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All-fiber wavelength-tunable picosecond nonlinear reflectivity measurement setup for characterization of semiconductor saturable absorber mirrors

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ABSTRACT

Semiconductor saturable absorber mirror (SESAM) is the key component for many passively mode-locked ultrafast laser sources. Particular set of nonlinear parameters is required to achieve self-starting mode-locking or avoid undesirable q-switch mode-locking for the ultra-short pulse laser. In this paper, we introduce a novel all-fiber wavelength-tunable picosecond pulse duration setup for the measurement of nonlinear properties of saturable absorber mirrors at around 1 μm center wavelength. The main advantage of an all-fiber configuration is the simplicity of measuring the fiber-integrated or fiber-pigtailed saturable absorbers. A tunable picosecond fiber laser enables to investigate the nonlinear parameters at different wavelengths in ultrafast regime. To verify the capability of the setup, nonlinear parameters for different SESAMs with low and high modulation depth were measured. In the operating wavelength range 1020–1074 nm, <1% absolute nonlinear reflectivity accuracy was demonstrated. Achieved fluence range was from 100 nJ/cm^2 to 2 mJ/cm^2 with corresponding intensity from 10 kW/cm^2 to 300 MW/cm^2.

1. Introduction

Ultrashort pulse laser is an important research tool adapted in many scientific laboratories as well as industrial settings [1–3]. Mode-locking technique is exclusively applied to achieve ultrashort (<10 ps) pulse duration from the lasers. The peak-power-dependent transmission element with a sufficiently fast response can lock the longitudinal modes of the laser's resonator, which enables ultrashort pulse generation [4–7]. There are two main methods to obtain mode-locking operation – active and passive. Active technique usually involves an electro-optic or acousto-optic device which periodically modulates the losses of the resonator. By adjusting the frequency of the modulator close to the pulse repetition rate of the resonator it is possible to attenuate the trailing edges of the pulse after each round trip and shorten the pulse duration [8]. But when the pulse duration becomes sufficiently short, other limiting effects become dominant (e.g. chromatic dispersion or limited gain bandwidth) which restricts further pulse shortening [8]. Therefore, with this technique it is not possible to reach the pulse duration shorter then few picoseconds without an external pulse compression [9]. Also, the stable synchronization of actively mode-locked laser is very tricky to achieve [10]. Passive mode-locking utilizes saturable absorber element which has a peak-intensity dependent loss and no external modulator signal is required. With this technique it is possible to get the shortest [11], highest energy pulses [12] and highest average power [13] directly from the laser oscillator. Simplicity, robustness and low-noise performance of passive saturable absorber are the reasons that currently the absolute majority of commercial ultrafast lasers are built using passive mode-locking.

When initially introduced in 1966 [14] passive mode-locking technique suffered from lack of proper materials and technology to fabricate saturable absorber with required properties. Saturable absorbers based on organic dyes were employed in ultrafast lasers for more than 20 years. But a passively mode-locked laser with an expensive, toxic and maintenance intensive absorber was as difficult to work with as an actively mode-locked laser. In 1980s the progress in the high-brightness pump diodes caused these pump sources to replace inefficient, bulky and expensive flash-lamps. The effort to have a robust and simple passive component in a laser resonator became even more important to further simplify and reduce the cost of the diode-pumped ultrafast lasers. The

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breakthrough came with the invention of SESAM [15] and Kerr-lens mode-locking (KLM) [16].

KLM is a technique based on an artificial saturable absorber when intensity of the short pulse in a laser gain medium is so high that it induces the self-focusing of a laser beam and by incorporating an aperture it is possible to modulate the losses of the resonator. This nonlinear optical self-focusing process is known as Kerr effect. Although, the KLM technique is adopted in many scientific laboratories and suitable to generate shortest broadly tunable ultra-short pulses [17], it has some major shortcomings. Firstly, Kerr mode-locking is usually realised near the stability boundary of a resonator and therefore is quite sensitive to environmental changes (temperature, mechanical perturbations). Secondly, with KLM it is difficult to achieve a reliable self-starting mode-locking and often some additional starting mechanism is required [18].

Reliable self-starting passive mode-locking was achieved by introducing SESAM [4–6,15]. This type of absorbers is widely used for more than 25 years [19]. The improved performance of the passively mode-locked solid-state lasers and further development of the SESAM devices expanded the application area of ultrafast lasers allowing them to be used not only in a scientific environment, but also in the industry. SESAM is made of different layers of semiconductor material stacked with sub-nanometer accuracy. By controlling the growth parameters of the semiconductor material and properly choosing the cavity design it is possible to tune all the relevant parameters (e.g. recovery time, saturation fluence, modulation depth, absorption wavelength) of a SESAM [6,20,21]. These parameters are particularly important to satisfy the stability and self-starting conditions of solid-state laser mode-locking [22].

Typically an absorbing part of a SESAM device is made of a very thin (<10 nm) semiconductor layer embedded in another semiconductor. Such structure is called a quantum well (QW) [23]. This thin layer is essential for the nonlinear optical properties of the SESAM. A semiconductor QW is a two dimensional structure in which quantum confinement plays a major role by enhancing effect of saturation of the absorption [24]. It is also possible to use other types of the low-dimensional structures instead of a semiconductor QWs. Although there are a lot of promising new nano-materials with good nonlinear optical properties (e.g. quantum dot absorbers [25], carbon nanotubes [26] and graphene [27]), a lot of work remains to be done to fabricate reliable and reproducible saturable absorbers of this type. In contrast, fabrication of SESAM devices with the molecular beam epitaxy (MBE) is highly precise and robust procedure [6].

Due to the rapid development of optical communication industry, especially of optical fiber and semiconductor laser diode technologies, fiber lasers emerged and began to expand into the field of ultrashort pulse lasers. These lasers have a number of desired qualities: ultrafast fiber lasers can be made environmentally stable, maintenance free, low cost and compact size [28]. Moreover, a small quantum defect in the Yb-doped fiber leads to high power efficiency and reduced thermal effects in the high output power lasers. Recent advances in Yb doped ultrafast fiber lasers also benefitted from SESAM technology [5]. Compared to Kerr type mode-locking it has similar advantages as in solid state lasers: easy self-starting operation, flexibility of obtainable laser parameters (pulse duration, power etc.) and excellent environmental stability. The major obstacle remains degradation of semiconductor material in the SESAM's structure due to high intensity of the incident radiation (hundreds MW/cm^2 [29]. This problem is more severe in fiber lasers than in solid state lasers [30]. First, the nonlinearity which is necessary to achieve mode-locking in typical ultrashort pulse fiber lasers is of the order of ~10% compared to ~1% in solid state lasers [31]. This put constrains on the design of the SESAM and implies that non-saturable losses are also quite high. Second, material degradation of the SESAM in solid state laser is quite easily mitigated by moving an incident light spot (which is typically ten to hundred microns in diameter) to a different location on the SESAM chip. This in principal can be done in fiber lasers too. However the concept of monolithic fiber laser with a robust no-alignment operation is compromised when there is a need for movable SESAM.

To complicate the problem further, there seems to be almost no scientific activity in researching for long lifetime SESAM architectures suitable for fiber lasers. Therefore in order to design and manufacture the SESAMs with required nonlinear properties comprehensive characterization techniques must be developed for experimental evaluation of the grown structures. In this work we set to develop set-up for spectral characterization of nonlinear properties of SESAMs and other saturable absorbers at around 1um wavelength, corresponding to usual window of operation of Yb-doped fiber lasers.

2. Methodology

To reveal the most important parameters of the saturable absorber, nonlinear reflectivity measurement technique, where absorber reflectivity is measured as a function of incident optical intensity is often used [32]. Two regimes of saturation of absorption can be distinguished. First, when incident pulse duration is much longer than carrier relaxation time in the SESAM structure (typically ~1–10 ps for mode-locking), saturation process can be well described as a function of intensity (measured in W/cm^2). However such regime is rarely achieved in practical ultrafast lasers. Second, when incident pulse duration is much shorter compared to the carrier relaxation time, is well described in terms on incident energy fluence [33] (measured in J/cm^2). In this case the saturation level does not depend on the pulse duration as the absorber remains saturated long time after the ultrashort pulse has passed. Using this approximation it is possible to define saturation fluence (F_{sat}), modulation depth (ΔR), low intensity reflectivity (R_0), saturated reflectivity R_{sat} and nonsaturable losses (ΔR_{ns}). F_{sat} is the pulse fluence at which reflectivity of the absorber increases from the initial low intensity reflectivity R_0 to 1/e level of the fully saturated nonlinear reflectivity R_{sat}. The modulation depth ΔR is the nonlinear change of the reflectivity. The nonsaturable losses ΔR_{ns} is the difference between the 100% reflectivity and the reflectivity R_{sat}. When measuring at the higher fluences, it is often necessary to include the inverse absorption coefficient F_2. The F_2 depends on two-photon absorption (TPA) and other nonlinear effects in the absorber material. For SESAMs, the chosen design may also affect an inverse absorption coefficient [34]. Fig. 1 depicts all the most important nonlinear parameters of typical saturable absorber. Logarithmic scale for the incident energy fluence is used as the nonlinear saturation takes place in a large range of fluence values (~3 orders of magnitude).

Generally, for a flat-top-shaped beam profile, the non-linear reflectivity of saturable absorber with respect to a pulse energy fluence (F_p) can be approximated by [29]:

$$R(F_p) = 1 - \Delta R_{ns} - \Delta R \frac{1 - e^{(-F_p/F_{sat})}}{F_p/F_{sat}} - F_p/F_2. \quad (1)$$

All static non-linear response parameters of saturable absorber can be found by fitting the experimental data to the Eq. (1). Some additional approximation must be used for beams with non-uniform intensity distribution. For the Gaussian-shaped beam, the equivalent incident fluence can be calculated:

$$F_p = \frac{E_p}{A_{eff}}, \quad (2)$$

here E_p is the pulse energy, A_{eff} is the effective area calculated from beam radius at the 1/e^2 intensity level from the peak.