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Transition metal dichalcogenides based saturable absorbers for pulsed laser technology☆

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ABSTRACT

Ultrashort pulsed laser is an indispensable tool for the evolution of photonic technology in the present and future. This laser has been progressing tremendously with new pulse regimes and incorporating novel devices inside its cavity. Recently, a nanomaterial based saturable absorber (SA) was used in ultrafast laser that has improved the lasing performance and caused a reduction in the physical dimension when compared to conventional SAs. To date, the nanomaterials that are exploited for the development of SA devices are carbon nanotubes, graphene, topological insulators, transition metal dichalcogenides (TMDs) and black phosphorous. These materials have unique advantages such as high nonlinear optical response, fiber compatibility and ease of fabrication. In these, TMDs are prominent and an emerging two-dimensional nanomaterial for photonics and optoelectronics applications. Therefore, we review the reports of Q-switched and mode-locked pulsed lasers using TMDs (specifically MoS_2, $MoSe_2$, WS_2 and WSe_2) based SAs.

1. Introduction

Pulsed lasers have a wide range of applications in the fields of biomedical imaging, optical communication, metrology, spectroscopy and material processing [1–5]. The demand for short and stable laser pulses, for the above mentioned applications, has motivated researchers to explore various pulse generating schemes. This includes active or passive Q-switching (i.e., modulation based on quality-factor of the laser cavity) [6–8] and mode-locking techniques (i.e., phase-locking of oscillating cavity modes) [9,10] using various pulse shaping elements inside the laser cavity. In these, passive Q-switching and mode-locking are highly preferred due to their unique advantages such as compact nature, low cost and reliable performance. A saturable absorber (SA) is an important device in a laser cavity which generates short pulses using Q-switching or mode-locking techniques. SAs are broadly classified as real SAs [9,11], devices that exhibit a decrease in nonlinear absorption with an increase in light intensity, and artificial SAs [12–14], devices that utilize nonlinear effects to imitate the action of a real saturable absorber by instigating an intensity-dependent transmission. Pulsed lasers with an artificial SA have limitations in the reliability and reproducibility due to the change in the state of polarization caused by environmental perturbations like temperature, stress or strain [13]. Among the various types of real SAs, the semiconductor saturable absorber mirrors (SESAMs) [15,16] are widely used in conventional laser systems because of their remarkable properties such as large modulation depth and low saturation absorbing threshold. Though SESAMs have manifold merits, they also hold some drawbacks which include a complicated fabrication procedure, limited bandwidth operation, low recovery time and bulky nature [17]. To overcome these limitations, researchers have explored the saturable absorption property in carbon based nanomaterials such as carbon nanotubes and graphene. S.Y. Set et al. [18] proposed the first SA using single walled carbon nanotubes (SWCNTs) [19,20] for mode-locked fiber laser. Although CNT based SA has enhanced the saturable absorption properties compared to conventional SAs, it has major drawbacks such as narrowband operation and a low damage threshold [11,21–24]. Unlike SWCNT, graphene is a well-known 2D nanomaterial which has been widely investigated for its nonlinear optical properties. Graphene based SA can be used for a wide wavelength ranging from 0.8 μm to 3 μm. It has interesting characteristics such as high thermal stability, fast nonlinear optical response and a broadband absorption [11,25,26]. On the other

☆ Fully documented templates are available in the elsarticle package on CTAN.

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hand, graphene exhibits two main disadvantages like weak modulation depth (typically ~ less than 1 % per layer [17]) and zero-optical bandgap. Therefore, there is much interest in new nanomaterials that can address the above issues.

In recent years, several SAs have been fabricated from 2-Dimensional materials such as topological insulators (TIs) [27–35], transition metal dichalcogides (TMDs) [36–40] and black phosperous (BP) [41–43]. Among these, TMDs stand out for their distinct characteristics.

The family of TMDs consists of more than forty types of layered materials with MX_2 stoichiometry, where M is a transition metal (e.g Mo,W) and X is a chalcogen (e.g S or Se) [44]. Fig. 1 (a) shows the schematic structure of a TMD element in which each TMD layer is structured as a trilayered sheet formed by two layers of chalcogen atoms sandwiching a layer of transition metal atoms by strong covalent bonds. Based on the transition metal atoms oxidation states, TMDs can exhibit either metallic (e.g. NbS_2) or semiconducting (e.g. MoS_2) properties in nature [45]. Semiconducting TMDs (e.g., MoS_2, $MoSe_2$, WS_2, WSe_2) are currently utilized for photonic and optoelectronic device development applications based on earlier fundamental studies conducted in the 1960s [46,47]. In the recent past, modern fabrication and characterization techniques have opened up new opportunities to investigate the novel characteristics of TMDs to be applied in various fields. Similar to other layered materials, the individual layers in TMD bulk crystals are bonded together by relatively weak van der Waals forces [44] that allows for easier exfoliation into single and few layer forms [48]. The optoelectronic properties of TMDs are strongly layer-dependent [45]. For instance, the bandgap of TMDs generally migrates from indirect to direct and vice versa which is briefed as follows [49]: for MoS_2 the bulk indirect bandgap of 1.3 eV (961 mm) converts to a direct bandgap of 1.8 eV (689 nm) in mono-layered form [50], for $MoSe_2$ the bulk indirect bandgap 1.1 eV (1128 nm) gap migrates to a direct bandgap 1.55 eV (800 nm) in single-layered form [51], and for WS_2 the bulk indirect bandgap 1.4 eV (886 nm) increases to a direct bandgap 2.1 eV (590 nm) transition in a mono-layered form [50]. Such layer-dependent characteristics show that TMDs are comparable or even superior to the zero-gap graphene for a variety of optoelectronic and photonic applications [52]. In addition to the above quality, the mono or few layered TMDs (MoS_2,

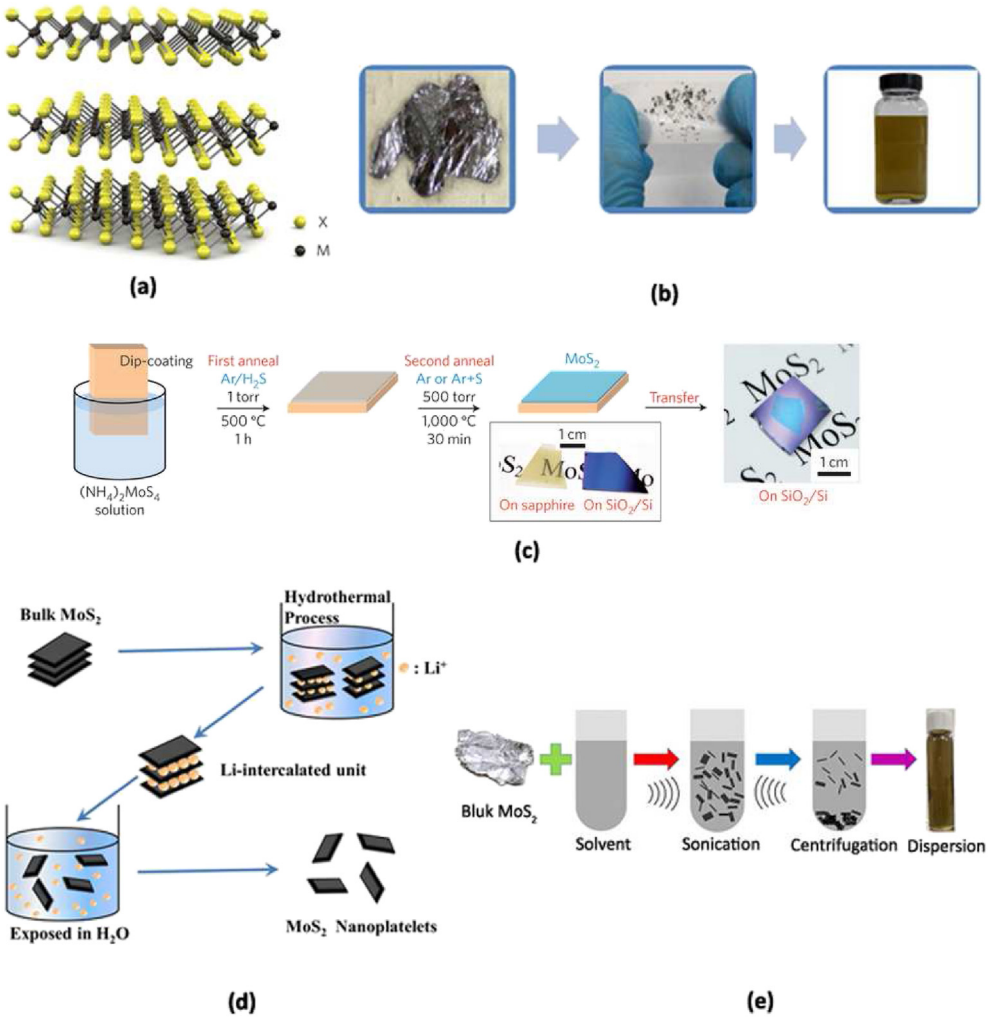

Fig. 1. (a) Schematic view of a MX_2 structure, with the metal atoms (M) in grey and the chalcogen atoms (X) in yellow (reprinted with permission from Ref. [45]. © *2012 Nature Publishing Group*), (b) TMDs nano-sheets prepared by mechanical exfoliation technique (reprinted with permission from Ref. [72]. © *2014 Elsevier B.V.*), (c) CVD growth process of MoS_2 sample through a dip-coated precursor on the substrate with the presence of Ar gas and S vapor (reprinted with permission from Ref. [45]. © *2012 Nature Publishing Group*), (d) MoS_2 nano-sheets prepared by hydrothermal process using Li-Intercalation (reprinted with permission from Ref. [59]. © *2014 Optical Society of America*), (e) Schematic diagram of liquid exfoliation method for preparing MoS_2 nano-sheets. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)