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Molybdenum disulfide side-polished fiber saturable absorber Q-switched fiber laser

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A B S T R A C T

A Q-switched fiber laser based on a Molybdenum disulfide (MoS_2) saturable absorber (SA) is proposed and demonstrated. A 3 m long erbium-doped fiber with an absorption coefficient of 11.3 dB/m at 979 nm acts as the linear gain medium of the laser. The SA is formed by depositing a MoS_2 layer on a self-fabricated side-polished fiber (SPF), which can be easily fabricated in less than 15 min. The proposed laser has a Q-switching threshold of 14.8 mW, and is capable of generating a pulsed output with a repetition rate and pulse-width of up to 25.27 kHz and 3.19 μs at a maximum pump power of 45.6 mW, as well as an average output power and pulse energy of 2.27 mW and 0.09 μJ at the same pump power. The pulses have an average signal-to-noise ratio of 37.8 dB, indicating a stable output and making the proposed laser highly suited for a variety of sensor, communications, and industrial applications.

1. Introduction

Q-switching and mode-locking in laser cavities are amongst the two most common passive methods for generating a pulsed laser output [1–5]. While mode-locked fiber lasers are preferred for applications that require pulses in the MHz range, Q-switched pulses are on the other hand of interest for applications requiring slower pulse rates, in the kHz range, and with higher output powers [6–10]. While Q-switching can be realized through both active and passive means, passive Q-switching is commonly preferred as it possess numerous advantages over active methods, including its very small form factor and robust nature, as well as not requiring complex electronics, which makes the passive approach very cost-effective [11–13].

Passive Q-switching is typically realized using either semiconductor saturable absorption mirrors (SESAMs) [14] or saturable absorbers (SAs). SESAMs were originally the preferred choice for generating Q-switched outputs, but the bulky size, relatively high cost and complexity of SESAMs drove researchers to seek other viable alternatives, particularly those that could be used to induce Q-switching while still maintaining an overall efficient and compact system [15]. The emergence of 2-dimensional (2-D) and 3-dimensional (3-D) materials which could act as SAs, beginning with the discovery of graphene and its unique optical properties [16,17] has pushed this development to a new level. Soon, a host of new 2-D and 3-D materials with similar properties including graphene derivatives such as graphene oxide and carbon nanotubes (CNTs) [18], topological insulators (TIs) [19] and transmetal dichalcogenides (TMDs) [20] as well as exotic materials such as black phosphorous [21] were being explored for their potential to be employed as SAs. In this regard Molybdenum disulfide (MoS_2) [22], a TMD, has recently become the focus of SA development work. MoS_2 is unique, while in its monolayer form, it has a direct bandgap of ~1.9 eV [23], but when formed in multiple layers the direct bandgap disappears, now leaving an indirect bandgap [24]. Furthermore, MoS_2 demonstrates third-order nonlinear tendencies [25] and ultrafast carrier dynamics [26], further opening the potential of MoS_2 for the generation of laser pulses.

In this work, MoS_2 layers are employed as an SA in an optical cavity by embedding them in a side-polished fiber (SPF). The SPF is created by partially removing the cladding of a conventional single-mode fiber (SMF-28), allowing the evanescent field of a propagating signal to radiate and interact with its surroundings [27–31]. The MoS_2 layer is embedded onto the SPF, thus creating the desired SA. This is the first time, to the best knowledge of the authors, of an SA developed using and SPF with embedded MoS_2 layers.

This work differs with other similar configurations as the SPF fabrication technique employed here is a simple and very cost effective approach. Furthermore, the self-developed polishing stage is also highly compact, and with further enhancements and modifications can be made even more so. This is also the first time, to the best knowledge of the

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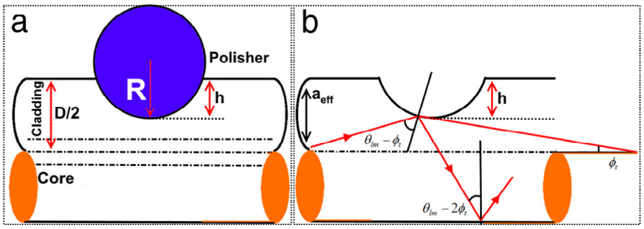

Fig. 1. (a) Optical fiber schematic, where a is the core radius, D is the cladding diameter, h is the penetration depth and R is the cylindrical polisher's radius. (b) Ray tracing within the side-polished fiber, a_{eff} is the effective mode radius.

authors, of the generation of Q-switched pulses from an SPF embedded with MoS2 nanoparticles as an SA.

2. Interaction of light propagating in the SPF

The SPF in this work is fabricated from a conventional SMF-28, and creates a 2 mm long polished region in the SMF-28. During the fabrication process, it is necessary to keep in mind that the thickness of the cladding layer plays a crucial role in the performance of the SPF and thus the SA. Significant loss can be incurred direct interaction between the evanescent field of the guided mode and the imperfect fiber surface facing the external environment [32,33], thus requiring the cladding to have a thickness of greater than a few μm [34]. The interaction between the propagating field and its evanescent wave with the surrounding cladding and environment is shown in Fig. 1.

The propagating modes can be transformed into radiation modes linked to the cutoff penetration depth (h_c). A meridional angle of incidence, θ_{lm} and an effective mode radius a_{eff}, corresponding to each mode of radial order m and azimuthal order l [35,36] can be defined as:

$$\theta_{lm} = \sin^{-1}(\beta_{lm}/kn_1) \quad (1)$$

$$a_{eff} = a + x_s(\theta_{lm}). \quad (2)$$

The propagation constant is defined by β_{lm} for the lm mode while the enlargement caused by the Goos–Hanchen shift is defined as x_s and $k = 2\pi/\lambda$ as the wave number. Assuming that $n_1 \approx n_2$, the TE and TM modes thus have the same enlargement, which can be calculated from equation [37] as follows:

$$x_s = 1/\left[k(n_1^2 \sin^2\theta_{lm} - n_2^2)^{1/2}\right]. \quad (3)$$

In this manner, if the diameter of the polished region of the SMF-28 reaches a value of $r = a_{eff}$, then the reflection's angle becomes $\theta_{lm} - \phi_t$, where ϕ_t is the angle between the tangential plane to the polished surface and the z-axis. It will then impinge on the diametrically opposite interface with an angle of incidence which is $\theta_{lm} - 2\phi_t$, in relation to the normal to the interface. Therefore, by changing the thickness of the cladding at its deepest point, the angle of incidence will move toward the critical angle. The cutoff angle ϕ_c can be calculated by following

$$\phi_c = (\theta_{lm} - \theta_{cr})/2 \quad (4)$$

where, the θ_{cr} is the total internal reflection. The cutoff penetration depth (h_c), therefore can be calculated as:

$$h_c = D/2 - a_{eff} + R(1 - \cos\phi_c). \quad (5)$$

Mechanical cladding removal can be easily achieved using a simple polishing and lapping procedure, although this requires care as the nature of the fiber makes it very easy to over-polish the fiber, thus reaching the core if the polishing process is not continuously monitored.

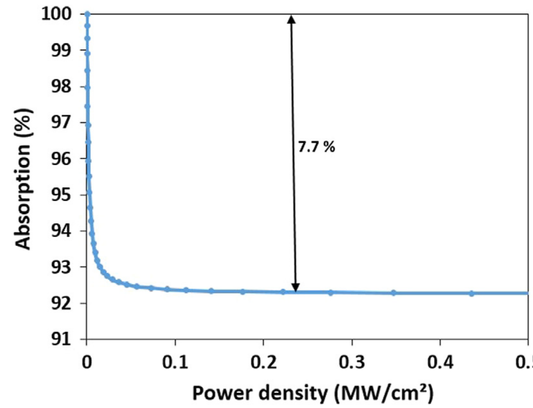

Fig. 2. Modulation depth of MoS_2 saturable absorber.

3. Experiment setup

3.1. Nonlinear absorption properties of MoS_2 SA

The balanced twin detector technique is used to study the nonlinear characteristics of the MoS_2 as an SA. The pulse-seed is obtained from a mode-locked fiber laser with a central wavelength, pulse width and repetition rate of 1550 nm, 0.70 ps and 28.7 MHz respectively. The seed pulse is channeled to a low-dispersion amplifier and variable optical attenuator before being split up by a 3-dB coupler. One output of the coupler is designated as the reference, and connected directly to a Thorlabs optical power meter (OPM), while the other output is linked to the MoS_2 SA before being connected to a second input of the OPM. The collected data is then inserted into Eq. (6):

$$\alpha(I) = \frac{\alpha_s}{1 + \frac{I}{I_{sat}}} + \alpha_{ns} \quad (6)$$

where α is absorption, I is intensity, α_s is saturable absorption, α_{ns} is non-saturable absorption and I_{sat} is saturation intensity. The obtained data is then fitted into a plot as in Fig. 2. From the graph, the modulation depth was computed at 7.7% and a saturation intensity of 0.002 MW/cm^2 was obtained.

3.2. Fabrication of the SPF based SA

The setup of the polishing rig is given in Fig. 3. The rig comprises of two Newport M-562-D optical alignment stages together with Newport 561-FH fiber holders which are used to clamp the fiber securely into position. The middle of the SMF-28 is stripped of its protective coating at a length of about 3 cm and cleaned with alcohol before being secured as shown in Fig. 3.

The distance between the fiber holders, L_0 is approximately 5.2 cm and the center of the stripped part, $L_0/2$ is 2.6 cm. The polishing wheel of the rig is assembled by wrapping silicon carbide paper with a grit size of 1000 around a wheel attached to the drive shaft of a common electric motor to create a uniform polishing wheel with a diameter of 2.5 cm. The motor has a maximum rotational speed of 11 442 revolutions per minute (RPM) with an output torque of 1.04×10^{-3} N m. The polishing wheel is secured on a Newport M-561D alignment stage and placed perpendicularly between two Newport M-562-D optical alignment stages.

The polisher wheel is adjusted so that the stripped portion of the fiber is in contact with the wheel, with slight pressure being placed onto the fiber. This is to make the polishing process easier. To monitor the polishing process, a tunable laser source (TLS) with an output power of 8 dBm power at 1550 nm is launched into the fiber while Thorlabs optical power meter (OPM) is used to monitor the power transmission at