Recent advances and applications of ultrashort pulses from femtosecond fiber lasers

ISSN 1870-9095

Ritu Walia[1], **Kamal Nain Chopra**[2]
[1]*Department of Physics, Maharaja Agrasen Institute of Technology, GGSIPU Delhi, India.*
[2]*FormerScientist G, Laser Science and Technology Centre, DRDO, Metcalfe House, Delhi-110054; and Former Research Scientist, Optoelectronics Lab, Department of Physics, Indian Institute of Technology, Hauz Khas, New Delhi, India.*

E-mail: drrituwalia@gmail.com

(Received 6 July 2023, accepted 20 November 2023)

Abstract

High Powers from Femtosecond Fiber Lasers has become very useful for a variety of applications including laser processing, medical bio-optics, and opto-electronics. Designing and synthesis of such systems is a complicated technique, in the sense that various Mathematical and Characteristics considerations of intensity autocorrelation of output pulses, and the autocorrelation of the compressed pulses have to be taken into account. The purpose of the present paper is to provide the technical analysis of the Modeling and Designing of these systems, besides giving a brief qualitative review of some of the recent important investigations on such systems.

Keywords: Yb and Erb fiber lasers, Femtosecond Fiber Lasers, Temporal Pulse Characterization Techniques

Resumen

Las altas potencias de los láseres de fibra de femtosegundo se han vuelto muy útiles para una variedad de aplicaciones que incluyen procesamiento láser, bioóptica médica y optoelectrónica. El diseño y la síntesis de tales sistemas es una técnica complicada, en el sentido de que se deben tener en cuenta varias consideraciones matemáticas y características de la autocorrelación de intensidad de los pulsos de salida y la autocorrelación de los pulsos comprimidos. El propósito del presente artículo es proporcionar el análisis técnico del Modelado y Diseño de estos sistemas, además de dar una breve revisión cualitativa de algunas de las recientes investigaciones importantes sobre dichos sistemas.

Palabras clave: Láseres de fibra Yb y Erb, Láseres de fibra de femtosegundo, Técnicas de caracterización de pulso temporal.

I. INTRODUCTION

The treatment of the lens tissue, fs-laser surgery provides precise opening of the lens capsule, capsulorhexisto remove clouded lens tissue in case of a cataract. Ultrashort laser pulses are used as a laser scalpel for removing a thrombus as a treatment for the apoplectic stroke. The high intensity of focused ultrashort laser pulses allows various medical applications like precise modification and ablation of treatment. The researchers have focused on the interaction of femtosecond laser pulses with transparent tissue, especially for applications in ophthalmology. By focusing ultrashort laser pulses into transparent material, the high intensity within the focal volume leads to nonlinear absorption; and so the absorbed energy induces a micro plasma, causing the formation of a micro bubble, which separates the tissue in a small region of only several micrometers. By moving the laser and hence the focus, precise cuts can be realized avoiding the need of opening the eyeball. With the advent of fiber lasers, many research efforts [1, 2, 3, 4, 5, 6, 7, 8] have been made for designing and developing new types of fiber lasers with entirely new capabilities. Thulium and holmium emit in the 2μm band, which is very important, and interestingly, some non-oxide fibers can be useful in the mid-IR. Recently, some advances have been made in the areas like - fiber Optical Parametric Oscillators (An optical parametric oscillator is a parametric oscillator, which oscillates at optical frequencies, and converts an input laser wave called "pump" with frequency into two output waves of lower frequency and, by means of second-order nonlinear optical interaction. The two frequencies being called as signal and idler respectively), super continuum sources, and higher femtosecond pulse energy. Ytterbium (Yb)- and erbium (Er)-doped fiber lasers have been of great use in applications from high-power materials to femtosecond sources for the routine purposes. In addition, new different types of fiber lasers with novel capabilities e.g. Commercial thulium-doped fiber lasers able to deliver 200 W continuous wave in the 2 μm band, have great utility for the medical and military applications; Holmium-doped fibers can work at 2.17 μm; and Non-silica fibers emit on longer mid-infrared wavelengths. Some interesting developments have taken place - Novel fiber designs capable of (i) increasing the nonlinearity for applications in optical parametric oscillators and super continuum sources (The ultra-wide band optical spectra can be generated by using ultrashort-pulse lasers and suitable specialty fibers, which are referred to as a super continuum., and (ii) reducing the nonlinearity for increasing energy in short pulses.

Yb and Er have strong absorption lines, matching the output of powerful pump diodes, along with emitting wavelengths, at which the silica fibers have low attenuation. The problem, however, in this case is, that they cover bands around 1030nm and 1550 nm, and not around the 1300 nm. In addition, they have too high absorption beyond ~ 2.17 µm, and thus for the mid-IR, the fiber lasers require other host materials. An advantage in these lasers is that of the tight optical confinement, though the concentrating power results in increasing the nonlinear effects, which limits the energy in short pulses. Some micro structured fiber designs have been made having increased effective mode area, with reduced power density and nonlinear effects.

The effective mode area can also be reduced by increasing nonlinearity for use in OPOs or super continuum sources. The exploration of the novel fiber lasers has thus focused on finding the new materials and designs useful for increasing the range of the applications of the fiber lasers e.g. bismuth has been used to demonstrate CW laser emission with power of ~ watt, with many fiber lines between 1150 and 1550 nm, not available in Yb and Er fiber lasers.

As mentioned above, the most developed fiber laser is based on thulium, which is commercially available in various models, with power as high as > 200 W CW at 1900 to 2040 nm; with M/s. IPG Photonics (Oxford, MA) for industrial applications, and 1 W single-frequency laser with 50 kHz linewidth, and also a 250 µJ Q-switched model and a mode-locked laser delivering 35 nJ pulses. CW power ~ kilowatt-class, with M/s. AdValue Photonics (Tucson, AZ). Another interesting development in the field has been the use of the non-silica glasses, which have the advantage of much lower losses at wavelengths > 1.9 µm, making them a strong candidate for use as hosts in case of the mid-IR fiber lasers. Ono of the most useful host has been the fluoride glass ZBLAN (ZrF4-BaF2-LaF3-AlF3-NaF), which has helped in the development of the mid-infrared fiber lasers, from 0.3 to 4.3 µm. Use has also been made of another useful material - tellurite (TeO2), mixed with 30% tungsten oxide (WO3) and 10% lanthanum oxide (La2O3) for fabricating double-clad fibers. By pumping at 800 nm with laser diodes, 494 mW at 1.9 µm from a 20 cm length of thulium doped fiber and 35 mW at 2.1 µm from a 7 cm length of fiber co-doped with thulium and holmium have been produced by the team of researchers at the Shanghai Institute of Optics and Fine Mechanics (Shanghai, China).

Higher powers from femtosecond fiber lasers have been achieved by: (i) Anomalous dispersion and self-focusing nonlinearity, which dominates the pulse shaping in most of the femtosecond lasers, since the fabrication of solitons stabilizes pulse shape , though at the cost of limiting the pulse energy to 1-2 orders lower than in bulk titanium-sapphire lasers; and (ii) using Yb-doped fibers as the silica fibers have normal dispersion at 1 µm wavelength, in which case, dissipative solitons can be generated by chirping pulses and filtering them to trim the fringes of the spectrum, and interestingly, these solitons remain stable even at 2 orders of energy higher than that of an ordinary soliton. A group of researchers at the Friedrich Schiller University (Jena, Germany) has been able to produce 0.9 µJ pulses having average power of ~ 66 W, by using a microstructured Doped photonic crystal PCF with an 80 µm core in the gain fiber, which is much higher average power than that achieved in Ti-sapphire.

II. THEORY OF FEMTOSECOND FIBER LASERS

The real electric field $E(t)$ of an ultrashort pulse is oscillating at an angular frequency ω_0 corresponding to the central wavelength of the pulse, which is expressed in the form of the complex field, that can be separated into (i) a temporal intensity function $I(t)$, and (ii) a temporal phase function, as given below:

$$E(t)=\{I(t)\}^{\frac{1}{2}}e^{i\omega_0 t}e^{i\psi(t)}\cdot \tag{1}$$

The complex electric field in the frequency domain is obtained from the Fourier transform (FT) of, and is given below:

$$E(\omega)=FT\{E(t)\}\cdot \tag{2}$$

In the same manner, the intensity and a phase function can also be defined in the frequency domain. The temporal pulse characterization techniques of the pulses are based on evaluating the well known intensity autocorrelation function given by:

$$S(\delta)=\int_{-\infty}^{\infty} I(t)I(t-\delta)dt \ , \tag{3}$$

which is a useful tool in designing the pulses of the femtosecond lasers Obviously, $S(\delta)$ is determined as thetime integral of temporal pulse intensity function $I(t)$ multiplied by its shifted replica $I(t-\delta)$, which is in fact used as a gate to scan the same pulse, and is always symmetric and centred around $\delta=0$. The pulse width τ is related to the width of the autocorrelation function τ_{AC} as given below:

$$\tau_{AC}=(\frac{1}{D_{AC}})\tau\cdot \tag{4}$$

Where D_{AC} is the deconvolution factor depending on the pulse shape. The values of these factors for the different commonly used pulse shapes can be calculated from the above equations.Assuming that the spectral phase varies slowly with the frequency ω!, it can be expanded into the Taylor series around the carrier frequency ω_0, as given below:

$$\varphi(\omega)=\sum_{k=0}^{\infty}\frac{\varphi^{(k)}(\omega_0)}{k\dagger}(\omega-\omega_0)^k, \tag{5}$$

with

$$\varphi^{(k)}(\omega_0)=\frac{\partial^k\varphi(\omega)}{\partial\omega^k}_{at\omega=\omega_0} \ , \qquad (6),$$

where $k\dagger$ is k factorial. Thefirst term ω_0 in the Eq. (6) describes the absolute phase of the pulse in the time domain; the first derivative $\varphi'(\omega_0) = T_g(\omega_0)$ is called the group delay(GD), which in fact leadsto a shift of the pulse envelope in the time domain,; the second derivative $\varphi''(\omega_0) = D_2(\omega_0)$ is the \group delay dispersion (GDD); the third derivative $\varphi'''(\omega_0) = D_3(\omega_0)$ is the \third order dispersion (TOD); and the fourth derivative $\varphi''''(\omega_0) = D_4(\omega_0)$ is the fourthorderdispersion (FOD) .

Because of the fact that these higher order derivatives describe the frequency dependence of the GD, they result in the dispersive effects and changes in the temporal structure of the pulse envelope. It may be noted that in many cases, the results obtained in practice are slightly different from the computed ones, and therefore, the corrections have to be applied, based on the feedback from the experimentally achieved values. This requires lot of experience and expertise of the designers, and sometimes software has to be used. Based on this modeling, some investigation shave already been made and their results have been reported in the literature. The results of the measured intensity autocorrelation of output pulses (left), and the autocorrelation of the compressed pulses (right) for the Yb-doped Femtosecond Fiber Lasers, as available in the literature, have been reproduced below:

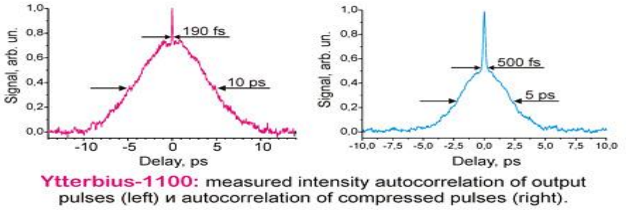

Figure 1. Measured intensity autocorrelation of output pulses (left) and the autocorrelation of the compressed pulses (right) for the Yb-doped Femtosecond Fiber Lasers. Figure courtesy Del Mar Photonics www.dmphotonics.com.

Clearly, the designers have to optimize the pulse width and the pulse shape by applying the temporal pulse characterization techniques based on the intensity autocorrelation function, and considering the group delay, the group delay dispersion, the third order dispersion, and the fourth order dispersion. The femtosecond lasers are based on using ultrashort pulse of light, an electromagnetic pulse whose time duration is ~ of a picosecond (10^{-12} second) or less. Interestingly, such pulses have a broadband optical spectrum, and in addition can be created by mode-locked oscillators. Amplification of the ultrashort pulses is done by using the technique of chirped pulse amplification, in order to avoid damage to the gain medium of the amplifier. During the last fifteen years, with the advent of the development of femtosecond optical frequency combs, some notable advances have been made in a many diversified scientific areas. This is because of the fact that as compared to a conventional laser source, the femtosecond comb provides a broadband source with well-defined phase coherence across the optical spectrum, which makes it a unique tool for spectroscopic applications, simultaneously providing high spectral resolution and broad spectral coverage. Margolis [9] has presented a tutorial review, providing an introduction to femtosecond optical frequency combs, covering their principles of operation and examples of how they can be applied to spectroscopy, and thus, has demonstrated their potential as a versatile spectroscopic tool, which is expected to play a useful role in the future advances in the field of chemical sciences. Pulse trains with multi-GHz repetition rates are required for applications including the telecommunications, and optical sampling, because of their unique characteristics of output power and the pulse quality. As reported in the literature, various novel laser sources generating multi-GHz picosecond pulses with high quality and high output power, like - Nd:YVO4 lasers in the 1-mm region with up to ~ 160 GHz, Er:Yb:glass lasers in the 1.5-mm region with up to ~50 GHz have already been developed.

Since high pulse energies or low numerical apertures are required for the treatment, nonlinear effects such as self-focusing and fila mentation may decrease the confinement, and hence the quality of the laser-induced modifications. This is the case for applications in deeper eye segments, where high pulse energies and low numerical apertures are required. To overcome this problem, simultaneous spatial and temporal focusing (SSTF) is required to induce precise optical breakdown; and also the spectral components of the incident laser pulse are spatially separated by means of a grating stretcher setup. Because of the reduction in local bandwidth, this separation results in a rainbow-like, collimated beam with increased pulse duration. Thus, the entire spectral bandwidth is recovered where the spectral components overlap again - within the focal volume of a lens. Therefore, the ultrashort pulse exists in the focal region only, and hence reducing nonlinear side effects such as self-focusing and fila mentation. The Setup for simultaneous spatial and temporal focusing of an ultrashort laser pulse has been shown below:

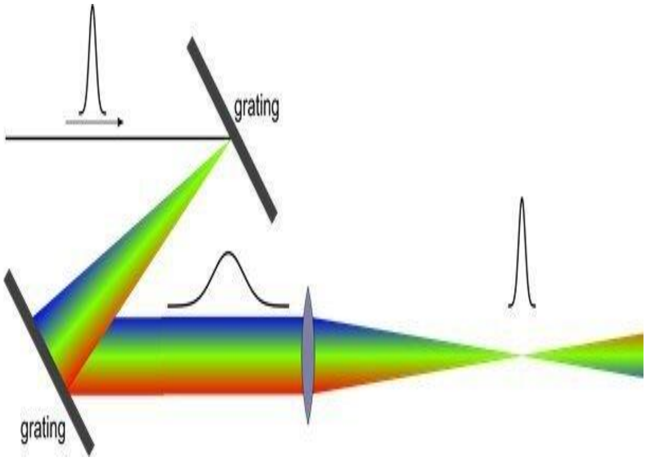

Figure 2. Setup for simultaneous spatial and temporal focusing of an ultrashort laser pulse. Figure courtesy Univ. Jena, IAP.

III. CONCLUDING REMARKS

With the advent of the Fiber laser technology and the advances made in it, dramatic progress has recently been made, regarding the output power and ultrashort-pulses e.g. Output powers of ≥KW have been demonstrated for CW single mode fiber lasers, and Pulse energies of >10 μJ are now commercially available for ultrafast fiber lasers. An important class of such lasers, which is commercially available, is: Yb-doped fiber lasers, based on using ytterbium-doped silica single-mode fibers as the gain medium with a center wavelength ~ 1030 nm. The core diameter is respectively ~ a few micrometers and ~ 30 μm, for single-mode fibers and the large effective area fibers. Interestingly, a high average power (>1 W) ultrafast fiber laser consists of a fiber oscillator, a pulse stretcher, a pulse picker, a couple of stages of fiber amplifiers, and a pulse compressor, the fiber oscillator having pulse energy output of ~100 pJ and ~10 MHz pulse repetition rate. The fiber lasers have many advantages including the compact size, good beam quality, and high mechanical stability. However, the fiber lasers, especially ultrafast lasers, have certain disadvantages like – the limited peak power, and the impact of the nonlinear effect on the performance. In fact, the ultrafast lasers have very high peak power, and also the fiber gain media have very small physical diameter along with a large physical length. This results in the pulse fluence inside the fiber being very high even for the moderate pulse energy, leading to the appearance of the nonlinear effects like - self-phase modulation, and Raman scattering. The impact of such effects is that the pulse temporal profile from the ultrafast fiber laser has a large pedestal background, meaning that a great portion of the pulse energy is distributed within a much larger time duration.

Nie *et al*. [10] have reported an Yb fiber oscillator producing high-energy femtosecond pulse clusters. Based on the visualization by averaging autocorrelation, the output pulses have been found to consist of femtosecond pulse clusters, which appear as a picosecond envelope with a ~ 100-fs pulse in its center. Using more than 200-m fiber,the pulse energy has been scaled up to 450 nJ. It has been emphasized that this high energy in a cluster of femtosecond pulses has an important application, in the form of the laser-induced breakdown spectroscopy. Kharenko and Babin [11] have reviewed the results of the design and study of femtosecond fiber lasers, by considering various methods of mode-locking and generation regimes, and paying special attention to the regime of dissipative solitons in an all-fiber resonator with normal dispersion. Also, the main results and analysis of the possibilities of energy scaling of femtosecond pulses have been given.

Another important application of such lasers is the Tactical Ultrashort Pulsed Laser for Army Platforms. Interestingly, according to Industry Tap, the laser is more than a million times powerful than any used before, and this weapon can speedily fire metal-vaporizing pulses, just like a machine gun, which can easily vaporize its targets and disrupt enemy tech signals. Lucas and Zhang [12] have given a review of laser sources, along with their basic mechanisms, and potential applications. Xie *et al*. [13] have demonstrated the multi-mode microscopy based on a single femtosecond fiber laser. It has been shown that Coherent anti-Stokes Raman scattering (CARS), stimulated Raman scattering (SRS), and photothermal images can be obtained simultaneously with this simplified setup. Interestingly, the Distributions of lipid and hemoglobin in sliced mouse brain samples and blood cells have been imaged. It has been emphasized that since the dependency of signal amplitude on the pump power and pump modulation frequency has been characterized, the impact from different contributions can be isolated. Kieu *et al*. [14] have demonstrated the label-free multi-photon imaging of biological samples using a compact Er^{3+}-doped, compact and low cost femtosecond fiber laser mode-locked by a single-walled carbon nanotube (CNT). It has been shown that (i) various multiphoton imaging modalities like second harmonic generation (SHG), third harmonic generation (THG), two-photon excitation fluorescence (TPEF), and three-photon excitation fluorescence (3PEF)) can be effectively performed on various biological samples by using a compact handheld CNT mode-locked femtosecond fiber laser operating in the telecommunication window near 1560nm; and (ii) chlorophyll fluorescence in plant leaves and diatoms can be observed using 1560nm laser excitation via three-photon absorption.

Recently, large amount of interest has been shown in reseach on unconventional lasers. Chopra [15] has studied the Maximizing of the Net Modal Gain and Quantum Confinement in Quantum Cascade Lasers. Oktem *et al*. [16] have made very interesting and useful study on Soliton-similar ton Fibre Laser. Pinon and Anglos [17] have studied in detail the Optical emission studies of plasma induced by single and double Femtosecond Laser Pulses. Kobtsev and Smirnov [18] have studied and discussed the Fiber Lasers mode-locked due to Nonlinear Polarization evolution: golden mean of Cavity Length. Another very interesting work on the fiber lasers and the wavelength-tunable soliton pulses [19], has been reported a decade back, in which it has been claimed that all-fiber wideband tunable ultrashort pulse sources have been developed as compact and stable systems. It is important to note that these compact and stable systems have been found to be very useful in some practical applications - ultrashort laser pulse technology has been extensively used in diversified fields like laser processing, medical bio-optics, and opto-electronics. It is to be kept in mind that such ultrashort-pulse lasers produce lot of heat, and therefore, require water-cooling, which causes some limitations in their use. Recently, some interesting development of compact ultrashort-pulse fiber lasers has taken place, in which the lasers consist of fiber-optic devices, producing stable pulses without the requirement of water cooling. The limitation, however, is that the wavelength of the output pulses, can be varied only within the gain bandwidth of the fiber amplifier, which is <100nm.

Nishizawa and Goto ([19] have generated (i) ultrashort pulses tunable from 1.55 to 2.0μm using a 1.55μm Er-doped ultrashort-pulse fiber laser , and (ii) 1.0 to 1.7μm tunable pulses with a 1.0μm Yb-doped ultrashort-pulse fiber laser using photonic-crystal fibers as the nonlinear fibers. Their results for the Optical spectra of wavelength-tunable soliton pulses, generated through nonlinear effects have been shown below:

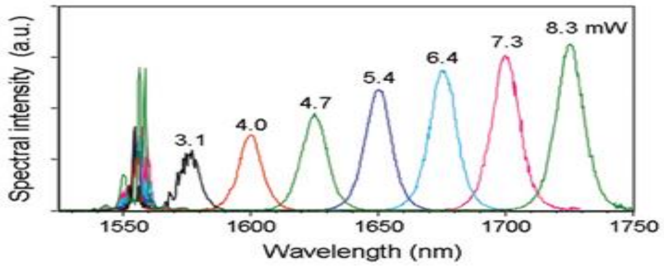

Figure 3. Optical spectra of wavelength-tunable soliton pulses, generated through nonlinear effects.Figure courtesy Nishizawa Norihiko and Goto Toshio, Novel super-continuum fiber lasers and wavelength-tunable soliton pulses, 12 December 2006, SPIE Newsroom. DOI: 10.1117/2.1200612.0519 , http://www.spie.org/x8486.xml.

It is clear from this Figure that an increase in fiber input power, results in the continuous red-shift of the centralwavelength. The Fig. 3 (b) illustrates that the wavelength can be tuned from 1.55 to 2.0 μm with a shift of 1.06 to 1.7μm wavelength.

Christian et al. [20] have given One-Temperature Analytical Model for Femto-/Atto-Second Laser–Metals Drilling. Their resultsof the thermal distribution within the Al sample in the case of 1, 25, 50, and 75 fs, respectively. These figures show a thermal wave propagating, designated as a change in thermal distribution, from the location of laser–Al interaction, which is due to the inherent characteristics of the non-Fourier heat equation. The temperature for all simulations (in arbitrary units) is self-consistent, so one can easily compare the results. It can be observed that as the pulse duration increases, the change in the thermal distribution becomes insignificant in the case of laser–Al interaction. The average power in a provided pulse can be expressed as:

$$Pavg=(Ppeak\tau)/\Delta t, \tag{7}$$

where, Pavg is the average power, τ is the measure of the time between the beginning and end of the pulse typically based on the full width half maximum (FWHM) of the pulse shape, Ppeak is the peak power, and Δt is the time between the start of one pulse and the start of the next. It is to be noted that as Δt decreases, the total energy of pulse width in FWHM increases.

Ding *et al.* [21] have recently given a broad review of Mode-locking, which is the technique for the generation of ultrashort optical pulses in laser systems, and have presented a comprehensive study of achieving high-energy pulses in a ring cavity fiber laser, which is passively mode-locked by a series of waveplates and a polarizer. It has been shown that the multipulsing instability can be circumvented in favor of bifurcating to higher-energy single pulses by appropriately adjusting the group velocity dispersion in the fiber and the wave plate/polarizer settings in the saturable absorber. It has been emphasized that these findings have the potential of being used as practical guidelines for designing high-power lasers, because of the fact that theoretical model relates directly to the experimental settings. Mahbouband Zendagui [22] have done the Numerical Simulations of Femtosecond Pulse Propagation in Photonic Crystal Fibers, and presented a Comparative Study of the S-SSFM and RK4IP algorithms.

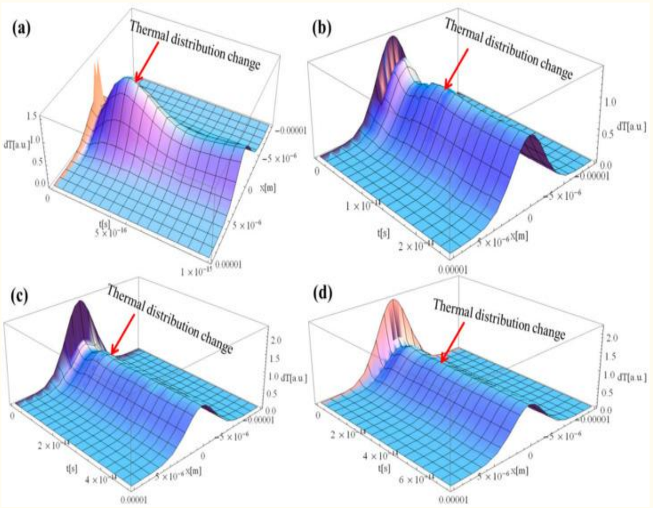

Figure 4. Laser–Al interaction for different duration of the laser pulse: (a) 1, (b) 25, (c) 50, and (d) 75 fsiFigure courtesy Materials (Basel). 2022 Jul; 15(14): 5010.

They have investigated the propagation of femtosecond pulse in photonic crystal fibers (PCFs), which is actually of great interest for many applications. It has been discussed that the generalized nonlinear Schrödinger equation (GNLSE) describes the different physical phenomena, like dispersion and some nonlinear effects including the self phase modulation (SPM), self steepening and Raman scattering encountered when the femtosecond pulses propagate in the PCF. Richardson *et al*. [23] have reviewed the current status and future perspectives of the High-power fiber lasers.Thais *et al*. [24] have discussed that the Femtosecond laser technology has become widely adopted by ophthalmic surgeons, and have discussed the applications and advantages of femtosecond lasers over traditional manual techniques, and related unique complications in cataract surgery and corneal refractive surgical procedures, including: LASIK flap creation, intracorneal ring segment implantation, presbyopic treatments, keratoplasty, astigmatic keratotomy, and intrastromal lenticule procedures. Mateusz and Cedric [25] have given a mini review, in which they have discussed that (i) the Cartract surgery is among the most frequently performed surgical procedures worldwide and has a tremendous impact on patients' quality of life. Phacoemulsification (PCS) is accepted as a standard of care; its technique has continuously evolved and already achieved good anatomical, visual, and refractive outcomes; and (ii) Lasers in ophthalmology are widely used in clinical practice, femtosecond lasers (FSLs) for corneal surgery in particular. It was natural to assess the usefulness of FSL in cataract surgery as this technology was within reach. It has been emphasized that (i) precise and reproducible cuttings provided by FSL platforms could improve standardization of care and limit the risk associated with the human element in surgery and provide a step toward robot-assisted surgery; and (ii) Femtosecond laser-assisted cataract surgery (FLACS) has been a topic of research in many studies and clinical trials that attempted to assess its potential benefits and cost-effectiveness over PCS. In view of all these novel studies and the associated developments in the applications, it can be safely concluded that the field of "Higher Powers from Femtosecond Fiber Lasers" is evolving and growing fast.

REFERENCES

[1] Carter A., Bryce, S. and Kanishka, T., *Thulium-doped fiber forms kilowatt-class laser*, (Laser Focus World, April 2009).

[2] Wise, F. W., *Femtosecond fiber lasers based on dissipative processes for nonlinear microscopy*, IEEE J. Sel. Top. Quantum Electron **18**, 1412 (2012).

[3] Nguyen, T. N., Kieu, K., Maslov, A. V., Miyawaki, M., and Peyghambarian, N., *Normal dispersion femtosecond fiber optical parametric oscillator*, Optics Lett. **38**, 3616-3619 (2013).

[4] Saad, M., *Heavy metal fluoride glass fibers and their applications*, *inPassive Components and Fiber-Based Devices VIII*, ed. Bishnu P. Pal, Proc. SPIE, 8307 (2011) 83070N.

[5] Tsang, Y. H. and El-Taher, A. E., *Efficient lasing at near 3 μm by a Dy-doped ZBLAN fiber laser pumped at ~1.1 μm by an Yb fiber laser*, Laser Phys. Lett. **8**, 11, 818 (2011);

[6] Jiang, S., *Two-micron thulium-doped fiber lasers achieve 10-kW peak power*, Laser Focus World **49**, 52 (2013).

[7] Peacock, A. C., Sparks, J. R. and Healy, N., *Semiconductor optical fibres: Progress and opportunities, Laser and Photon*, Reviews **8**, 53-72 (2014).

[8)] Chopra, K. N., *A Technical Note on the Diode Pumped Er Fiber Lasers and a short Review of some Important Novel Studies*, Atti Fond G. Ronchi **69**, 299-310 (2014).

[9] Margolis, H., *Spectroscopic applications of femtosecond optical frequency combs*, Chem. Soc. Rev. **41**, 5174-5184 (2012).

[10] Nie, B., Parker, G., and Dantus, M., *Energy scaling of Yb fiber oscillator producing clustersof femtosecond pulses*, Optical Engineering **53**, 051505 (2014).

[11] Kharenko, D. S. and Babin, S. A., *Generation of dissipative solitons in femtosecond fiber lasers*, Optoelectronics, Instrumentation and Data Processing **49**, 399-415 (2013).

[12] Lucas, L. and Zhang, J., *Femtosecond laser micromachining: A back-to-basics primer*, http://www.industrial lasers.com/articles/print/volume-27/issue-04/features/fermtosecond-laser-micromachining-a-back-to-basics-primer.html. 07/01/2012.

[13] Xie, R., Su, J., Rentchler, E., Zhang, Z., Johnson, C., Shi, H., and Hu, R., *Multi-modal label-free imaging based on a femtosecond fiber laser*, Biomedical Optics Express **5**, 2395 (2014). DOI:10.1364/BOE.5.002390 |.

[14] Kieu, K., Mehravar, S., Gowda, R., Norwood, R. A., and Peyghambarian, N., *Label-free multi-photon imaging using a compact femtosecond fiber laser mode-locked by carbon nanotube saturable absorber*, Biomed Opt Express **4**, 2187–2195 (2013). \Published online Sep 17, 2013. doi: 10.1364/BOE.4.002187PMCID: PMC3799676.

[15] Chopra, K. N., *Mathematical Modeling for Maximizing the Net Modal Gain and Quantum Confinement in Quantum Cascade Lasers*, Atti Fond G. Ronchi **70**, 165-177 (2015).

[16] Oktem, B., Ulgudur, C., and Ilday, F., *Soliton-similariton Fibre Laser*, Nat. Photonics **4**, 307–311 (2010).

[17] Pinon, V. and Anglos, D., *Optical emission studies of plasma induced by single and double Femtosecond Laser Pulses*, Spectrochim. Acta B **64**, 950–960 (2009).

[18] Kobtsev, S. M. and Smirnov, S. V., *Fiber Lasers mode-locked due to Nonlinear Polarization evolution: golden mean of Cavity Length*, Laser Phys. **21**, 272–276 (2011).

[19] Nishizawa, N. and Goto, T., *Novel super-continuum fiber lasers and wavelength-tunable soliton pulses*, 12 December (2006), SPIE Newsroom. DOI: 10.1117/2.1200612.0519 , http://www.spie.org/x8486.xml. [20] Mihailescu, C. N., Mahmood, M. A., Mihailescu, N., *Oane M., One-Temperature Analytical Model for Femto-/Atto-Second Laser–Metals Drilling: A Novel Approach, Materials (Basel).* (2022) Jul; 15(14): 5010. Published online 2022 Jul 19. doi: 10.3390/ma15145010, PMCID: PMC9320566, PMID: 35888476

[21] Ding, E., Renninger, W, H. , Wise, F. W., Grelu, S. and Kutz, J. N., *High-Energy Passive Mode-Locking of Fiber Lasers*, International Journal of Optics, 354156 (2012).

[22] Mahboub, M. and Zendagui, T., *Numerical Simulations of Femtosecond Pulse Propagation in Photonic Crystal Fibers, Comparative Study of the S-SSFM and RK4IP*, Applied Mathematical Sciences **6**, 5841 – 5850 (2012).

(23) Richardson, D. J., Nilsson, J. and Clarkson, W. A., *High-power fiber lasers: Current status and future perspectives (Invited)*, J. Opt. Soc. Am. B **27**, B63 (2010).

[24] Pinheiro, T., Garcia, R., Mukai, A., Giacomin, N. T., Guimarães de Souza, R. and Bechara, S. J., *Advances in femtosecond laser technology*, Clin Ophthalmol. **10**, 697–703 (2016). Published online 2016 Apr 19. doi: 10.2147/OPTH.S99741
PMCID: PMC4844446, PMID: 27143847.

[25] Kecik, M. and Schweitzer, C., *Femtosecond laser-assisted cataract surgery: Update and perspectives*, Front. Med. **10**, 3389 (2023).

https://doi.org/10.3389/fmed.2023.1131314.