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Spooling diameter dependent Q-switched output in depressed cladding erbium doped laser with $MoWS_2$ saturable absorber

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ABSTRACT

A tunable, Q-switched depressed-cladding erbium-doped fiber (DC-EDF) laser employing a molybdenum tungsten disulfide ($MoWS_2$) thin film as a saturable absorber (SA) is reported. The output of the laser can be controlled by adjusting the spooling diameter of the gain medium, with continuous wave operation obtained from 1466 nm to 1502 nm and 1473 nm to 1525 nm for DC-EDF spooling diameters of 5.5 cm and 6.5 cm respectively. The Q-switched output, obtained by incorporating an $MoWS_2$ based SA into the cavity shortens the tuning range to between 1476.0 nm and 1496.0 nm as well as 1486.0 to 1496.0 nm for the same spooling diameters. The outputs have repetition rates ranging from 21.7 kHz to 44.6 kHz and a minimum pulse width and maximum pulse energy of 2.4 μs and 11.0 nJ, for the DC-EDF with a spooling diameter of 5.5 cm. The DC EDF with a spooling diameter of 6.5 cm is able to generate pulses with a repetition rate of between 32.2 kHz and 40.9 kHz with a minimum pulse width and maximum pulse energy of 2.8 μs and 10.1 nJ.

1. Introduction

Q-switched fiber lasers have recently become the focus of significant research interest due to their ability to generate long duration optical pulses. These lasers find many significant applications in areas such as medicine, environmental sensing and monitoring, nonlinear optics and material processing [1–4]. Q-switched fiber lasers have numerous advantages over their bulk counterparts, including a generally simple and compact design as well as flexibility in usage while at the same time being highly efficient and able to produce a high quality output beam [5]. On top of this, Q-switched lasers with wavelength tunability are highly desired for applications such as wavelength division multiplexing (WDM) network testing, biomedical research and spectroscopy [6], driving more research efforts into the development of these lasers.

Generally, two techniques are used to generate Q-switched pulses; namely active and passive Q-switching. Both approaches have their own advantages and disadvantages; for the case of active Q-switching, users have significant control over the repetition rate and the optical pulse duration [7]. This however comes with the disadvantage of having a low peak power and low damage threshold as well as making the overall system expensive and complex, as the use of an acoustic-optic or electro-optic modulator in the system is typically required [8]. Passive Q-switching on the other hand, is significantly less complex and cost effective than active Q-switching, with the most common approach being the incorporation of thin film saturable absorbers (SAs) into the laser cavity [9,10]. However, unlike active Q-switching, there is significantly less control over the various output parameters of the pulses, though in many real-world applications this can be acceptable.

Until recently, semiconductor saturable absorber mirrors (SESAMs) have been the most common and successful means of obtaining passively Q-switched pulses [11]. However, SESAMs themselves are expensive, bulky and sometimes can be inflexible. They require complex and highly specialized equipment to fabricate [11] and have a narrow operational bandwidth [8]. As a result of this, thin film SAs have now become the forefront of research into SAs for the passive Q-switching and mode-locking of fiber lasers. Initial efforts focusing on single-walled carbon nanotubes (SWCNTs) [12,13] and graphene [4,14] have successfully demonstrated the use of these materials as SAs in fiber laser cavities. This subsequently spurred the development of other 2-dimensional nanomaterials for use as SAs [15], including topological insulators [8,16], titanium dioxide [17], silver [18] and black phosphorus [19] which have all been successfully demonstrated as SAs for Q-switching and mode-locking applications.

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In addition to the aforementioned materials, transition metal dichalcogenides (TMDs) [20], such as molybdenum sulfide (MoS_2), tungsten diselenide (WSe_2), molybdenum diselenide ($MoSe_2$) and tungsten disulfide (WS_2) have also shown significant potential for use as SAs. TMDs are highly desirable optical materials due to their layer dependent optical properties and ability to alternate their band gap between the indirect and direct states at near-infrared wavelengths [21]. In addition to functioning as SAs, TMDs are also suitable for various other photonics applications as they demonstrate strong photoluminescence, strong optical absorption and high nonlinearity [22]. In this study a ternary phase TMD, molybdenum tungsten disulfide ($MoWS_2$), is used as an SA for generating Q-switched pulses in an optical fiber laser. Ternary phase TMDs have thermodynamic stability [23] and exhibit a tunable electronic structure that allows the intralayer and interlayer atomic displacement to be controlled. This leads to the efficient tuning of their physical and electronic properties [24] and also allows for the easy engineering of the band gaps by controlling the composition of the materials [23], an advantage in optoelectronic applications. As demonstrated by Li et al. [25], $MoWS_2$ has an "electron-rich" condition as the electrons can directly transfer from the WS_2 to MoS_2 layers due to their massive edge site and also shows a smaller band gap that results in better conductivity [25].

In line with the development of SAs for Q-switching and mode-locking applications, depressed-cladding erbium-doped fibers (DC-EDFs) have garnered interest as a gain medium for fiber amplifiers and lasers operating in the S-band region [16,26-29]. The DC-EDF allowed for operation in the S-band region by controlling the spooling diameter of the fiber and demonstrations of S-band DC-EDF amplifiers by Foroni et al. [28] and Rosolem et al. [27] showed that tighter DC-EDF spooling diameters result in the amplified spontaneous emission (ASE) spectrum being shifted to the shorter wavelength ranges of 1480–1520 nm. While there have been previous works using erbium-doped fibers (EDFs) [8] and DC-EDFs [29] as the gain medium for generating S-band pulsed lasers, these system are confined to only a very limited region of the S-band. Furthermore, the aforementioned works do not examine the effects of the gain medium's spooling diameter towards the characteristics of the generated pulses. In this work, a proposed Q-switched laser using a DC-EDF as the gain medium and an $MoWS_2$ based SA is proposed and demonstrated for a widely tunable pulsed output in the S-band region. By manipulating the spooling diameter of the gain medium, the tunability range can be in the S-band region can be controlled. This is, to the best of author's knowledge, the first demonstration of a tunable, passively Q-switched DC-EDF fiber laser using an $MoWS_2$ based SA and controllable from the gain medium's spooling diameter.

2. Preparation and characterization of $MoWS_2$

The SA used in this work is formed from $MoWS_2$ nanosheets with a few-layer thickness. The nanosheets are prepared using the well-known hydrothermal exfoliation technique that has been described in detail in previous works [30,31]. The characterization of $MoWS_2$ based SA using X-ray diffraction (XRD) analysis is given in Fig. 1(a). The measurement was made at an excitation wavelength of 1.541 Å, resulting in diffraction peaks being observed at 13.96°, 33.52° and 59.12°, corresponding to the [0 0 1], [1 0 1] and [1 1 0] planes respectively and auguring well with that of standard hexagonal MoS_2 from the JCPDS Card No. 37-1492 [32]. It was observed that the $MoWS_2$ nanosheets have a high degree of crystallinity due to the sharp and clean diffraction peaks, and that the peak observed along the [0 0 2] plane in the case of the $MoWS_2$ nanosheets is slightly less than that of MoS_2 and WS_2 which are

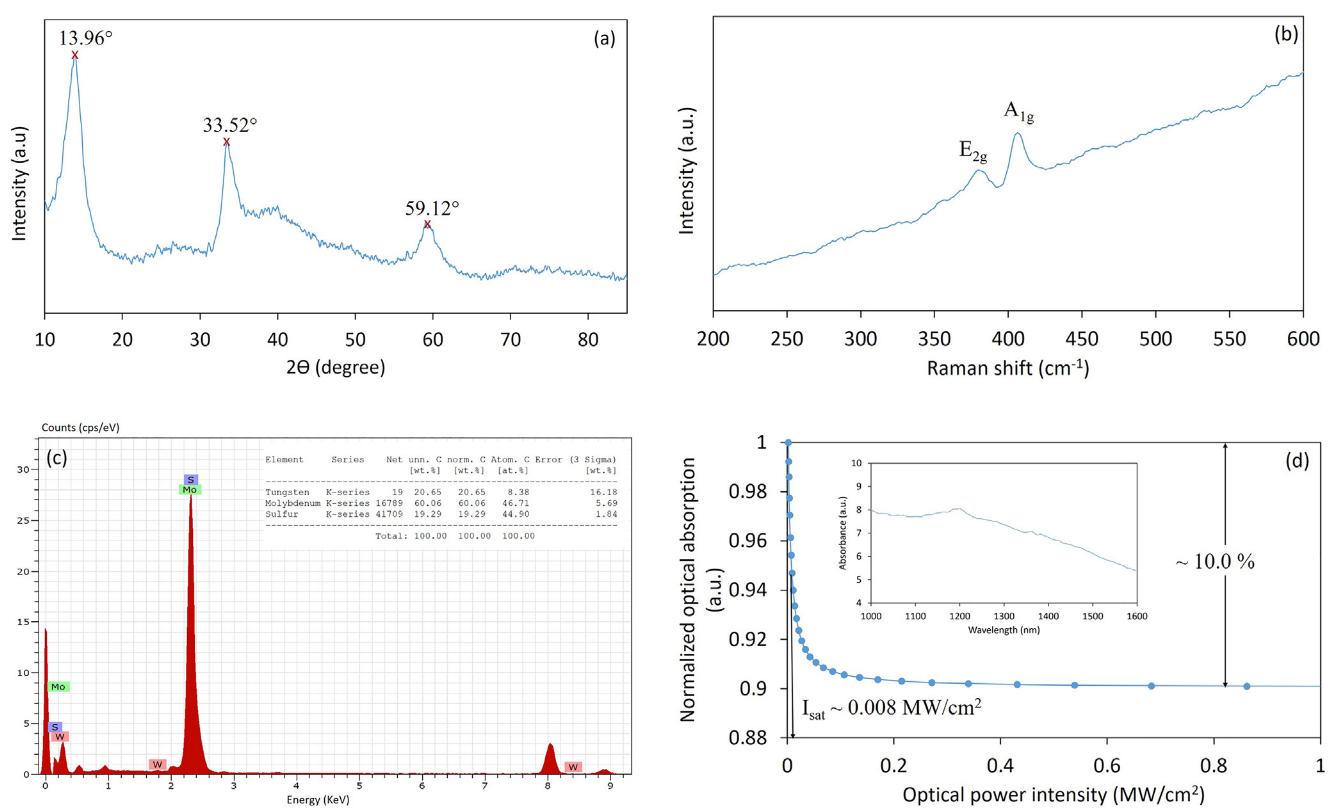

Fig. 1. Characterization of the $MoWS_2$ sample, showing (a) XRD analysis, (b) Raman spectrum, (c) EDX measurement and (d) nonlinear absorption characterization and linear absorption spectrum (inset) of $MoWS_2$ nanosheets. XRD and EDX analysis was done at the School of Electrical Engineering, VIT University.