Fig. 7b) shows the spectral output of the final amplifier with the 7nm grating. The bandwidth of the output pulse is ~5nm ($\Delta\nu\Delta\tau$ ~0.7). Pulse energies from the system were limited to <10 µJ because the fiber amplifiers were not optimized for maximum gain and minimum nonlinearities, but clearly with a more optimal choice of fiber this system has the potential to reach similar pulse energies to those previously achieved using fiber amplifiers and bulk stretchers. The minimum duration of our pulses was limited by the bandwidth of our amplifier.

4. Microstructured optical fibers

Microstructured optical fibers (MOF) are of great practical interest because the incorporation of air holes to define the cladding region allows for an increased range of fiber parameters compared to conventional fiber [14]. These fibers are now being researched to replace bulk components in high power pulsed fiber laser systems. For MOF with a solid core, guidance is due to the average index contrast between the core and microstructured surround. Photonic bandgap (PBG) fibers [15, 16] use diffraction, rather than total internal reflection for light guidance, and thus enable fibers in which the light field is confined to an air, or even a vacuum, core.

For average index guiding fibers, the large index difference between air and glass leads to a range of unique dispersion and nonlinear properties. As an example, the dispersion has been shown to be particularly sensitive to the hole arrangement, and a wide range of dispersion properties have been demonstrated, including anomalous dispersion down to visible wavelengths, broadband flattened dispersion [17] or large normal dispersion [18]. The effective mode area in a MOF can also be tailored by up to three orders of magnitude by altering the scale of the transverse refractive index profile [17] opening up possibilities for fibers with either high or low optical nonlinearities as required for a wide variety of applications.

Average index guiding MOF fabricated to have anomalous dispersion at wavelengths below 1.3 µm must have a small core (typically <2.5 µm diameter) and a high air fill fraction in the cladding. This results in a strong (anomalous) waveguide contribution to the dispersion to compensate for the (normal) material dispersion of silica at these wavelengths. For fiber based femtosecond mode-locked lasers, the pulse formation is determined by the balance of dispersion and nonlinearity [19]. The grating pairs typically used to provide anomalous in Yb-fiber mode-locked lasers require precise alignment, and an Yb fiber laser in which anomalous GVD was provided by a solid core MOF has recently been demonstrated [20, 21]

The small core naturally leads to the fiber having an exceptionally high effective nonlinearity, which reduces the power threshold for soliton generation. The nonlinearity can be further increased by use of highly nonlinear glass. Small core, high nonlinearity MOF has therefore been demonstrated to provide an ideal medium for supercontinuum generation which, due to the “frequency comb” incorporated within the spectrum, is providing for great advances in metrology [22].

Using such high nonlinearity MOF, we have demonstrated soliton propagation and visible supercontinuum generation from an all fiber source. The small core MOF used for our experiments was has a small ~1.6µm diameter core with an effective mode area (A_{eff}) ~3µm^2 at λ=1.06µm, approximately 20 times smaller than for conventional fibers at this wavelength [23]. The experimental setup of the ultrashort pulse source was as shown in Fig. 1, except that we used a lower power final amplifier. To demonstrate linear dispersion and soliton formation, we used low energy (<30 pJ) pulses directly from the oscillator [7]. For soliton propagation over 60 m of fiber, we used higher energy pulses from the first amplifier, without compensating the chirp using the grating compressor. The spectrum shown in Fig. 8.a) clearly demonstrates single colour Raman solitons, which were tunable with increasing launched pulse energy out to a maximum wavelength of ~1.12 µm. This complements our work on SSFS in an active Yb-doped small core MOF where we achieved a much broader continuous tuning range from 1.06 – 1.33 µm [24]. The inset to Fig. 8.a) shows the SHG autocorrelation of the 400 fs transmitted solitons, and of the 6 ps launched pulses and we calculated the 60m length to correspond to transmission over 475 soliton periods. For supercontinuum generation we increased the peak power of the launched pulses to ~20kW (350fs FWHM, 7.5nJ) by using the second, cladding pumped Yb-doped fiber amplifier, a modulator to reduce the pulse repetition rate, and a diffraction grating compressor to remove the chirp. The output of the fiber became a spectacular blue/white colour and the ultra-broad supercontinuum spectrum in Fig. 8.b) shows the enormous broadening into the visible region.

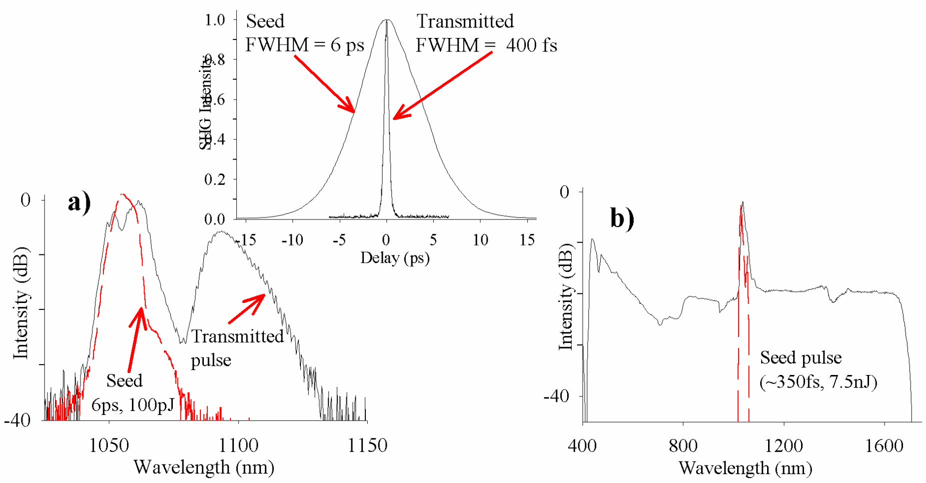

Fig.8. a) Spectra of input pulses (FWHM 6ps, 100pJ) and wavelength shifted (SSFS) pulses after transmission through 60m of small core holey fiber. Inset: Autocorrelation of 70 pJ pulses; at the input (positively chirped, FWHM 6ps), and after transmission through 60m of fiber (FWHM ~400fs). b) Broadband continuum obtained by launching 20kW peak power pulses (FWHM~350fs, 7.5nJ) into holey fiber.

The low pulse energies (20pJ, 200 W typical peak power) and ~1m lengths of this fiber required to form solitons [25-27], are at least an order of magnitude lower than those previously required for similar experiments in conventional fiber at 1550nm[28], making these nonlinear effects readily accessible for practical applications. We have also demonstrated different coloured supercontinuum spectra enabled by variation in dispersion between cores in a multi-core MOF, which highlights the possibility of designing a fiber with an array of cores of different dimensions for tailored spectral generation from a single fiber structure [29].

Low nonlinearity average index MOF can be fabricated using reduced air fill fraction in the cladding and a large diameter solid core. The low nonlinearity allows for power scaling of amplifiers and for high energy pulse delivery. Furthermore, double clad structures can be fabricated for amplifiers, and these fibers can be used in so-called “Air-clad” form, where a high index contrast creates an exceptionally large NA for the high-power, low brightness diode pumps, and which enables the cladding diameter to be reduced to create good pump overlap with the doped core for efficient pump absorption. A second design of microstructure then creates a large mode for the rare-earth-doped core structure. Recently such a single-mode Ytterbium-doped MOF was demonstrated with an exceptionally low nonlinearity due to a mode-field area of nearly 1000 μm^2 (MFD = 35 μm) [30].

It has also been demonstrated that nonlinear fiber compression was possible at unprecedented average power levels by use of a large-mode-area MOF and a passively mode-locked thin disk Yb:YAG laser operating at 1030 nm. The optical spectrum of the 810-fs pump pulses was broadened by nonlinear propagation in the fiber and the resultant chirp was removed with a dispersive prism pair to achieve 18 W of average power in 33-fs pulses with a peak power of 12 MW and a repetition rate of 34 MHz. The output beam was nearly diffraction limited and was linearly polarized[31].

PBG fibers have the potential to overcome the limitations of material nonlinearity because the majority of the power is contained within a hollow-core and is delivered in a single mode. In air core PBGF, optical nonlinearities are reduced by more than a factor of 1000 compared with silica-core fibers, and delivery of micro joule femtosecond pulses is possible without the temporal broadening that would occur in conventional silica fibers. It has been reported that large values of the dispersion (normal at the shorter-wavelength band edge and anomalous at the longer-wavelength band edge) is inherent from the Kramers-Kronig relations to any optical structure that has relatively sharp transmission features, which leads to a zero-dispersion point in the bandgap, and therefore the existence of a range in the transmission gap where the dispersion is large and anomalous appears to be a generic feature of these types of PBGFs [32]. PBG fibers are currently under intensive investigation for high power pulsed amplification applications. The transmission of femtosecond solitons with very high (5.5 MW) peak powers has also been demonstrated [32]. The anomalous dispersion combined with low nonlinearity has created a fiber alternative to the bulk grating-compressor component for CPA systems [33, 34]. The use of photonic bandgap fiber to provide anomalous GVD in a femtosecond fiber laser has also now been reported, and due to the low birefringence and low nonlinearity of PBGF compared to anomalously dispersive silica core MOF, stable, good-quality pulses with energy as large as 2 nJ were achieved [35]. For high energy nano-second pulse delivery in micro-machining applications, the energies and high beam quality that have been delivered through the PBG fibers are significantly higher than has been reported with conventional step-index single-mode fibers, because the PBGF mode has peak intensity in the gas core, which increased the facet damage threshold [36].

5. Summary and future outlook

In summary, we have reviewed the tremendous recent developments achieved towards creating practical short-pulse fiber laser systems. The principal challenge continues to be management of nonlinear effects due to the high pulse peak powers while retaining the inherent fiber advantages of being compact and robust. New components are being developed for all aspects of these fiber systems. In this paper we have highlighted the applications of large mode fiber for producing increased powers. In particular, we presented a high average power (25 W) parabolic scheme, and a gain-switched laser diode source with 60 W fiber amplifier operating at 1550 nm. We also considered the development of a CFBG stretcher with both 2nd and 3rd order dispersion to match the bulk compressor. This technology was presented in the first demonstration of an Yb-fiber CPA incorporating such a CFBG, and is an important step towards practical fiberised systems. Finally, we reviewed the unique optical properties of recently developed microstructured fibers. We showed the application of these fibers for supercontinuum generation as components for fiber based CPA systems. These systems highlight the potential of fiber technology for the development of practical high-power ultrashort-pulse fiber-based lasers for industrial and scientific uses.

For the future, we might envisage further scaling up of the average powers from pulsed fiber systems, the introduction of new components into practical systems, and the application of nonlinear compression to generate pulse bandwidths beyond the available Er and Yb gain bandwidths, and hence to produce extremely short pulses for demanding new applications.

Acknowledgements

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