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Effects of adding metals to MoS_2 in a ytterbium doped Q-switched fiber laser

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ABSTRACT

Molybdenum disulfide (MoS_2) is widely used in lubricants, metallic alloys and in electronic and optical components. It is also used as saturable absorbers (SAs) in lasers (e.g. fiber lasers): a simple deposition of MoS_2 on the fiber end can create a saturable absorber without the necessity of extensive alignment of the optical beam. In this article, we study the effects of adding different metals (Cr, Au, and Al) to MoS_2 in a ytterbium (Yb)-doped Q-switched fiber laser. Experimental results show that the addition of a thin layer of gold and aluminium can reduce pulse durations to about 5.8 μs and 8.5 μs, respectively, compared with pure MoS_2 with pulse duration of 12 μs. Experimental analysis of the combined metal and MoS_2 based composite SAs can be useful in fiber laser applications where it may also find applications in medical, three dimensional (3D) active imaging and dental applications.

1. Introduction

Amongst the different types of pulsed lasers (e.g. mode-locked and Q-switched lasers), Q-switched lasers are still attractive because of their relatively low cost. Q-switching relies on initially preventing the laser cavity from oscillating while population inversion is built in the active medium and thereafter restoring the cavity oscillations by drastically increasing its quality factor (Q) [1], so that high peak optical pulses are then generated. Q-switched fiber lasers are of great interest because of their potential applications in fields such as range finding, medicine, micromachining, metrology, fiber optic sensing and telecommunications [2–4]. The cavity switching can be achieved in different ways such as using an external modulator (active) or by using a saturable absorber (passive). In addition, passive Q-switching technique based on SAs has advantages over active Q-switching such as compactness, simplicity, and flexibility of implementation [2].

Different types of saturable absorbers have been used in Q-switched lasers: semiconductor saturable absorber mirrors (SESAMs), graphene and its oxides [5–13], topological insulators [14,15] and transition metal dichalcogenides (TMDs) [16–19] and carbon nanotubes [6,20,21]. In contrast with SESAMs, these materials have advantages such as operation over a larger bandwidth, higher damage threshold, significantly easier alignment constraints and lower fabrication costs – they have been used in both Q-switched and mode-locked lasers. In addition to the aforementioned materials, molybdenum disulfide (MoS_2) has particularly received significant attention for its distinctive semiconducting property with tunable bandgaps and abundance in nature [22–24]. MoS_2 is a TMD with an indirect bandgap of 1.29 eV, which can be increased to 1.80 eV with lateral quantum confinement [24,25]. In addition, saturation threshold of MoS_2 is much lower than other materials, which indicates that it is easier to create a pulsed fiber laser with MoS_2. Moreover, MoS_2 has similar bonding characteristics-it has strong intra-layer bonding and weak van der Waals force between layers. The layer structure allows fabrication of thin films automatically where the quantum confinement can significantly modify the electronic and optical properties.

Since the initial demonstration by Wang and co-workers [26] that MoS_2 can work as a saturable absorber, it has been widely used in pulsed lasers. In fact, MoS_2 saturable absorption at longer wavelengths has been explained by sub-bandgap photon energies [27,28]. Different researchers have successfully reported mode-locked and Q-switched fiber laser based on MoS_2 [29–32]. In addition, MoS_2 also been used in widely tunable fiber lasers [33–35].

In addition to MoS_2 as a saturable absorber, different metals such as gold, aluminium can be added to MoS_2 to form composite saturable absorbers in Yb-doped fiber laser system. In this article, we study the effects of adding a thin layer of different metals (Cr, Au, Al) to MoS_2 saturable absorber in a Q-switched fiber laser. It is shown that the addition of a thin layer of Au and Al can lead to the reduction in the pulse duration of Q-switched ytterbium doped fiber laser although gold is more effective than aluminium.

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In addition, chromium with MoS_2 has no effect in the pulse duration of the laser.

These lasers may find applications in medical [36], 3D-active imaging [37] and dental applications [38]. In medical applications, microsecond pulses have offered the potential of delivering drugs to patients [38], while microsecond pulses can be used to clean the tooth surface without damaging the teeth [39].

2. Preparation of the samples

Molybdenum disulfide in powdered form (particle diameter less than 90 nm) was purchased from Sigma-Aldrich: nanoparticles are used rather than few layers MoS_2. Since this chemical is toxic, it is manipulated inside a fumehood. The powder is then dissolved into boiling water and mixed for 30 min in an ultrasonic bath. After dissolving MoS_2 into water, the fiber tip is immersed into the MoS_2 solution for 5 min – the fiber tip is then left inside the fumehood so that water evaporates and a thin layer of the substance is attached to the fiber.

After the water evaporated, we observed the fiber tips initially with a microscope and then with a surface profilometer (Bruker's Dektak® stylus profiler): the particles form clusters around the fiber that are not very uniform as can be observed in Fig. 1. The thickness of the particles clusters in different fiber tips varied from 1 μm to 20 μm, generally covering the fiber but with regions where only a few particles are attached to the fiber end. A typical thickness measurement of MoS_2 around the center to the fiber (core and cladding diameter of around 5.3 μm and 125 μm, respectively) is shown in Fig. 1: the thickness varies across the fiber in a typical sample. Since absorption of MoS_2 is low (11.62 cm^{-1} [27]), thickness variations from 1 μm to 20 μm will not significantly affect the performance of the composite SAs.

On the other hand, whenever a metal is deposited on the fiber, it is deposited by using a Temescal electron-beam evaporator (Temescal BJD-2000) which has a six-pocket electron beam gun and a thermal evaporation source. The metals that can be deposited with the system include chromium (Cr), gold (Au), aluminium (Al) and other metals. All materials are deposited in a vacuum chamber which avoids contamination of the samples.

3. Experimental setup and results

Fig. 2 shows a schematic of the experimental setup of the constructed fiber laser – it is a ring laser that is pumped by a 980 nm

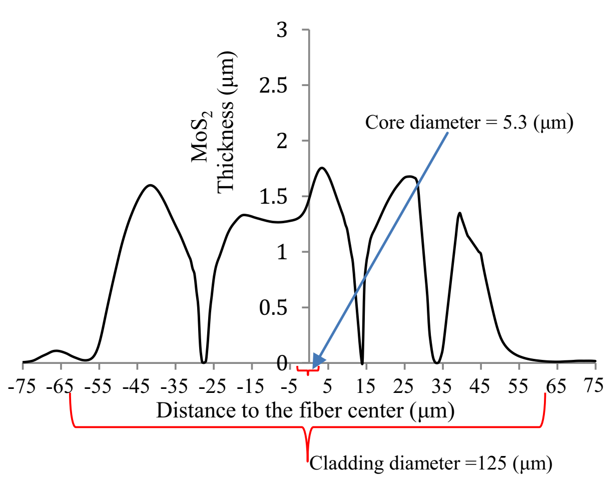

Fig. 1. A typical measurement of MoS_2 thickness (μm) as a function of distance (μm) to the fiber center.

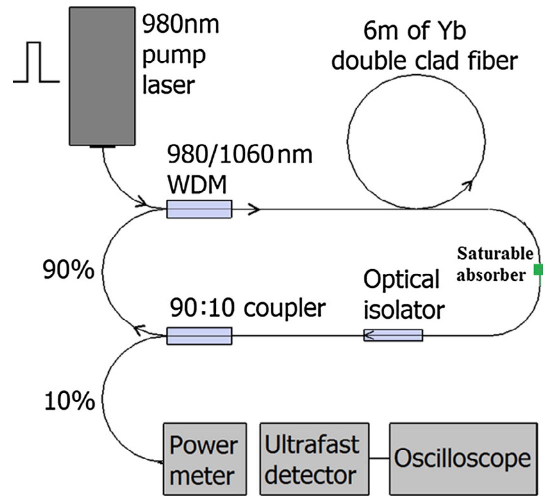

Fig. 2. Schematic of the experimental setup of the constructed laser.

continuous wave (CW) laser (MLD-H-975-2W) which can be externally modulated by a signal generator and is coupled to a 100 μm multimode fiber. The maximum power coupled to the multimode fiber can be up to 1.5 W, but the maximum power is reduced to 800 mW after passing through the wavelength division multiplexer (WDM) coupler. Unless otherwise stated, the repetition rate of the pump laser is 1 kHz with a duty cycle of 50%. The 980/1060 nm WDM coupler allows the 980 nm pump signal to reach the ytterbium double clad fiber but prevents a 1094 nm generated signal to come back to the pump laser. A 6 m *Yb* double clad fiber is used as an active medium (YB 1200-6/125 DC), with a core diameter of 6 μm and a 125 μm first cladding diameter – more than 90% of the pump power is absorbed by the 6 m active fiber. The total cavity length is estimated to be around 8 m, with 6 m of Yb doped double clad active fiber.

When the ytterbium-doped fiber is pumped at 980 nm, it emits light at around 1060 nm (actual emission wavelength range is 1000–1100 nm [40]) – once light is emitted, the saturable absorber tends to strongly attenuate low power signals and weakly attenuate high power signals, therefore generating light pulses. The optical isolator prevents light from circulating in the counter-clockwise direction. A 90:10 coupler is then used to couple 10% of the circulating laser signal to either a fast detector (rise time of 1 ns) followed by an oscilloscope, optical spectrum analyzer or power meter as discussed by Mironov et al. [41].

The emission power spectra for the composite SA based Q-switched fiber laser is shown in Fig. 3: only two cases are considered, gold and aluminium. The emission spectra are centered around 1098 nm, with multiple peaks due to several longitudinal modes propagating in the ring laser. The power spectrum for Al based composite SA is different from gold (as shown in Fig. 3(a) for gold and (b) for aluminium) because aluminium is more reflective than gold at 1090 nm, leading to the generation of additional modes in the laser cavity and the broadening of the spectra. For identical 20 nm layers of gold and aluminium, aluminium is 30% more reflective than gold [42]. The spectrum is limited to 1100 nm due to the silicon detector (the bandgap of silicon is about 1.1 eV) inside the spectrum analyzer (CCS 200 [40]) with the precision of the measurement guaranteed by manufacture [40]. In addition, this limitation does not affect the precision of the results as explained in different articles [13,43].

The pump laser can be modulated at a maximum repetition rate of 3 kHz (1 kHz used in this work), which allows the generation of a train of periodic Q-switched pulses which are easily visualized with an oscilloscope.