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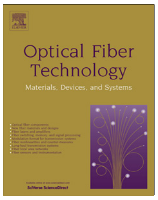

Invited Papers

Ultrafast fibre laser sources: Examples of recent developments

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ABSTRACT

We summarise a number of recent experimental developments in the field of ultrafast compact all-fibre lasers, including: ionically-doped coloured glass saturable absorbers; Tm:fibre lasers utilising graphene around 2 μm; alternative layered materials including MoS_2; passively synchronised, coupled-cavity ultrafast dual-wavelength fibre lasers; and schemes for the generation of high repetition rate femtosecond pulses based on phase modulation, and spectral masking of CW radiation. The breadth of light sources covered in this review highlights the diversity of approaches in ongoing research in the field of ultrafast fibre optics.

1. Introduction

Optical fibres provide a convenient platform for the development and monolithic integration of a laser system; consequently, fibre technologies have significantly impacted upon the field of laser engineering, and hold a dominant position in the commercial laser market. Ultrafast fibre lasers – light sources that emit bursts of radiation on time-scales of the order of, or less than, several tens of picoseconds – have been widely studied, with emphasis focussing on the nature of the gain media and the modulation mechanisms and dynamics that promote short-pulse generation. The near-infrared (~1.0–2.0 μm, near-IR) region is now well addressed by silica glass fibre amplifiers, including active media doped with ytterbium (Yb); bismuth (Bi); erbium (Er) and thulium (Tm), allowing almost continuous coverage of this wavelength region [1–5]. Raman gain in silica optical fibres has also been shown to support mode-locked operation [6,7], and can thus be adopted in regions not covered by rare-earth doped fibre media, although this approach often leads to excess system noise [6,8]. Modulation schemes, both passive and active, as well as dispersion and nonlinearity engineering of the laser cavity, permit modes of pulsed operation from the femtosecond scale, with bandwidth-limited durations, to several nanoseconds, with predominantly linear chirp and high energy, that can be recompressed after stages of amplification in master-oscillator, power fibre-amplifier (MOPFA) architectures.

Although short-pulse fibre laser development is entering its fourth decade the field remains fertile, benefitting from disruptive technological advances in parallel scientific disciplines such as, materials science and engineering. Here, we summarise a selection of recent results from the continuing research effort focussed on the development of pulsed fibre laser geometries. In particular, we consider: the use of ionically-doped coloured glass as saturable absorbers to mode-lock fibre lasers; the current status of mode-locked lasers operating in the 2 μm spectral range, utilising Tm-doped fibre amplifier technology; early reports of Molybdenum Disulfide (MoS_2) as a novel two-dimensional (2D) ultrafast optical switch for short pulse generation; passively coupled-cavity mode-locked oscillators, that provide a convenient monolithic source of synchronous dual-wavelength near-IR generation; and high-repetition rate ultrashort pulse sources based on fibre amplification and spectral masking of phase-modulated signals from continuous-wave (CW) diode seed lasers.

2. Ionically-doped coloured glass for mode-locking fibre lasers

Saturable absorbers (SAs) are optical devices that exhibit an intensity dependent transmission: asborbing lower intensity light more strongly than higher intensity light, and thus promoting pulsed operation. Such nonlinear absorbers are widely deployed in mode-locked lasers to initiate self-starting and stable short-pulse operation [9,10]. Key parameters for a saturable absorber are:

i *Absorption wavelength* – defining its region of operation that has to coincide with the gain bandwidth of the corresponding lasing medium.
ii *Recovery time* – setting a limit on the switching speed of the device that can affect the duration of the achievable pulses.
iii *Saturation intensity* – the light intensity necessary to saturate the absorption of the device; and should be equivalent to the intra-cavity intensities reached in the laser system.
iv *Modulation depth* – the maximum change of absorption.

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v *Damage threshold* – the maximum light intensity that a device can tolerate before catastrophic damage occurs; and must be higher than the intra-cavity intensities reached in the laser system.

Materials possessing the aforementioned key properties are of significant interest, and thus intensively studied. To date, a number of SAs, with parameters specific for use in fibre lasers, have been investigated and employed to achieve reliable mode-locked performance including, semiconductor-based absorbers [11]; carbon nanotubes (CNTs) [12,13]; and more recently, graphene [12,14–16]. Although these technologies offer many advantages, such as broadband and reliable operation, they are not without limitations, namely, relatively high production costs and low damage thresholds. In contrast, ionically-doped coloured glasses [17–19] used as a saturable absorber in fibre lasers may solve these issues, providing a more thermally robust solution allowing potential for higher achievable output powers, supported by the performance of mode-locked solid-state lasers based on this approach [18,20–28], as well as offering the potential for broadband wavelength operation.

Using a Z-scan technique we measured the nonlinear transmission of a low-cost, commercially available ionically-doped coloured glass filter (Schott RG1000). We demonstrated that this device offered sufficient intensity contrast (or modulation depth) to promote mode-locking of a low power Yb-doped fibre laser. This proof-of-concept demonstration of mode-locking a fibre laser, importantly, where the requirements on the absorber differ significantly to solid-state counterparts due to differences in the gain dynamics and the magnitude of the nonlinearity and dispersion, could open the possibility of achieving elevated output energies from all-fibre, passively mode-locked pulsed lasers.

2.1. Z-scan characterisation of nonlinear absorption

The nonlinear absorption of the ionically-doped coloured glass (Schott RG 1000) was characterised using an open-aperture Z-scan measurement. The pump source, providing picosecond pulses centred at 1063 nm, was a commercial Yb-doped mode-locked fibre laser (Fianium Inc.), followed by an Yb-doped fibre amplifier (IPG Photonics). The output was split using a 93%:7% fused fibre coupler [see Fig. 1(a)]. The smaller fraction of pump light was detected using an optical power meter, forming a reference arm. The 93% was coupled into a small-core, high numerical aperture fibre (Nufern UHNA3), the output of which was imaged onto the sample by a pair of 12 mm focal length lenses.

A 2 × 2 mm square piece of the the Schott glass, with a thickness of 240 μm, was placed in the sample arm and moved through the focal point by an automated translation stage. Light transmitted through the sample was collected by a third lens and detected by a second photodiode. In order to fully saturate the sample's absorption, the pump source was amplified to 0.5 W, producing 8.9 ps pulses at 50 MHz repetition rate. The corresponding maximum intensity at focus was approximately 17 GW cm^{-2}.

The power on the sample and reference arms were recorded, moving the sample incrementally through the focal plane, integrated with the precision stepper motor. This approach allowed rapid, accurate and reproducible acquisition of multiple datasets. A dataset from a representative scan, at a fixed transverse position on the ionically-doped glass sample, is shown in Fig. 1(b). The red curve is a fit to the experimental data based on the slow saturable absorption model [30,31]. The relaxation time of the ionically-doped glass was estimated to be on the order of tens of picoseconds, based on literature values from Chen et al. [17] and Yumashev et al. [32]. This is much longer than the duration of the pump pulse and so the use of the slow saturable absorption model is valid. Accordingly, the saturation fluence is 3.0 mJ cm^{-2}. The $1/e$ value of 8.8 mJ cm^{-2} is highlighted with a solid black line. The modulation depth, which is the contrast between the fully absorbing and fully saturated state of the device, is highlighted with a solid black arrow and is ~3% for the 240 μm thick ionically-doped glass sample used in this measurement.

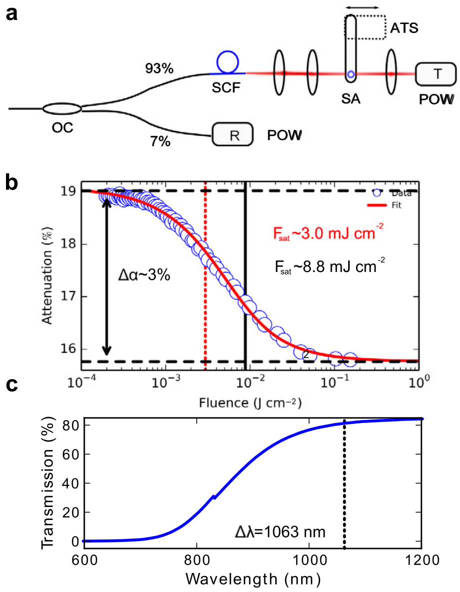

Fig. 1. (a) Schematic of the Z-scan setup. OC, output coupler; SCF, small-core fibre; R, reference; POW, optical power meter; SA, scanning arm; ATS, automated translation-stage; T, transmitted signal. (b) Representative dataset from open-aperture Z-scan measurement (after Ref. [29]). (c) Linear transmission spectrum of the ionically-doped glass sample. The vertical black line denotes the wavelength of the pump source used in the open aperture Z-scan measurements.

The density of the active ions was not homogeneous across the test sample. The sample inhomogeneity was mapped by raster scanning the sample. The nonlinear saturation curve was measured at 0.5 mm spatial increments in the XY plain, across the 2 × 2 mm sample, with a uniform thickness of 240 μm. Fig. 2 plots the variation in the modulation depth and saturation fluence based on the resulting data. The resolution (or minimal spatial increment) was limited by the achievable spot size through the Z-scan system optics. As shown in Fig. 2, the modulation depth and the corresponding saturation fluence of the investigated sample varies significantly from 0% to 3% and 0 to 8.8 mJ cm^{-2}, respectively. It is clear that the density of the absorbing ions, present in the glass host, is non-uniform. Improved doping control would lead to a higher degree of sample homogeneity and enhanced device performance.

To characterise the linear absorption, the spectrally dependent transmission was measured using a commercial spectrophotometer, plotted in Fig. 1(c). The dashed line shows the region where nonlinear saturation measurements were performed using the open-aperture Z-scan technique. A 240 μm thick sample has a corresponding linear transmission of 80%, at 1063 nm. Based on the absorption curves shown in Refs. [28,33], it indicates that the ionic doping of this coloured glass is likely to be CuInSSe, although the exact composition data is not available from the manufacturer.

2.2. All-fibre soliton-laser

Although ionically-doped coloured glass filters have been widely employed to mode-lock solid-state bulk lasers, only recently have they been demonstrated in the context of fibre systems [29], where the demands on the pulse-shaping action of the

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