The development and application of femtosecond laser systems

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Abstract: Some background as well as recent progress in the development of femtosecond lasers are discussed together with a brief outline of a few representative emergent applications in biology and medicine that are underpinned by access to such sources. We also provide a short summary of other contributions in this focus issue.

OCIS codes: (320.7090) Ultrafast lasers; (140.4050) Mode-locked lasers; (170.0170) Medical optics and biotechnology; (170.7160) Ultrafast technology.

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1. Introduction

This brief overview highlights some of the progress that has taken place in the development and application of femtosecond laser systems within the 21-year period since the first reporting of the self-mode-locked (KLM) Ti:sapphire laser [1]. The selected examples represent some of the fundamental and applied science that has been enabled by this breakthrough in combination with other complementary photonics-related developments. Given that this cannot be a comprehensive coverage it should be appreciated that the intention is primarily to illustrate key source developments with some of the typical implementations that have been opened up in biomedical photonics.

1.1 Historical background

The development of a diverse range of laser sources operating in the femtosecond time domain, and more recently in the sub-femtosecond region, has been a consistent theme within the photonics research sector for much of the past two decades. Although the publication of

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the first results of the self-mode-locked Ti:sapphire laser is acknowledged as being a key transition point [2], it is well known that the field of ultrafast optics emerged from pioneering mode locking studies of solid-state and organic dye lasers in the 1960s and early 1970s [3,4]. Whilst practical investigations were on-going, seminal contributions to the underpinning theory were produced by Haus [5,6] and New [7]. Although organic dye solutions provided adequate gain bandwidths in colliding-pulse, passively mode-locked dye lasers to facilitate the generation of sub-100fs optical pulses [8], the poor practicality and low efficiency features of such lasers consigned them mainly to laboratory setups.

Despite their limitations, there were many impressive research-based applications using femtosecond dye lasers in either oscillator [9] or oscillator-amplifier configurations [9]. From the historical perspective, it should also be recognized that in the 1980s, whenever some research emphasis transferred to the study of nonlinear effects in optical fibers, a significant international effort was devoted to femtosecond lasers that operated in the near-infrared spectral region where color-center crystals were used as the gain media [10]. Although sharing the common drawback of a lack of day-to-day practicality, it is important to appreciate how the knowledge base from these early types of femtosecond lasers subsequently shaped the development of the post-1990 categories of the much more practical and versatile ultrashort-pulse sources that ushered in an era where access to, for example, attosecond-duration pulses [11] and stabilized frequency combs [12] has become relatively straight forward.

Within the context of this Focus Issue of Optics Express, there is a justification for mentioning the concept of the soliton color-center laser [10] and the related technique of coupled-cavity (also called additive-pulse) mode locking [13] because the initial observation in 1989 of the self/Kerr-lens mode-locking phenomenon [2] was built upon this foundation. Given the wealth of background published material that exists for femtosecond color-center lasers, it suffices to mention here that access to the large gain bandwidths was promoted by the spectral broadening (through self-phase modulation) that could be induced in the spatially confined core of a monomode optical fiber [13]. Because it was necessary to engage coherently an enlarged comb of longitudinal modes to support laser pulses having durations around 100fs or thereabouts, it was essential that the cavity containing the 'nonlinear element' – often a monomode optical fiber – was matched with interferometric precision to the master cavity of the color-center laser oscillator [10]. Complementarily, the demonstration by Moulton [14] in the mid-1980s of laser quality titanium-doped sapphire crystals represented a timely advance because this offered broad bandwidth solid-state gain media for room temperature laser operation. In fact, it was while implementing the coupled-cavity mode-locking technique with a Ti:sapphire laser in the authors' laboratory in 1989 that it was confirmed that the nonlinearity of the laser crystal itself was sufficient to enable the phase locking of a suitably large number of oscillator modes to constitute the generation of sub-100fs pulses [2]. Thus the simplified "self-mode-locked" or "Kerr-lens mode-locked - KLM" Ti:sapphire laser was born and this was immediately acknowledged as a key building block of a new generation of practical and much more powerful femtosecond lasers. Indeed, with peak optical pulse powers greater than 5 MW becoming available from a KLM Ti:sapphire laser [15] as compared to the dye-laser pulse peak powers in the kW regime there was no longer a requirement to involve oscillator-amplifier combinations for many of the applications envisaged!

Although the simplicity, versatility and high-power performance characteristics of the KLM Ti:sapphire lasers were to be welcomed, the requirement to optimize cavity-design parameters to facilitate the exploitation of the optical Kerr effect [16] represented an operational challenge to the implementation of the KLM technique more generally. Fortunately, this design constraint was alleviated substantially by the availability of semiconductor saturable absorber mirrors (SESAMs) [17] and saturable Bragg reflectors (SBRs) [18] that could be incorporated to initiate and sustain the relevant self-mode-locking processes. With careful design consideration of broadband semiconductor saturable absorber mirrors used in conjunction with double-chirped resonator mirrors, it has been shown that it is

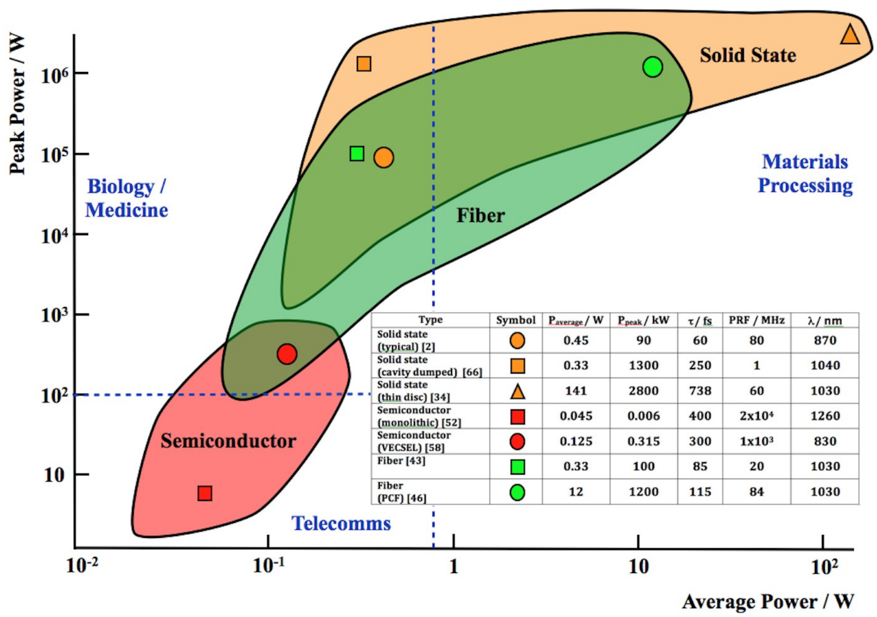
#158848 - $15.00 USD Received 28 Nov 2011; revised 26 Jan 2012; accepted 30 Jan 2012; published 13 Mar 2012

possible to accompany a self-starting KLM laser operation with access to a large proportion of the gain bandwidth to produce pulses as short as 6.5 fs [19]. Over the past two decades, continuing substantial effort has been devoted to the design and development of a wide range of SESAM/SBR options [20] so that, when required, there can be an availability of such devices that have compatibility with most femtosecond laser types and including a growing range of solid-state, semiconductor and fiber lasers. Indeed, developments in this area have underpinned a range of commercial femtosecond laser systems that require the reliable "turn key" pulsed operation enabled by SESAM devices.

2. Source developments

Rather than deal with every aspect of source development that has occurred in the past two decades, it suffices within the context of this paper to highlight a few specific advances that have served to enlarge the applications space for coherent femtosecond optical pulses. This selection is made feasible by identifying some of the new gain media and control techniques that have impacted the operational status and the enhanced versatility of modern femtosecond-laser configurations.

The diversity of ultrashort pulse laser oscillators is illustrated in Fig. 1 that shows a plot of peak power versus average power. Indicative positions are given for the key source technologies, though it must be acknowledged that the performance from each type of source may vary outside these limits particularly when extra-cavity amplification / pulse compression is undertaken. Also placed in the figure are three applications sectors with desirable source parameters. It is interesting to note that oscillators continue to develop rapidly enabling broad coverage of the peak power / average power space to be achieved and opening up new fields of application.



Type	Symbol	$P_{average}$ / W	P_{peak} / kW	τ / fs	PRF / MHz	λ / nm
Solid state (typical) [2]	○	0.45	90	60	80	870
Solid state (cavity dumped) [66]	□	0.33	1300	250	1	1040
Solid state (thin disc) [34]	△	141	2800	738	60	1030
Semiconductor (monolithic) [52]	□	0.045	0.006	400	$2x10^4$	1260
Semiconductor (VECSEL) [58]	○	0.125	0.315	300	$1x10^3$	830
Fiber [43]	□	0.33	100	85	20	1030
Fiber (PCF) [46]	○	12	1200	115	84	1030

Fig. 1. A plot of peak power versus average power for a range of ultrashort pulse laser oscillator technologies. Also included are indicative application areas placed in appropriate regions of laser performance. The inset in the figure shows the performance of the sources indicated.

#158848 - $15.00 USD Received 28 Nov 2011; revised 26 Jan 2012; accepted 30 Jan 2012; published 13 Mar 2012

2.1 Solid-state lasers

Interestingly, while the basic setup for the archetypal KLM Ti:sapphire laser remains a foundation on which many subsequent system developments have been based, a common and desirable feature is that the gain media should lend themselves to diode laser pumping and facilitate access to smooth and broad lasing spectra. In this regard, further progress in the identification of novel gain media resulted in the development of a range of ultrafast solid-state lasers that are compatible with direct laser diode pumping and that operate from the near/mid-infrared spectral range. In particular, Cr^{3+}-doped colquiriites (Cr:LiSAF, Cr:LiCAF, and Cr:LiSGaF) (0.8-0.9 μm) represent currently low-cost alternatives to Ti:sapphire laser technology [21]. Cr^{4+}-doped Mg_2SiO_4 (forsterite) [22] and $Y_3Al_5O_{12}$ (YAG) [23] laser systems are able to support the generation of high-energy sub-50 fs pulses in the 1.3 μm and 1.55 μm regions which are ideal for many biological [24] and datacomms applications [25]. Cr^{2+}-doped chalcogenide materials (Cr:ZnSe, Cr:ZnS) are an attractive option for broadband femtosecond laser developments in the mid-IR (~2.4 μm) [26] which are especially well suited to sensitive and high-resolution molecular spectroscopy [27,28].

Although crystalline gain media with rare-earth ion doping (Nd^{3+}, Yb^{3+}, Er^{3+}, Tm^{3+}, Ho^{3+}) do not offer such broadband gain spectra as their transition-metal counterparts, the distinctively attractive features of this class of laser include low operational threshold, high efficiency and an ability to be configured into extremely compact configurations. Indeed, pulse repetition frequencies up to 160 GHz and 100 GHz for picosecond-pulse generation have been demonstrated for Nd:YVO_4 [29] and Er:glass [30] mode-locked oscillators operating around 1 μm and 1.5 μm, respectively. More recently, low-cost, efficient and compact femtosecond laser systems become widely available around 1 μm due to the introduction a range of Yb^{3+}-doped gain media assisted by the timely and rapid progress in the production of InGaAs-based pump laser diodes. Currently, ytterbium-based femtosecond lasers produce pulses as short as 35 fs (Yb:YCOB) [31] and operate with an optical-to-optical efficiency that can reach 50% [32]. When deployed in a thin-disk laser configuration that offers efficient heat removal capabilities [33], Yb-based lasers can generate average powers up to 141 W at a pulse duration of 738 fs (Yb:Lu_2O_3) [34]. It should be noted that higher average powers are only available currently from more complex oscillator-amplifier systems such as a fiber laser with a chirped-pulse-amplifier (830 W, 640 fs) [35] or using a slab amplifier (400 W, 680 fs) [36]. It can therefore be expected that Yb-laser systems that produce sufficient peak powers directly to enable efficient nonlinear frequency conversion in processes such as high harmonic generation or octave-spanning supercontinuum generation in a photonic crystal fiber [37] will facilitate the additional demands of an ever-growing applications sector. This will be especially true where physical compactness, low cost and robustness represent the desired attributes.

This developmental progress is ongoing in ultrafast solid-state lasers where, for example, quantum-dot-based SESAMs [38] that are characterized by faster response times and lower saturation fluencies than their quantum-well counterparts can facilitate efficient mode locking at high repetition rates. Another direction in ultrafast laser technology has been facilitated by the introduction of carbon nanotubes [39] and graphene [40] as saturable absorbers. These offer the key advantages of ultrabroad operating range from the near- to-mid infrared (especially in case of grapheme [41]), ultrafast recovery time [42] with fabrication techniques that do not require the use of costly clean room facilities. Moreover, such nonlinear media can be deposited onto any intracavity element thereby making the design of solid-state lasers ever more practical and physically compact.

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2.2 Fiber lasers

The outstanding research undertaken on fiber lasers and fiber amplifiers in the 1980s provided a robust scientific and technological base for the subsequent development of a wide range of fiber-based ultrafast sources that continue to find increased applicability together with attractive user compatibility. Whilst in their earliest embodiments femtosecond fiber lasers often struggled to attain the levels of pulse energy and peak power associated with solid-state mode-locked lasers, more recently developed options have revealed the operational potential of these systems. For instance, in 2005 Buckley et al demonstrated a fiber laser that produced sub-100 fs pulses having a pulse energy of 14nJ and peak power at the 100 kW level [43]. More complex, but still compact, source arrangements have also yielded exceptionally short pulse durations of 8 fs [44], high repetition frequencies (10 GHz) [45] and through the possibility to engineer the fiber gain medium, MW level peak power (>10 W average power) devices [46]. A further interesting feature of fiber-based systems is their potential to deliver new mode locking schemes such as the recently demonstrated soliton-similariton technique through careful dispersion management [47]. Femtosecond fiber lasers have now matured into an applicable technology that is being deployed, for example, in metrology [48], bio-science [49] and materials processing [50].

Generally, femtosecond fiber lasers are based on transitions from rare-earth ions operating in the near-infrared and are often based on Yb-, Er- or Tm-doped gain media. Their relatively high peak powers are well matched to nonlinear optical conversion and indeed a range of commercial products are now available which give comparable performance to Ti:sapphire oscillators (e.g. IMRA Femtolite FX-100 or PolarOnyx Mercury Lasers.) The output from fiber lasers is also well matched to the photonic crystal fibers that are often used to generate supercontinuum radiation from which a range of all-fiber-supercontinuum sources have been developed [51]. This versatility of performance when combined with their inherent practicality makes modern femtosecond fiber lasers a very important enlargement of the ultrafast source portfolio that is available to scientists and technologists for applications that now span a broad range of disciplines.

2.3 Semiconductor lasers

Although it would seem attractive to have stand-alone, electrically-pumped, semiconductor diode lasers as user-compatible sources of femtosecond optical pulses having comparable characteristics to those produced by solid-state or fiber lasers, but progress to date toward this objective has been rather limited. While gain media based on quantum-dot semiconductor structures do offer some access to enlarged bandwidths and the generation of sub-picosecond optical pulses at 20GHz repetition rates has been reported [52] there are still questions as to the generation of truly femtosecond-duration coherent pulses from a laser of this type. An interesting class of devices based on super-radiant emission from quantum-dot structures has also been recently reported [53]. Whilst research in this area remains ongoing such technologies hold out the potential for femtosecond semiconductor devices with pulse repetition frequencies in the low MHz region and thus the high peak powers more often associated with solid-state laser systems [54].

The alternative schemes involving optical pumping with extended external cavities with vertical-cavity, surface-emitting semiconductor gain chips [VECSELs] [55] represent a much more feasible approach for the device options that are available at present. Using this arrangement pulse durations as short as 60 fs have been achieved [56] and recent experimental demonstrations have yielded pulse durations in the 800fs regime at average power levels exceeding 1W and around 400 fs at an average power just below 150 mW have been reported for a VECSEL operated at a central wavelength of 970nm [57] and peak powers in excess of 300 W from a GHz PRF device [58]. It is noteworthy that in this instance both the saturable absorber and gain elements were quantum-dot-based and the achievement of an average

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power in the 1W regime is a very encouraging result for an attractively compact design of femtosecond laser.

2.4 The control of femtosecond lasers

One clear objective in the refinement of femtosecond laser designs is to produce sources that are versatile and adaptable to permit the user to choose the specific operating condition which best suits a specific application. In many cases there have been great advances in the extra-cavity control of the output from ultrafast lasers allowing, for example, pulses with specifically controlled wavelength / profiles to be produced through the use of liquid crystal phase modulators [59] or deformable mirrors [60]. Whilst such approaches offer excellent performance, perhaps the simplest approach to control is to influence the intracavity behavior of the laser thereby permitting the direct control of the oscillator output. Recent demonstrations with the authors' laboratory has shown that intracavity deformable mirrors may also be used to control several aspects of laser behavior including phase profiles and pulse durations [61].

A further goal relates to direct control of the laser through the manipulation of other components within the laser cavity. One component that has the clear potential to provide some element of control is the SESAM/SBR that is often used to initiate and sustain mode locking. In these devices, the quantum-confined structures can be externally manipulated through both optical and electronic means to provide some level of active control over a passive structure. One example is the use of an external laser diode beam to provide direct and rapid (~75 μs) heating of an SBR coincident with the intracavity laser spot to provide controllable switching between CW and mode-locked operation [62]. Electronic control of saturable mirrors in solid-state lasers has also been demonstrated and SESAMs which offer controllable modulation depths [63] and tunable pulse durations from 17.4 ps to 6.4 ps [64] and these serve to illustrate the promise of this approach for producing easily controlled output from ultrafast lasers.

Control of the pulse repetition frequency (PRF) of femtosecond lasers remains a challenge as the PRF is generally set by the round-trip time of a single pulse circulating within the cavity. Some progress has been made in this area by the use of subsidiary Fabry-Perot (F-P) cavities that are length matched to harmonics of the primary cavity to provide PRF multiplication. In this regard, Chen et al have used a dispersion-compensated F-P cavity to multiply the repetition frequency of a femtosecond Er-fiber laser from 200 MHz to 2 GHz [65]. A complementary approach that has been used to obtain PRF-tuning in the kHz to MHz regime is through cavity dumping that can be used to obtain MW peak powers directly from laser oscillators. Killi et al have shown that a diode-pumped Yb:glass laser can produce 1.5 MW peak power pulses at a pulse repetition frequency of 500 kHz [66].

3. Some representative applications in biology and medicine

The demonstration of a wide range of user-compatible ultrafast lasers has been pivotal to their deployments in a wide and varied range of applications. In this section the role that ultrafast lasers have played in assisting the development of cross-disciplinary research and related applications in biomedicine will be discussed. This is considered to be a good exemplar topic because it highlights the impact that ultrafast sources can have from a fundamental research level through to novel medical procedures that are gaining more widespread acceptance. Before discussing this, however, it should be re-iterated that this represents only a very small part of the applications space for such systems that have included fundamental investigations through to translations into fields including, but not limited to, chemistry [67], metrology [68], materials science [69], tele/data-communications [70] and energy research [71].

#158848 - $15.00 USD Received 28 Nov 2011; revised 26 Jan 2012; accepted 30 Jan 2012; published 13 Mar 2012

3.1 Nonlinear spectroscopic and fluorescence techniques

A very well known and trailblazing use of ultrafast lasers relates to two-photon microscopy [72]. In this process, the focused near-infrared laser radiation is used to excite fluorescence from a region of interest. By contrast with a single-photon excitation at a shorter wavelength, in this case the excited region is defined by the three-dimensional positioning of the focal zone due to the intensity dependence of the nonlinear process, thereby allowing z-sectioning to be performed by adjusting the focal position without the need for a more complex confocal arrangement. By using excitation in the near-infrared where biological transmission is maximized, such techniques provide scope for in-depth tissue imaging and, when the average power is kept low, subject the sample to reduced heating compared to other approaches. Whilst in its early days this technique was confined within a laboratory, more recent developments in endoscopy are beginning to show clinical promise in deep tissue imaging [73] and in *in vivo* brain imaging [74].

In recognizing that photonics-based techniques can offer complementarity with modalities such as MRI, research in stimulated Raman scattering (SRS) in particular, demonstrates clearly where femtosecond lasers can play a key role. Specifically, SRS microscopy has been developed to the point where video-rate imaging can begin to be an attractive asset in practical medical diagnostics. Indeed, building on the pioneering research being led by Xie's group in Harvard University [75] there have emerged several striking examples of highly specific and label-free molecular imaging where advantage is taken of an amplitude-shaping concept within SRS by using 'spectrally-tailored excitation' (or STE) in a scheme designated as STE-SRS [76]. This is made possible by combining broadband (femtosecond) and narrower band (picosecond) laser excitations to achieve STE-SRS microscopy with exceptional specificity and sensitivity in, for instance, the 3-D spectral imaging of protein [76].

3.2 Opthalmology

It is quite fascinating that lasers have retained a high profile throughout their history in various applications within ophthalmology. This is true also for the subset of femtosecond lasers for implementations ranging from corneal surgery [77] through to possibilities relating to photo-therapies for dealing with cataracts [78].

To be specific, the commercialized IntraLase procedure [79] that evolved from initial fundamental and pioneering research undertaken at the University of Michigan [77] involves the use of femtosecond laser pulses that are focused to a point within the cornea with the creation of thousands of microscopic bubbles. The attraction of the IntraLase procedure is that an eye surgeon can design and control with high precision the physical aspects of a corneal flap such as its thickness, its circumference, and the angle of its edges, such that the protective flap can be tailored to an individual eye. The flap is then lifted to provide access to an excimer laser beam for photorefractive correction and the procedure is complete when the 'hinged' flap is securely repositioned on its beveled edge. This type of procedure lends itself to rapid healing and recovery and is well suited to patients having some corneal parameters (eg steep, flat or thin corneas) for whom surgery performed with a standard micro-keratome would be less appropriate. More recently, a procedure has been developed that relies entirely on a femtosecond laser system (femtosecond lenticular extraction – FLEx) based on a commercial instrument that removes the need for an excimer laser in the process [80].

The prospects for a non-invasive therapy involving femtosecond laser pulses in a two-photon-based procedure for the reversal of cataractous effects in the lens of the eye appear to be quite exciting. In this case, an induced photochemical bleaching of the accumulated yellow chromophores is being researched as a means of recovering at least some of the transparency within the lens of the eye [81]. In these experiments to date involving human donor eyes, the raster-scanned, regeneratively-amplified femtosecond pulses from a Ti-sapphire laser (800 nm, 200-300 fs at 30-275 kHz pulse repetition frequency) have been shown to produce some degree of rejuvenation of the optical lens and so this approach if successful could have an

#158848 - $15.00 USD Received 28 Nov 2011; revised 26 Jan 2012; accepted 30 Jan 2012; published 13 Mar 2012

enormous potential in healthcare as a cost effective means of addressing the compromised vision that arises from cataracts.

Interestingly, another two-photon process involving the photosensitization of singlet oxygen production can also be exploited within cardiac tissue engineering. In a recently reported study [82], femtosecond pulses from a regeneratively-amplified Ti:sapphire laser were raster scanned over riboflavin-treated tissue to induce collagen cross linking and an increase in tissue stiffness was achieved without compromising cell viability in the region of exposure. This photonics-assisted route towards the generation of transplantable tissue surrogates having the necessary mechanical stability for cardiac surgery is therefore timely both as a potential therapy in its own right and as a means to address the recognized shortage of donor organs for transplantation [82].

3.3. Femtosecond-enabled photoporation and transfection

On a cellular level rather than on the tissue scale just mentioned, femtosecond-laser-based photoporation that facilitates the optical transfection [83] or injection of other materials [84] of biological cells is becoming a more widely used methodology in cell biology. This approach has the attraction that it offers cell specificity with high transfection efficiency as well as acceptable post-transfection cell viability [85]. Although the deployment of femtosecond lasers is not a prerequisite in photoporation techniques, the exposure of cells to high intensity ultrashort optical pulses has been shown to enhance localized permeability and there is the added attraction that confocal and multi-photon optical imaging can be incorporated as complementary features within the procedural setups. In simple terms, a beam from a femtosecond laser (commonly a Ti:sapphire laser) when focused on a cell membrane induces an increased permeability through a multi-photon poration process [86] such that foreign DNA in a surrounding medium, for example, can diffuse into the cell before the membrane self-heals. If this foreign DNA is transcribed and translated into protein then optical transfection is said to have occurred in the cell but where another membrane-impermeable macromolecule or object is introduced then photoporation has taken place.

Within the authors' labs, a range of further experiments have been undertaken in this field including the tailoring of the laser beam to have Bessel-like propagation characteristics. Such a development presents a significant practical refinement because the natural movement of the membrane of living cells could be better tolerated in contrast to the criticality of the focal plane associated with a Gaussian beam, and indeed, the usual tight focusing limitations of multi-photon techniques may be eased significantly [87]. Also, by exploiting beam manipulations using spatial light modulators it has been possible to demonstrate much more spatially versatile poration and transfection strategies involving single cells or cell clusters that make this technique increasingly user-compatible to the biology and medical research communities [88]. An interesting refinement of the technique that demonstrates the flexibility offered by ultrashort pulse lasers is to use the laser operating in a CW mode to facilitate optical tweezing of a cell into a chamber control the reagent of interest. Switching the laser to femtosecond-pulse operation then provides optical poration of the cell. The laser, operating CW can then be used to move the treated cell to another region for analysis without further interaction [89].

4. Developments described in this focus issue

In this focus issue of Optics Express we have welcomed contributions that exemplify some of the recent developments in ultrafast optical sources. Our focus has been on new source technologies as well as novel combinations of source modules and control techniques. We believe that these devices will enable new applications and demonstrate that ultrafast sources have moved away from the conventional paradigm of a totally passive device. We are confident that the next generation of ultrafast sources will have properties that can be more

#158848 - $15.00 USD Received 28 Nov 2011; revised 26 Jan 2012; accepted 30 Jan 2012; published 13 Mar 2012

readily specified for particular application-related requirements rather than matching applications that, to a large part, are dictated by the output characteristics of particular lasers.

Harth *et al*. [90] demonstrate how a controllable pulse duration may be obtained by modulation of the output from a CW semiconductor source. They also show that very impressive average output powers may be obtained by combining a semiconductor seed module with a solid-state amplifier. By contrast, the work of Kienle *et al*. [91] shows that the pulsed output from a semiconductor laser may be combined with fiber amplifier modules and an optical parametric oscillator to produce a high power source of ultrashort pulses that can be tuned near-continuously from 651 nm to 2851 nm. Zhang *et al.* [92] present results that show that tunable repetition rate, high energy, pulses (50 kHz to 1.7 MHz) with sub-60fs durations can be obtained from extremely compact amplifier configurations.

The work reported by Metzger *et al*. [93], Olle *et al*. [94], and Wilcox *et al*. [95] concentrates on semiconductor ultrashort-pulse laser technology. By combining established VECSEL technology with harmonic mode locking techniques, Wilcox and associates [95] demonstrate that it is possible to obtain very high repetition frequencies (175 GHz) with reasonable average output powers while eliminating Q-switching instabilities. Olle and colleagues [94] used novel methods to form pulses within a semiconductor laser to show that it is possible to obtain pulses with reasonably high peak powers directly from a semiconductor laser operating in the visible part of spectrum. Metzger *et al.* [93] show that with a careful algorithm design it is possible to obtain continuous pulse duration tuning from 500 fs to 2.2 ps directly from a very simple two-section semiconductor laser. This also provided a platform for control algorithms that automate the setup process to offer a very flexible interface and remote control tool for ultrafast lasers.

Leindecker *et al.* [96] describe how a femtosecond fiber laser operating near 2 µm can be used in combination with a degenerate OPO based on an orientation patterned GaAs nonlinear crystal to produce extremely broadband spectra in the infrared that extend over 3.5 µm centered at 4.1 µm. Such radiation has the potential for wide scale applications in atmospheric sensing and spectroscopy. In their paper, Baer *et al.* [97] discuss the current state of the art in, and potential for thin disk femtosecond lasers. These laser systems have the potential to deliver pulses with both extremely high average and peak power thus paving the way for new applications in, for example, materials processing. Finally, Savitski *et al.* [98] demonstrate a proof-of-principle experiment to show how the control of the pulse duration regime can be used to obtain different responses within in application. The use of the same laser to provide optical trapping and on-demand two-photon luminescence from a laser with an optically controlled SESAM represents another aspect of practical source refinement.

5. Concluding remarks

In this paper we have reviewed briefly some state-of-the-art developments in femtosecond optical sources that are based on solid-state, semiconductor and fiber lasers. Whilst not a comprehensive overview, this serves to show that in the 21 years since the demonstration of the first self-mode-locked (KLM) Ti:sapphire laser, the overall field involving practical ultrafast lasers has continued to develop strongly and there now exists a very diverse and versatile range of ultrafast source options.

More recently, a range of exciting developments in the control of femtosecond lasers has produced sources that can deliver a range of variable outputs under close user control. In our opinion, the conditions are favorable for further system refinements such that new generations of ultrafast lasers may be more readily optimized by non-specialist users to deliver performance characteristics that will be specifically tailored to application sectors. We believe that such lasers may be designed to be operated in several different temporal configurations to enhance functionality while reducing their overall cost and complexity. Indeed, as ultrafast sources continue to develop within an expanding applications space it can be expected that further major contributions will emerge from fundamental science through to a widening provision of photo-therapy and non-invasive surgery in clinical environments. The next

#158848 - $15.00 USD Received 28 Nov 2011; revised 26 Jan 2012; accepted 30 Jan 2012; published 13 Mar 2012

generation of femtosecond lasers is likely to continue to impact a broad range of science and technology that will rely on user-specified outputs rather than the output from the laser being the determining factor for the application. It is indeed impressive that even if the emerging application requires pulse shaping with zeptosecond precision, an already demonstrated technique confirms that this is feasible [99].

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