Femtosecond Fiber Lasers for Biomedical Solutions

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Abstract

Femtosecond fiber lasers are becoming an enabling technology for biomedical imaging and diagnostics from the bench to the bedside. Techniques used for achieving mode locked fiber lasers are discussed. These techniques include polarization shaping, pulse shaping, and spectral shaping. Mode locked fiber lasers operating at 1 μm, 1.55 μm, 2 μm and their harmonic generations (780-800 nm, 515-532 nm, 344-355 nm, 257-266 nm) are discussed. By using dispersion managed amplifiers, amplification and compression of 100 fs femtosecond pulses to 10 watts were demonstrated. These femtosecond fiber lasers are packaged in compact and robust modules and passed long term operation test without any degradation, and proved to be reliable light sources for clinic applications.

Key Words: Mode locked fiber laser; Ultrafast fiber laser; Harmonic generation; Fiber amplifier.

1. Introduction

For the past few years, femtosecond (fs) fiber lasers have been growing in popularity over conventional solid state lasers. A turn-key fs fiber laser solution offers unprecedented features of compactness, low maintenance, and low power consumption. Many types of fs fiber lasers have been developed for biomedical applications covering optical coherence tomography (OCT), multi-photon imaging (MPI), coherent anti-stoke Raman spectroscopic imaging (CARS), Raman spectroscopic imaging, nonlinear spectroscopy, confocal microscopy, cell dissection, nano surgery, and more [1-7].

For fiber laser and amplifier, a doped optical fiber is an essential component that used as a gain medium to generate and amplify an optical signal. In general, the signal to be amplified and a pump laser are multiplexed into the doped fiber, and the signal is amplified through interaction with the doping ions. The most common examples of doped optical fibers are the Erbium Doped Fiber (EDF), where the core of a silica fiber is doped with trivalent Erbium (Er) ions and can be efficiently pumped at a wavelength of 980 nm or 1480 nm, and exhibits gain in the 1.55 μm spectral region; the Ytterbium Doped Fiber (YDF), where the core of a silica fiber is doped with trivalent Ytterbium (Yb) ions and can be pumped at a wavelength of 980 nm or 915 nm, and exhibits gain in 1 μm spectral region; and the Thulium Doped Fiber (TDF), where the core of a silica fiber is doped with trivalent Thulium (Tm) ions and can be efficiently pumped at a wavelength of 780 nm, 1210 nm, or 1560 nm, and exhibits gain in the 2 μm spectral region. By using ZBLAN fibers (Er doped, Ho doped or Tm doped), the wavelengths can be extended to visible and mid-IR regions such as 2.7 and 3 microns. Unlike most other types of lasers, the laser cavity in a fiber laser is constructed monolithically by fusion splicing the different types of fibers. Semiconductor laser diodes or other fiber lasers are used to pump fiber lasers. They can support kilowatt level of continuous output power because the fiber's high surface area to volume ratio allows efficient cooling. The fiber waveguiding properties reduce or remove completely thermal distortion of the optical path thus resulting in typically diffraction-limited high-quality optical beam. Fiber lasers also feature compact layout compared to rod or gas lasers of comparable power, as the fiber can be bent to small diameters and coiled. Other advantages include high vibrational stability, extended lifetime and maintenance-free turnkey operation.

Several methods have been used to generate passive mode locking femtosecond pulses for fiber lasers: nonlinear polarization rotation, carbon nanotube, and saturable absorbing mirrors SESAM. All these methods can obtain stable mode locking operation with a reasonable performance and qualification. By adding amplifiers after the seed fiber oscillator and in cooperating with pulse shaping, spectral shaping and polarization shaping techniques, output power from 100's of mW to 100's Watts can be obtained with pulse duration compressible to less than 100 fs. For majority of biomedical applications, power level of several Watts is sufficient while most of the requirements are within 100 mW.

In this paper, we will discuss pulse shaping, spectral shaping and polarization shaping techniques used in fs fiber lasers in section 2 and present experimental results in section 3. Femtosecond fiber lasers operating at wavelengths of 1 μm, 1.55 μm, and 2 μm, and their harmonic generations including second harmonic generation

(SHG), third harmonic generation (THG), and fourth harmonic generation (FHG). A summary and conclusion will be given in Section 4.

2. Techniques for Femtosecond Fiber Lasers

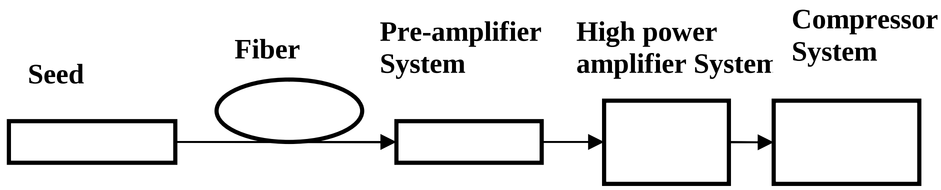


Figure 1. Block diagram of a high power fs fiber laser system

Figure 1 shows a typical function diagram of high power fs fiber lasers [8-14]. It includes a seed fiber oscillator operating at a repetition rate of 10's MHz, a piece of fiber stretcher for chirping the pulse, preamplifier system and high power amplifier system for boosting the signal power to the desired level, and a compressor (grating or fiber) to dechirp/compress the pulse back to shorter pulse duration. In order to handle the nonlinear effects and gain narrowing incurred in the fiber laser oscillator and fiber amplifiers and to reduce the pulse distortion, pulse shaping, spectral shaping and polarization shaping were used to mitigate the nonlinearity and gain narrowing. The following are given to further describe the three key technologies of pulse shaping, spectral shaping and polarization shaping:

Pulse shaping: Serious nonlinear effects such as self phase modulation (SPM) and Stimulated Raman Scattering (SRS) usually distort the pulse shape due to uncompressed nonlinear frequency chirp generated. However, by designing an amplifier with proper SPM, dispersion and TOD in **time domain**, this issue can be mitigated (Figure 2).

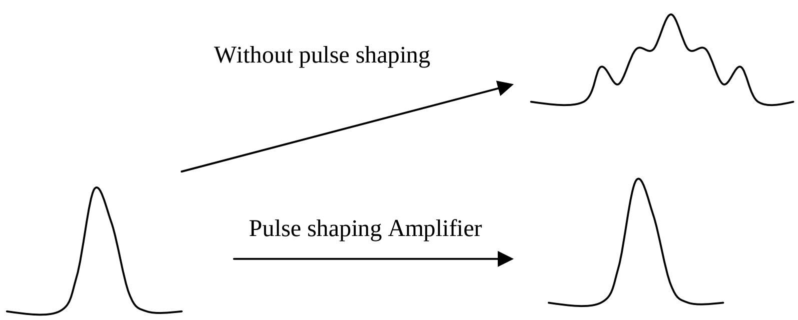


Figure 2. Illustration of pulse shaping

Spectral shaping: by controlling the spectrum in the fiber laser system (Figure 3) in **frequency domain**, the pulse can be amplified and the pulse shape can be maintained as well due to a tight correlation (Fourier transform relation) between time domain and frequency (spectrum) domain. By adding spectral filter in filtering the spectrum of the pulse, the time domain can have a good pulse shape. This adds another freedom for pulse shaping in addition to handling with SPM & dispersion in the time domain.

Polarization shaping: Due to a high peak power in the fiber laser and amplifier, the polarization of the pulse will change as a function of the power distribution level in the pulse envelop (in time domain) and accordingly as a function of wavelength of the pulse spectrum (in frequency domain) (Figure 4). This may cause a (polarization dependent) nonlinear chirp on the pulse which will distort the pulse and make the pulse uncompressable. By controlling the polarization (by using polarizer and wave retarder) to select a proper shape of the polarization related pulse (spectrum, the shape of the pulse can be manipulated to maintain a good pulse shape after amplification and compression).

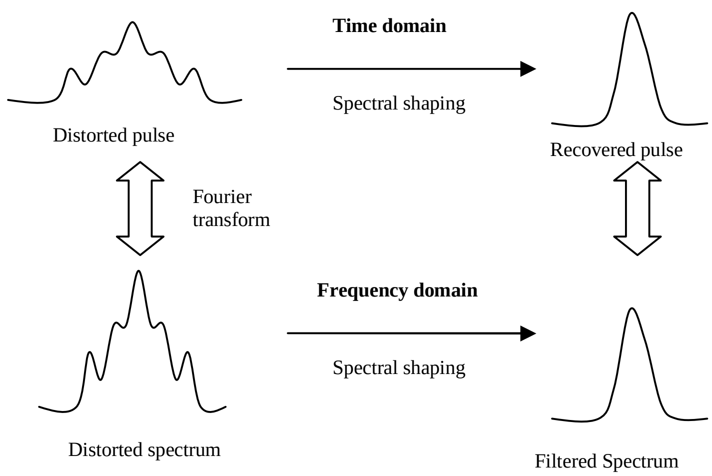


Figure 3. Illustration of spectral shaping

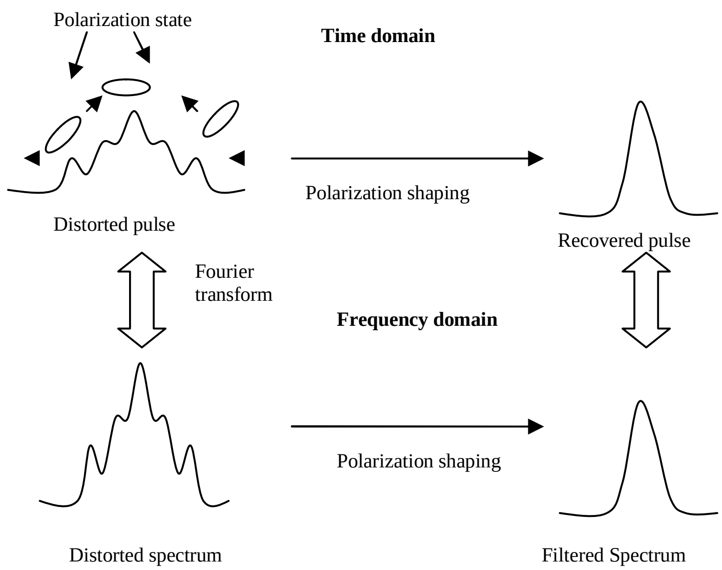


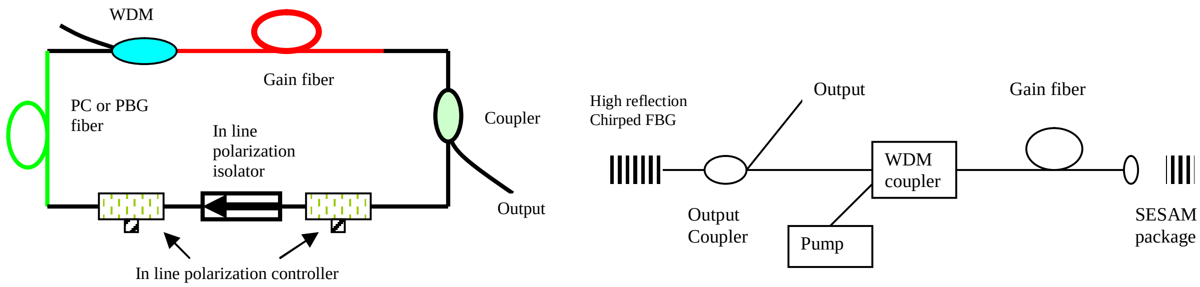
Figure 4. Illustration of polarization shaping

Next, we will discuss how these three techniques can be used in high power fs fiber lasers for mitigating nonlinearity and pulse distortion.

2.1. Seed Oscillator

Nonlinear polarization rotation (polarization shaping) and semiconductor saturable absorbing mirrors SESAM (pulse shaping) are the two common ways to create passive mode locking in fiber lasers. Generally the seed can output several ps chirped pulses. However, by placing the output fiber at the right location or using photonic crystal fiber with high dispersion, it is possible to extract highly chirped pulses (100s of ps) directly out of the cavity. Figure 5 gives schematic diagrams for those two popular approaches operating at 1 micron as an example. By using Photonic crystal (PC) [15] or photonic band gap (PBG) fiber, the pulse can get highly chirped pulse with short length, because PC and PBG fibers shows large dispersions (over 100 ps/nm/km absolute value) in normal and anomalous dispersions. Alternatively shown in Figure 5 (b), a chirped fiber Bragg grating (FBG) is used to compensate the dispersion of the fiber laser cavity using SESAM. In Figure 5, a wavelength division multiplexing (WDM) coupler is used to combine both signal and pump light into the gain fiber.

By using polarization shaping (employment of inline polarization dependent isolator and polarization controllers to act as a fast saturation absorber to select right polarization of the lasing pulse) or SESAM (fast pulse gating) and pulse shaping (cavity dispersion control), the mode-locking mechanism can be realized and very short transform limited pulse (< 100 fs) can be achieved from the seed oscillator. In our labs, we can achieve over 40 nm spectral bandwidth and compress below 50 fs.



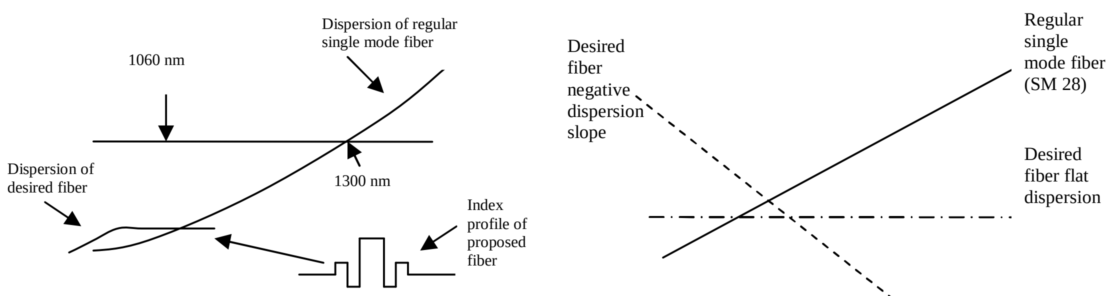
(a) (b)

Figure 5. Fiber based 1 micron mode locked fiber laser using (a) polarization shaping and (b) SESAM

2.2. Fiber stretcher

Between the seed and the amplifier, a piece of PC fiber with large dispersion or single mode (SM) fiber is spliced to further stretch the pulse to several tens of picoseconds. By using a depressed cladding structure, the stretcher can be designed to compensate the second order and third order dispersions of the compressor. A fiber that has a flat dispersion can be used to match with volume holographic grating (VHG) compressor as shown in Figure 6(a).

Moreover, due to the sign of TOD of both regular fiber and PBF/grating are same, it is desired to design a fiber with negative dispersion slope to further reduce the TOD effects from the PBF/gratings if nonlinear SPM cannot completely compensate the TOD of the PBF/gratings. Figure 6(b) shows two dispersions for desired fibers used for stretcher. This type of pulse shaping method helps maintain the pulse shape and reduce distortion in the whole fiber laser system.

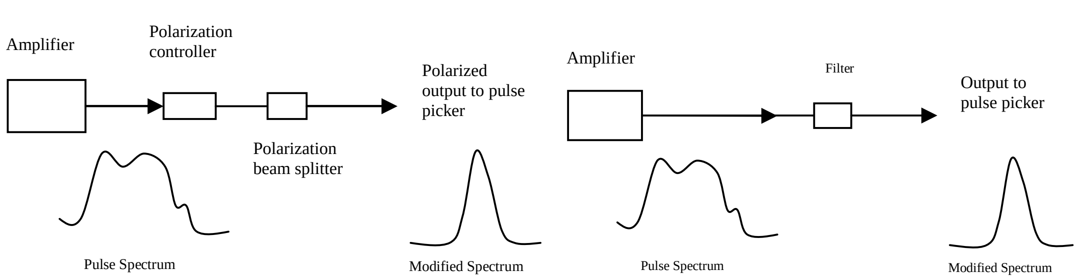


(a) (b)

Figure 6. Desired fiber dispersion and index profile of the fiber in reduction of TOD

2.3. Pre-amplifier system

In this stage, the signal will be amplified to a few hundreds mW by either single stage amplifier or multi-stage amplifiers. Spectral shaping and polarization shaping can be applied in this stage to filter/modify the pulse/spectrum if the pulse or spectrum has any imperfect shapes. Figure 7 shows some examples by using polarization shaping and spectral shaping.



(a) (b)

Figure 7. (a) Polarization shaping (b) Spectral shaping in fiber pre-amplifier system

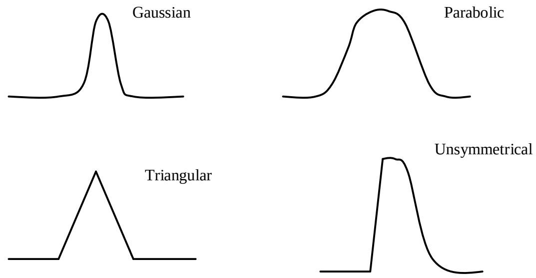


Figure 8. Filter shape for spectral shaping of the signal pulse

This stage may use PM version amplifier to maintain the spectral shape and keep the polarization unchanged. It may also involve a filter to further clean up the noise band outside the signal band and modify the spectrum to compensate the nonlinear effects and gain narrowing in high power amplifier stage.

Filters used for Spectral shaping in this stage can have various shapes in addition to the transform limited shapes (Gaussian or parabolic). Triangular and unsymmetrical shapes may also be the choices. Figure 8 shows some examples. The shape of the filter is selected to achieve better pulse shaping performance in the next stage of high power amplifier.

2.4. High power amplifier

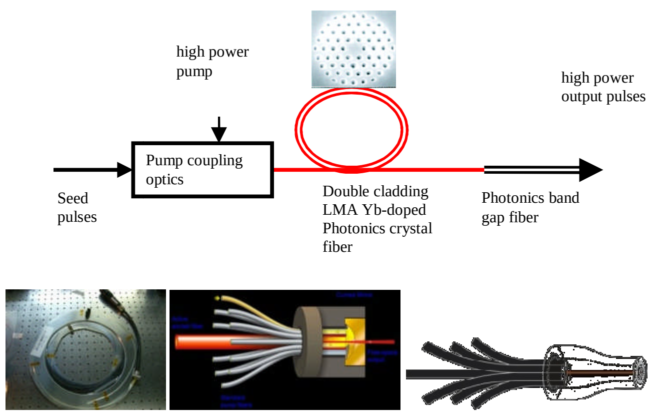
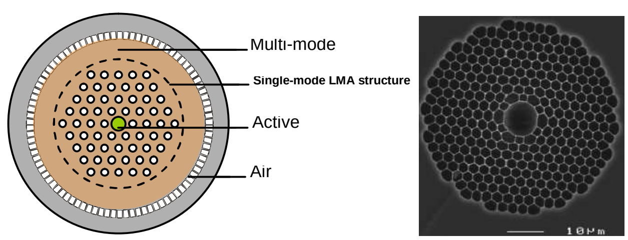


Figure 9. A high power PCF LMA fiber amplifier with integrated (20 pump ports) pump combiner



(a) (b)

Figure 10. (a) An example of double cladding LMA Yb doped photonics crystal fiber (Crystal Fibre, Denmark) and (b) An example for air core photonics band gap fiber (Crystal fiber, Denmark)

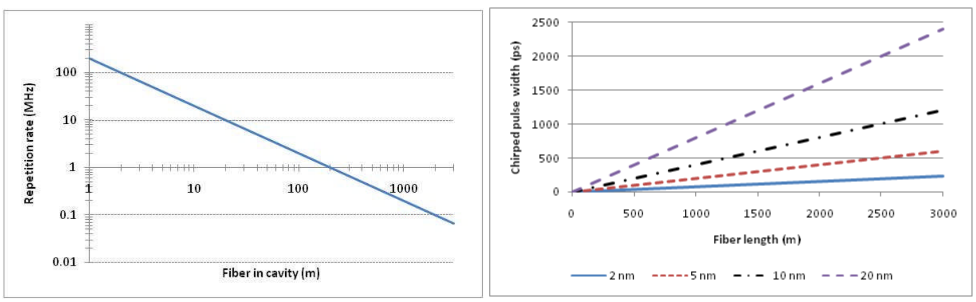
In the high power amplifier stage, double cladding rare earth doped fiber amplifiers are used for boosting the signal power. Either PM or non-PM version of double cladding (LMA) YDF can be used. Core diameters from 20 μm to 100 μm are commercially available for the LMA fiber. Spectral shaping and Pulse shaping are used to maintain a good shape of the pulse compressible to shorter pulse width. Figure 9 gives a schematic diagram of an example. In Figure 9, a high concentration double cladding (DC) Yb-doped photonics crystal (PC) fiber is used as a gain medium. 915nm, 965 nm, or 976 nm pump lasers are used to pump Yb ions for amplification of the chirped pulses (10's ps) through integrated coupling optics (Crystal Fiber, Figure 9) or fiber pump combiner. Amplification of the pulses can be achieved by using a short piece of high concentration double cladding Yd-doped phtonics crystal fiber with large mode area (LMA) as shown in Figure 10. The LMA of the DCYDF combined with short length help reduce the SPM, (stimulated Raman scattering) SRS and balance the nonlinear effects such as SPM and XPM with the dispersion (TOD) so the pulse width will not be distorted after amplification. This DC YDF can be a regular DC fiber as well in balancing the dispersion (TOD) and SPM. The chirped pulses can be further dechirped by a piece of air core photonics band gap (PBG) fiber (Figure 10), which can provide large anomalous dispersion (120 ps/nm/km, for example, from Crystal Fiber, Denmark.).

3. Experimental Results

3.1. 1 micron femtosecond fiber laser and harmonic generation

1 μm fiber laser uses Yb doped fiber as a gain medium for generation and amplification of 1020-1120 nm signals. From the tissue absorption and scattering properties, it is a wavelength that can balance the water absorption and penetration depth to achieve both high resolution and deeper tissue imaging.

In this section, we verified experimentally the method using polarization shaping and spectral shaping to generate mode locked femtosecond pulses. One piece of Yatterbium (Yb) doped fiber (YDF) was used in the fiber laser as a gain medium. The rest of the cavity is comprised of single mode fibers. A 980 nm high power pump laser diode was used to pump the YDF for amplification of the pulses circulating in the cavity. A polarization splitter is used to couple partial of the light out of the cavity at a given polarization state.



(a) (b)

Figure 11. (a) Repetition rate as a function of fiber length in a ring laser cavity (in logarithm scale) and (b) chirped pulse width as a function of the fiber length in the cavity (fiber B) by assuming no fiber A and fiber C)

Figure 11(a) shows a drawing for repetition rate as a function of cavity fiber length. At very low pulse repetition rate (PRR), longer fiber length is required. For example, at 10 MHz PRR, 20 m fiber is needed, while at 100 kHz PRR, 2000 m fiber is needed! Low PRR is very important to high energy ultrashort fiber laser in reducing the pulse picker for cost and size reduction.

At a given PRR, by changing the dispersion of the cavity, we can achieve different pulse operation with various pulse bandwidth and pulse width in combination with fiber position (SM fiber length distribution in positions A, B, and C). Figure 17 (b) shows the chirped pulse width as a function of the fiber length in the cavity (fiber B) by assuming no fiber A and fiber C. This will help eliminate the need for stretcher in high power and high energy ultrashort fiber laser systems.

An experiment has been done to verify the approach. By changing the fiber length and cavity dispersion as shown in Figure 5, we are able to get stable mode locking at any PRR from 100 kHz to 100 MHz. Figure 12 shows two examples of experimental results for output spectra.

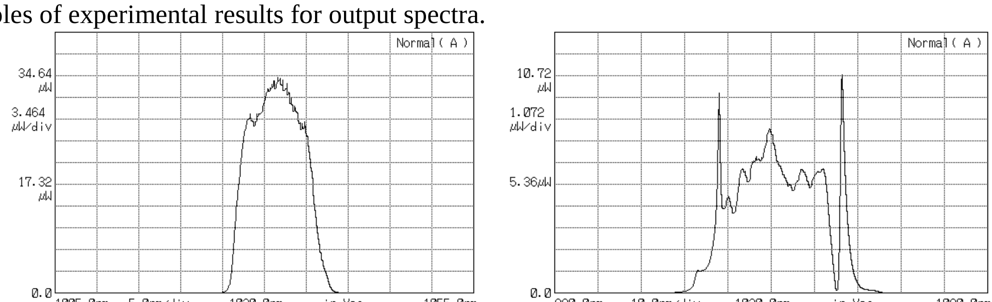
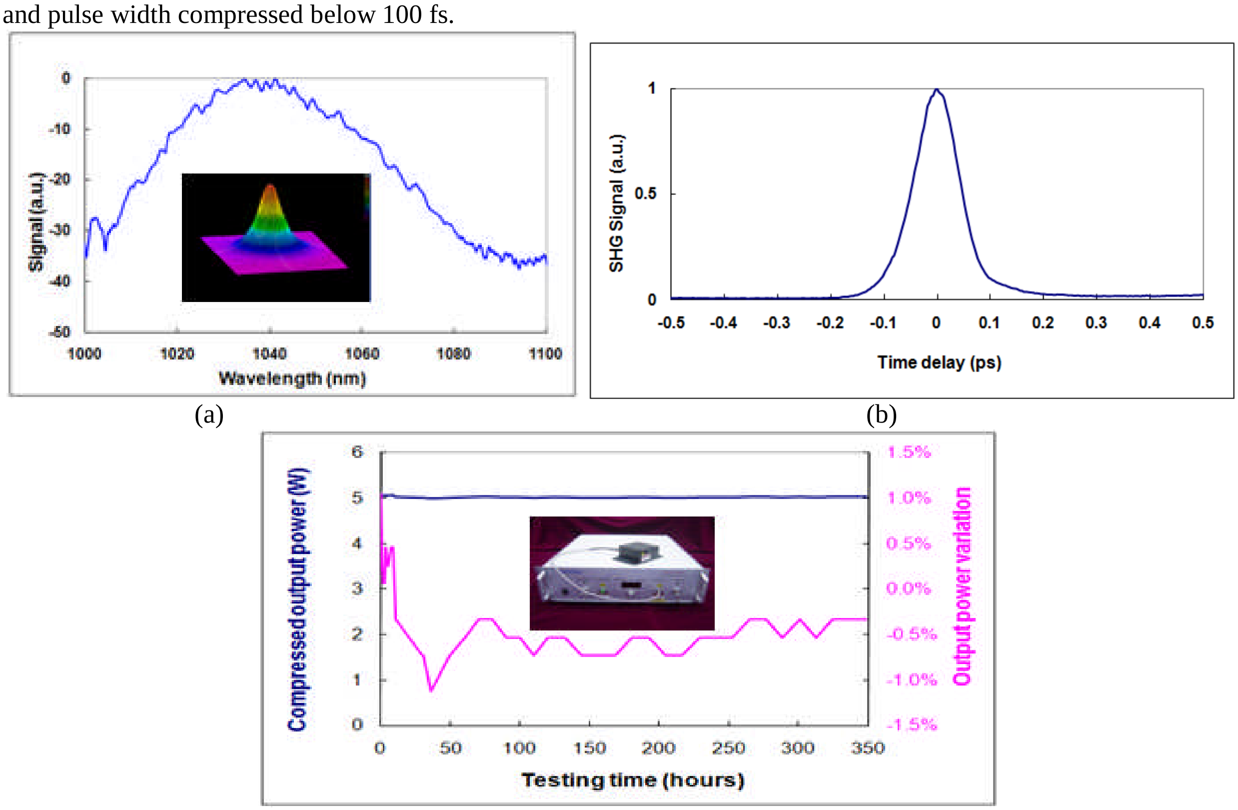


Figure 12. Spectra from seed osillators

One of the key pulse shaping techniques is to manipulate the dispersion and TOD of the fiber. Basically, the dispersion in the fiber is controlled by both material dispersion and waveguide dispersion. At the 1020-1090 nm spectral region, material dispersion shows a positive dispersion slope. With traditional fiber design such as that for SM 28, the dispersion slope or TOD always show a positive number around 0.3 ps/nm^2.km. However, by manipulating the fiber waveguide structure (e.g. depressed cladding structure), the waveguide dispersion can be introduced in modification of the material dispersion to obtain the expected dispersion and dispersion slope to make the whole fiber system with matched dispersion and TOD.

Another key spectral shaping technique used for reducing the pulse width is to obtain enough pulse spectral bandwidth by taking advantage of the SPM that may take place after the amplification stage such that the broadening spectrum will not be limited by the gain spectrum or narrowing effect of the amplifier. The length of the fiber implemented in the amplification stage should have appropriate length in order to generate the required spectrum bandwidth without having serious wave breaking effect. The SPM causes the spectrum broadening when the peak power of the pulse reaches to certain level for a given fiber type and length. The broadening factor is a function of the peak power, fiber structure, and fiber length. Depending on the pulse energy level and pulse width (that defines the peak power), the optimized broadening factor can be optimized by selecting the right length and fiber type. Moreover, proper control of SPM can balance the TOD mismatch between the fiber stretcher and bulk grating compressors.

These techniques resolve the trade-off between power scaling and pulse width broadening, in which the amplified spectral bandwidth can support the 100 fs pulse width without significant residual TOD and gain narrowing effects. We have developed highly reliable and compact fs fiber lasers with power scaling up to 10 W and pulse width compressed below 100 fs.

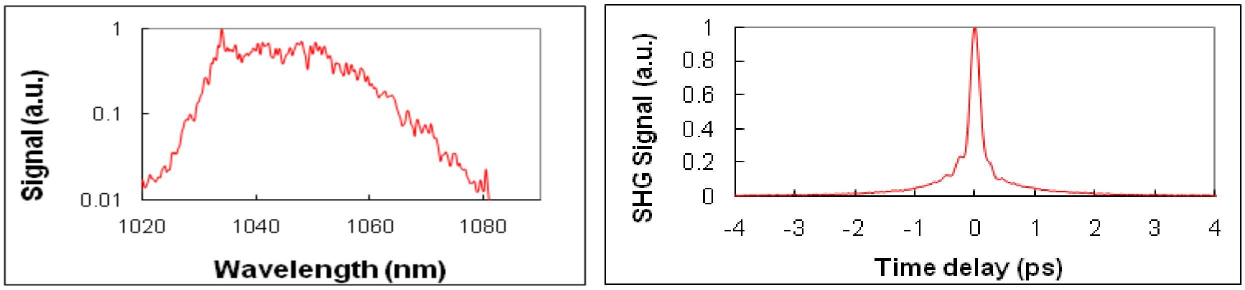


(a) (b)

(c)

Figure 13. (a) Spectrum with bean profile and (b) pulse width of a packaged 1 W fs fiber laser. (c) Stability of a packaged 5 W fs fiber laser.

As an example, Figure 13(a) and (b) shows an example of the 1 W 100 fs (assuming Gaussian shape) fiber laser performance from PolarOnyx. It has a pulse repetition rate of 33 MHz, compressed pulse energy of 30 nJ and average power of 1.4 W. The pulse width is 90 fs (Gaussian shape). The operating wavelength is around 1035 nm. It has a compact compressor integrated with the fiber laser for ease of operation and reliability. Figure 13(c) shows long term stability test of a 5 W fs fiber laser. Less than 1% instability provides an ideal tool for bio-imaging applications. As high as 10 W compressed output power with pulse width of 100 fs has been achieved by using the similar approaches. Figure 14 gives its spectrum and pulse width. The pulse width was compressed by 1450l/mm transmission grating pair and 600 l/mm grating pair. The pulse width was compressed to below 100 fs (Figure 14 b). Further engineering is on going for production. By adding OPO as a supplement, the wavelength can cover from Visible to mid-Infrared. This will further extend the capability of fs fiber laser.



(a) (b)

Figure 14. (a) Spectrum and (b) pulse width for a 10 W high power fs fiber laser

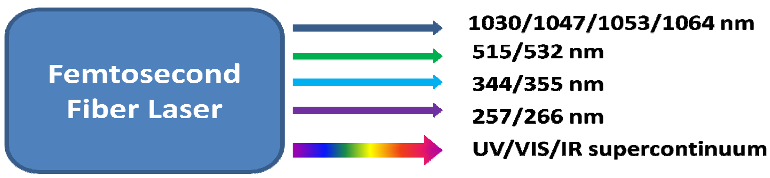
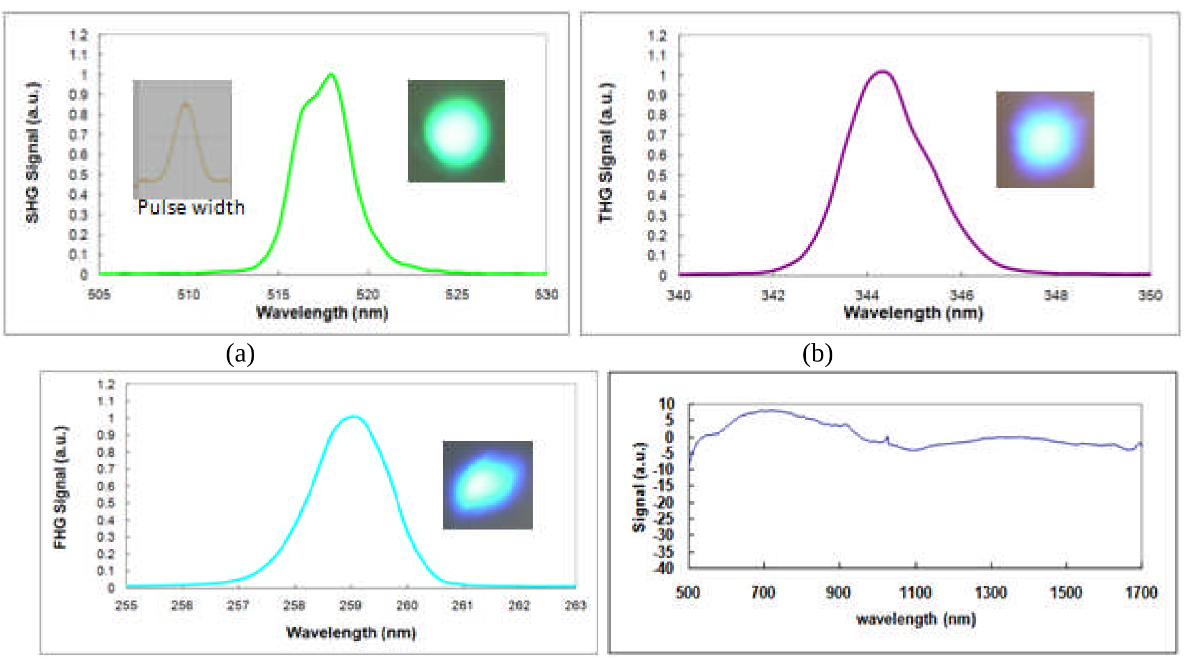


Figure 15. PolarOnyx's biomedical solution includes a high power 1 micron fs fiber laser, its second harmonic generation SHG (green), third harmonic generation THG (UV), and forth harmonic generation FHG (deep UV). By coupling the output pulses into a nonlinear fiber (PCF, for example), various types of supercontinuum (SC) (UV/VIS/IR) sources can be generated.



(a) (b)

(c) (d)

Figure 16. Spectrum, pulse width, and beam quality of harmonic generation (a-c) and supercontinuum (d) for a high power fs fiber laser

We have developed a complete packaged fs fiber laser with harmonic generations and supercontinuum generation for biomedical applications. Figure 15 shows a schematic diagram for the fs fiber laser based biomedical solution. It includes a high power fs fiber laser with SHG (40% efficiency), THG (10% efficiency), and FHG (20% efficiency). The pulses of harmonic generations have comparable pulse width with fundamental pulses. Supercontinuum is achieved by coupling light directly into various nonlinear fibers such as PCF. Figure 16 gives its performance summary of spectra, pulse widths, and beam qualities of fundamental wavelength, SHG, THG, FHG, and SC.

3.2. 1.55 micron femtosecond fiber laser and 780 nm generation

1.55 μm fiber laser uses Er doped fiber as a gain medium for generation and amplification of 1520-1610 nm signals. 1.55 micron wavelength fiber laser is getting interest due to its capability of multi photon imaging through third harmonic generation. By frequency doubling (SHG) of its fundamental light, 780 nm fs pulses can be obtained, which is ideal solution for replacement of bulky and expensive Ti:Sappire fs laser.

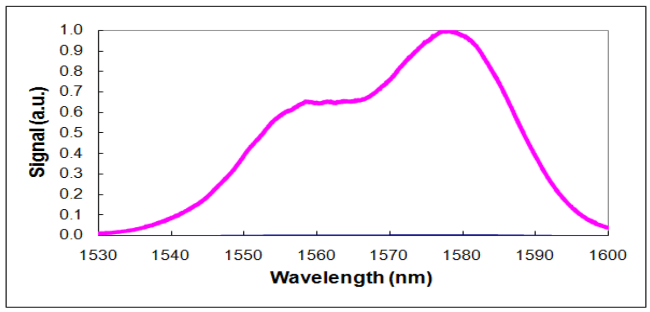
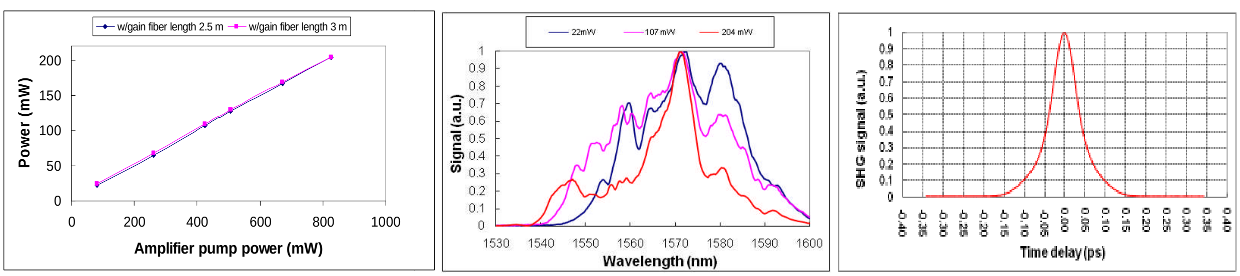
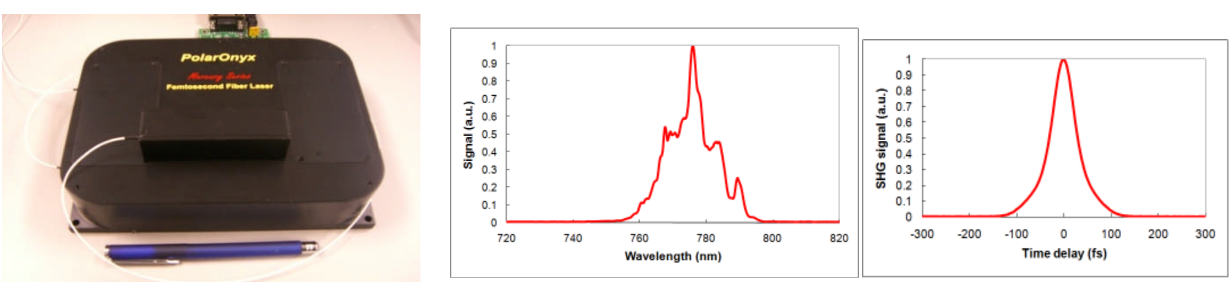


Figure 17. Seed laser spectrum from the output PM fiber



(a) (b) (c)

Figure 18. (a) Pre-amplifier output power with different gain fiber, (b) Pre-amplifier output spectra, and (c) Autocorrelation trace of pulse width measurement at PM LMA output fiber at 200 mW



(a) (b) (c)

Figure 19. (a) 1.55 micron fs fiber laser and its SHG module (sit on the top) and its SHG (b) spectrum and (c) pulse width

Stable mode locking laser with a repetition rate of 10 MHz to 100 MHz is obtained. Figure 17 shows an example of an ultra-broad spectrum with spectrum width of 35 nm (80 MHz) with uncompressed pulse width of 1 ps and an output power of 10 mW. The seed laser is integrated with a pre-amplifier with counter-pumping configuration. The pump lasers are two high power 976 nm with polarization beam combiner to increase pump power. The amplifier output power of 200mW was obtained as shown of Figure 18 (a). Its spectra at various pump powers are also given in Figure 18(b). The pulse width was compressed to 80 fs at 200 mW by using a piece of LMA PM fiber. Figure 18 (c) shows the experimental result of pulse width measurement.

SHG was done with a packaged 200 mW fs fiber laser at wavelength of 1.55 micron. Figure 19 shows the packaged module including the 1.55 micron fs fiber laser and its SHG module. A PPLN crystal is used to convert the fundamental light to 780 nm. 50 mW was achieved at 780 nm with a pulse width of 60 fs. Figure 19 shows curves for pulse width and spectra of 780 nm signal.

3.3. 2 micron femtosecond fiber laser

2 μm fiber laser uses Tm doped fiber as a gain medium for generation and amplification of 1700-2100 nm signals. The pump wavelengths can be in the spectral regions of 790 nm, 1210 nm and 1600 nm. Conventionally, 790 nm is the most popular pump wavelength due to the availability. As high power Er fiber laser at 1600 nm region becomes available, it will be widely used to pump Tm doped fiber laser since it can provide high efficiency and fiber delivery solution. 2 micron fs fiber laser is an ideal laser tool for precision surgery or cell ablation due to high peak absorption of water around 2 μm.

Tm doped fiber has a peak emission around 1.9 μm. To make the Tm doped fiber laser operate at 2 μm, a filter is inserted to force the laser operating at 2 μm spectral region (spectral shaping). Without DCF, the seed worked in soliton multi-pulse regime and switched to single pulse only just above threshold of generation. The spectrum shown in Figure 20 has a spectral bandwidth of 7 nm and showed Kelly peaks reduced from left side of central wavelength because they were cut by filter edge. The pulse repetition rate is around 20 MHz.

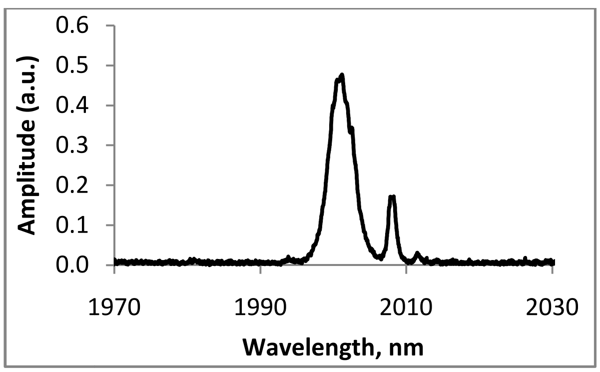


Figure 20. Spectra of seed generation in soliton mode

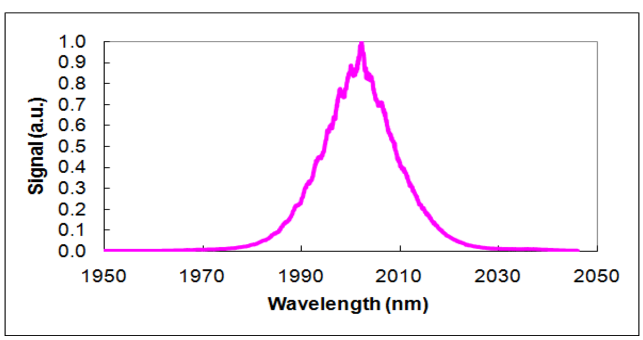


Figure 21. Seed spectrum with dispersion control

Commercial optical fibers have a dispersion of 40 ps/nm/km at a wavelength of 2 μm. To manage the dispersion in the mode locked fiber laser. We have designed a dispersion compensation fiber (DCF) fiber that shifting the dispersion to normal dispersion region and has a dispersion of -20 ps/nm/km. A piece of DCF is spliced into the cavity shown in Figure 5. Pulse train became single pulse and work in a stable operation at an output power of 12 mW. The spectral bandwidth is measured to be 15 nm as shown in Figure 21. The pulse repetition rate is around 8 MHz.

To make the high power amplifier be able to handle high peak power with minimum pulse distortion, large mode area (LMA) fiber is the most effective choice. Currently both LMA fiber from Nufern and PCF fiber from NKT are available. As shown in Figure 9, for high power amplifier using a combiner, up to nineteen diodes fiber output can be spliced to the input ports of the fiber combiner. The combiner was demonstrated over 95% coupling efficiency in the wide range of input power per port from 10 to 30 W. The gain DC TDF fiber was manufactured by NUFERN and consisted of 2 m PM, 250 μm cladding, 25 um core diameter, α_{abs}= 2.2 dB/m@793 nm. We have succeeded to boost the signal power to over 2 W (currently limited by the availability of high power 793 nm pumps.). The spectra after the high power amplifier at 2 W is similar to that of the seed in Figure 21 and does show that self phase modulation helps the spectrum broadening by effectively balancing gain narrowing in the amplifier (caused by uneven gain spectrum of the Tm gain medium).

A pair of 900 lines/mm gratings is used to compress the chirped pulse. The gratings have over 95% efficiency at 2000 nm and large angular tolerance (+/- 3-deg). After compression, the dechirped pulse was measured by an autocorrelator. Figure 22 gives the pulse width measurement which is 300 fs. Compression efficiency as high as 70% was achieved.

Our current system can be readily scaled up to 100 W by adding more high power 793 nm pumps. We are working with our vendors to fabricate the pumps now and will report our new research once we received the pumps.

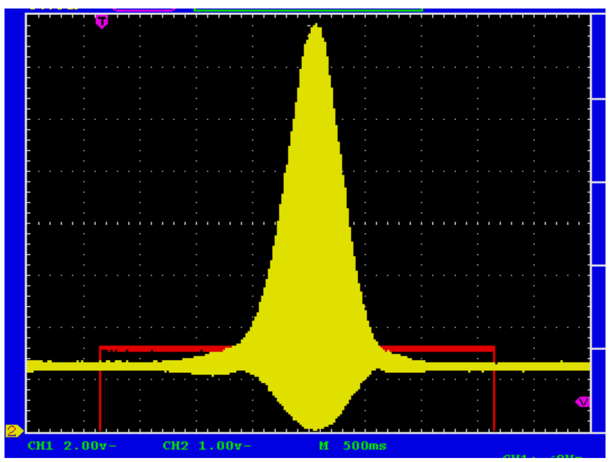


Figure 22. Autocorrelation trace of the compressed pulse width (300 fs)

4. Summary and Conclusion

Techniques used for achieving mode locked fiber lasers are discussed. These techniques include polarization shaping, pulse shaping, and spectral shaping. Mode locked fiber lasers operating at 1 μm, 1.55 μm, 2 μm and their harmonic generations (780-800 nm, 515-532 nm, 344-355 nm, 257-266 nm) are discussed. By using dispersion managed amplifiers, amplification and compression of 100 fs femtosecond pulses to 10 watts were demonstrated. These femtosecond fiber lasers are packaged in compact and robust modules and passed long term operation test without any degradation, and proved to be reliable light sources for clinic applications.

Ultrafast fiber lasers are experiencing rapid adoption in a great diverse fields and applications and are proved to be promising candidates for many applications in biomedical imaging and surgery processing. Fiber lasers exhibit a range of advantages over solid state sources, including: compact size, diffraction limited beam quality, high efficiency and extremely low-noise and maintenance-free operation. Over the next a few years, we will experience an explosive expansion of ultrafast fiber lasers into both existing fields by replacing traditional solid state lasers and exploring new fields in biomedical applications. In addition to current 1.55 micron and 1 micron wavelength regions, more wavelengths regions such as 2 micron, 2.7 micron, 3 micron, MIR (mid-infrared) and LWIR (long wave infrared), Visible and UV will be coming up to fit applications everywhere. High energy and high power fiber lasers will continuously be pushing for higher energy (>mJ), higher power (> kW), and shorter pulse (< 100 fs). The future of ultrafast fiber lasers is beyond our imagination and without boundary.

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5. References

1. Y. Jiang, I. Tomov, Y. Wang, and Z. Chen, "High-resolution second-harmonic optical coherence tomography of collagen in rat-tail tendon," Appl. Phys. Lett. **86**, 133901 (2005).
2. Yan-Hua Zhai, Christiane Goulart, Jay E. Sharping, Huifeng Wei, Su Chen, Weijun Tong, Mikhail N. Slipchenko, Delong Zhang, and Ji-Xin Cheng, “Multimodal coherent anti-Stokes Raman spectroscopic imaging with a fiber optical parametric oscillator,” Appl. Phys. Lett. **98**, 191106 (2011).
3. Chulmin Joo, Chun Zhan, Qing Li, and Siavash Yazdanfar, “Autoconfocal transmission microscopy based on two-photon-induced photocurrent of Si photodiodes,” OPTICS LETTERS **35 (1)**, 67 (2010).
4. Rajan Arora, Georgi I. Petrov, Jian Liu, and Vladislav V. Yakovlev, “Improving sensitivity in nonlinear Raman microspectroscopy imaging and sensing,” Journal of Biomedical Optics 16(2), 021114 (February 2011).
5. Shuo Tang, Jian Liu, Tatiana B. Krasieva, Zhongping Chen, and Bruce J. Tromberg, “Developing compact multiphoton systems using femtosecond fiber lasers,” Journal of Biomedical Optics 14 (3), 030508 (2009).
6. Khanh Kieu, Brian G. Saar, Gary R. Holtom, X. Sunney Xie, and Frank W. Wise, “High-power picosecond fiber source for coherent Raman microscopy,” OPTICS LETTERS 34(13), 2051 (2009).
7. Yan-Wei Tzeng, Yen-Yin Lin, Chen-Han Huang, Jian-Ming Liu, Hsiang-Chen Chui, Hsiang-Lin Liu, James M. Stone, Jonathan C. Knight, and Shi-Wei Chu, “Broadband tunable optical parametric amplification from a single 50 MHz ultrafast fiber laser,” OPTICS EXPRESS 17 (9), 7304-7309 (2009).
8. F. Ö. Ilday, J. Buckley, L. Kuznetsova, and F. W. Wise, " Generation of 36-femtosecond pulses from a ytterbium fiber laser," Opt. Express **11**, 3550 (2003).
9. Lyuba Kuznetsova, Shian Zhou, Andy Chong, and Frank W. Wise, “Single -mode fiber source of 0.8 μJ, 150-fs pulses at 1 μm,” *Proceedings of the Conference on Lasers and Electro-Optics* (Baltimore, May 2005), paper CTuCC7.
10. Z. Liu, L. Shah, I. Hartl, G. C. Cho and M. E. Fermann, "High-energy fiber chirped-pulse amplification system based on cubicons", *Proceedings of the Conference on Lasers and Electro-Optics* (Baltimore, May 2005), paper CThG4.
11. J. Limpert, et al., “High power rod-type photonic crystal fiber laser,” Opt. Express 13, 1055-1058 (2005).
12. J. Limpert, et al., “Low nonlinearity single transverse mode Yb doped photonic crystal fiber amplifier,” Opt. Express 12, 1313-1319 (2004).
13. J. Limpert, et al., “Thermo-optical properties of air-clad photonic crystal fiber lasers in high power operation,” Opt. Express 11, 2982-2990 (2003).
14. A. Tunnermann, et al., “Large mode area fibers for high power laser operation based on solid and air microstructured cores,” SPIE 5709, 301-309 (2005).
15. P. Russell, “Photonic crystal fibers,” Science 299, 358 (2003).