Dual-wavelength Q-switched pulse generation using D-fibre and MoS_2 saturable absorber

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Received: 31.08.2017

Abstract. We have demonstrated a dual-wavelength Q-switched generation of erbium-doped fibre laser, which is achieved using a D-fibre and several layers of molybdenum disulfide as a saturable absorber. Bulk MoS_2 has been processed using a liquid-phase exfoliation to obtain a layered structure. To provide a thin-film structure, MoS_2 has been mixed with a polyvinyl-alcohol polymer. The dual-wavelength spectrum of our device reveals two peaks centred at 1555 and 1562 nm. Q-switched operation at the both spectral peaks has been investigated using a tunable bandpass filter.

Keywords: dual wavelength operation, Q-switched, D-fibre

PACS: 42.60.Gd
UDC: 621.373.826

1. Introduction

Dual-wavelength Q-switched fibre lasers are among important research topics due to their potentials for terahertz pulse generation, light detection and ranging (e.g., in lidars), and sensing applications. Dual-wavelength Q-switched light generation usually involves different nonlinear optical methods, e.g. those based on birefringence with saturable absorption or nonlinear polarization rotation with saturable absorption [1–4]. One of the methods for the dual-wavelength laser generation, which is based on so-called D-fibres, offers the ability to control multi-modal interference. Through the proper control of the latter, stable dual-wavelength or multi-wavelength lasers with tunable central wavelength and channel spacing can easily be implemented. Note that tunability of the dual-wavelength lasers utilizing D-fibres increases still further their potential applications.

In addition, incorporation of a saturable absorber (SA) into optimized dual-wavelength laser cavity enables Q-switched pulse generation through a well-known passive technique. This Q-switching technique implies cost efficiency and simplicity of all-fibre laser design. Unlike many SAs explored till now (e.g., graphene, black phosphorus and topological insulators), transition-metal dichalcogenides have their intrinsic advantage of layer-dependent absorption properties that make them interesting for various photonic researches. In addition, the above dichalcogenides exhibit excellent photoluminescence, carrier dynamics and optical absorption [5, 6], thus making them favourable as SAs for inducing laser pulses. There are several types of transition-metal dichalcogenides, including selenide- and sulfide-based materials, among which MoS_2 is the most explored. MoS_2 manifests superior saturable-absorption properties, while its nonlinear optical response is stronger than that of graphene [7, 8]. As a result, MoS_2 have been widely studied for the photonics applications such as Q-switching and mode-locking [9–14].

In the present work we investigate dual-wavelength Q-switched pulse generation in a ring laser cavity incorporating both the MoS_2-based SA and the D-fibre. Our SA represents a MoS_2–polyvinyl alcohol polymer composite thin film fabricated from bulk MoS_2 using a liquid-phase epitaxy technique. Furthermore, Q-switching operation at each of the spectral peaks is studied using a tunable bandpass filter.

2. Experimental arrangement

The MoS_2 SA used in our experiments was fabricated in-house. Bulk MoS_2 was processed using a standard liquid-phase exfoliation to obtain several layers, and then mixed with a polyvinyl-alcohol polymer to produce a thin film. The details of the processing and the characteristics of the corresponding MoS_2 SAs had been reported in our previous work [15]. Experimental arrangement of the dual-wavelength Q-switched erbium-doped fibre laser (EDFL) is shown in Fig. 1. A laser cavity consisted of a 3 m long erbium-doped fibre (labeled as EDF in Fig. 1), a wavelength division multiplexer (WDM), a commercial D-fibre (Phoenix Photonics Ltd), a polarization controller (PC), an isolator (ISO), a 10 dB coupler, and a MoS_2 SA film. The erbium-doped fibre used as a gain medium had the doping concentration 2000 ppm. A 980 nm laser diode was used to pump the erbium-doped fibre through the wavelength division multiplexer. The rest of the cavity was made of a single-mode fibre. The isolator was used to ensure a unidirectional propagation of light in the ring cavity. The PC was incorporated into the cavity to tune the polarization state. The D-fibre was placed between the erbium-doped fibre and the 10 dB coupler to induce a dual-wavelength effect. Besides, the saturated-absorption effect was due to the MoS_2 SA, which was placed in the gap between the two FC/PC fibre ferrules. The output of our EDFL was tapped with the 10 dB coupler. The output was studied using an optical spectrum analyzer, an oscilloscope and a 12.5 GHz photodetector.

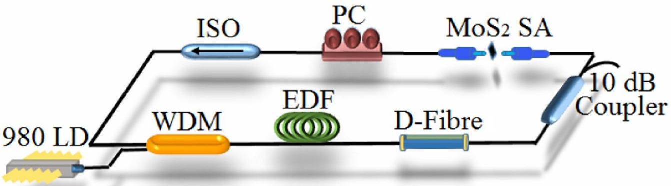

Fig. 1. General scheme of our dual-wavelength Q-switched EDFL.

3. Results and discussion

The dual-wavelength Q-switching has been initiated from the pumping powers 14.9–96.9 mW. For different pump-power levels, the Q-switched pulse trains evolve with time as shown in Fig. 2. When the pump power increase above the value of 96.9 mW, the pulse train starts to fluctuate and then vanishes. Fig. 3 displays the emission spectrum of the dual-wavelength Q-switched laser detected just at the pump power 96.9 mW. By properly adjusting the polarization controller, a stable dual-wavelength Q-switched lasing is achieved at the central wavelengths 1555 and 1562 nm. In this stable state of dual-wavelength Q-switched operation, we observe the channel spacing close to 7.0 nm. The difference observed between the two spectral profiles can be caused by a non-uniform amplified spontaneous emission gain in the erbium-doped fibre. With different gains, the two lasing components experience different degrees of the self-phase modulation effect. As a consequence, these components exhibit different spectral profiles.

Notice that the dual-wavelength generation is mainly caused by the D-fibre. When the light propagates in this fibre, it reveals different total internal reflection patterns at the core–cladding and core–air interfaces. The two different reflected light components co-propagate in the cavity and suffer interference. Under the condition of sufficient initial birefringent effect in the cavity, a stable dual-wavelength operation is obtained. Besides, when the D-fibre is removed from the cavity, only a single-wavelength regime is obtained. This further proves that it is the D-fibre that ensures the dual-wavelength generation.

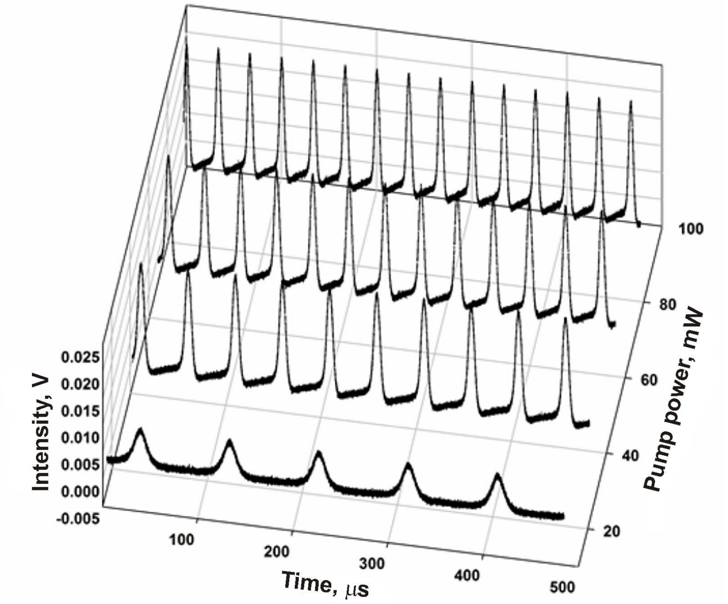

Fig. 2. Dual-wavelength Q-switched pulse trains detected at different pump-power levels: the light intensity is conventionally expressed in volts.

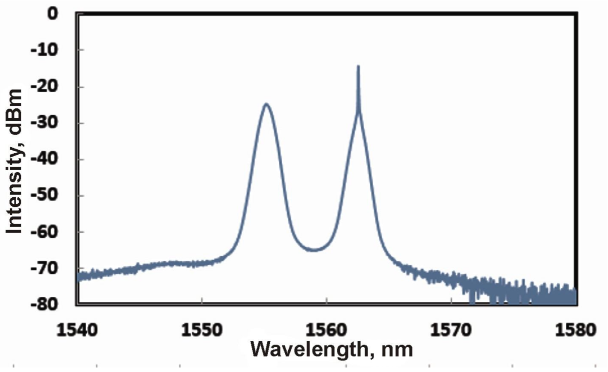

Fig. 3. Emission spectrum of our dual-wavelength Q-switched laser as measured at the pump power 96.9 mW.

Fig. 4 illustrates variations of the repetition rate and the pulse width occurring with increasing pump power level. The repetition rate of the pulses increases with increasing pump power, whereas the pulse width decreases under these conditions. With increasing pump power in the cavity, the gain in the excitation process is enhanced before a saturated state is reached. Hence, the pulse repetition rate is increased and a shorter pulse width is obtained. To be specific, the pulse repetition rate of our dual-wavelength Q-switched laser increases from 10.7 up to 30.0 kHz when the pump power increases from 14.9 to 96.9 mW. The Q-switched pulse width then decreases from 15.1 to 5.7 μs.

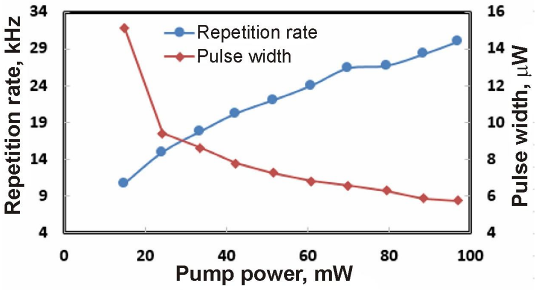

Fig. 4. Dependences of pulse repetition rate and pulse width on the pump power.

Dependences of the average output power and the pulse energy upon the pump power inside the Q-switching range are presented in Fig. 5. The both parameters of our Q-switched laser increase nearly linearly with increasing pump power. The output power changes from 0.07 to 1.00 mW, whereas the pulse energy is located in the range 6.6–33.3 nJ. The efficiency of the EDFL is calculated to be 1.1% from the slope of the output-power dependence. It is worthwhile that the efficiency of the dual-wavelength Q-switched laser based on the cavity suggested by us is somewhat higher than the values achieved with the other generation methods [2, 16] and close to those reported in Refs. [1, 4].

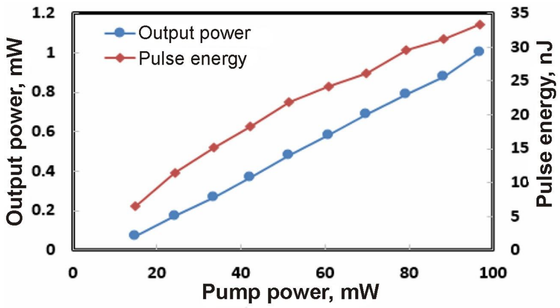

Fig. 5. Dependences of output power and pulse energy on the pump power.

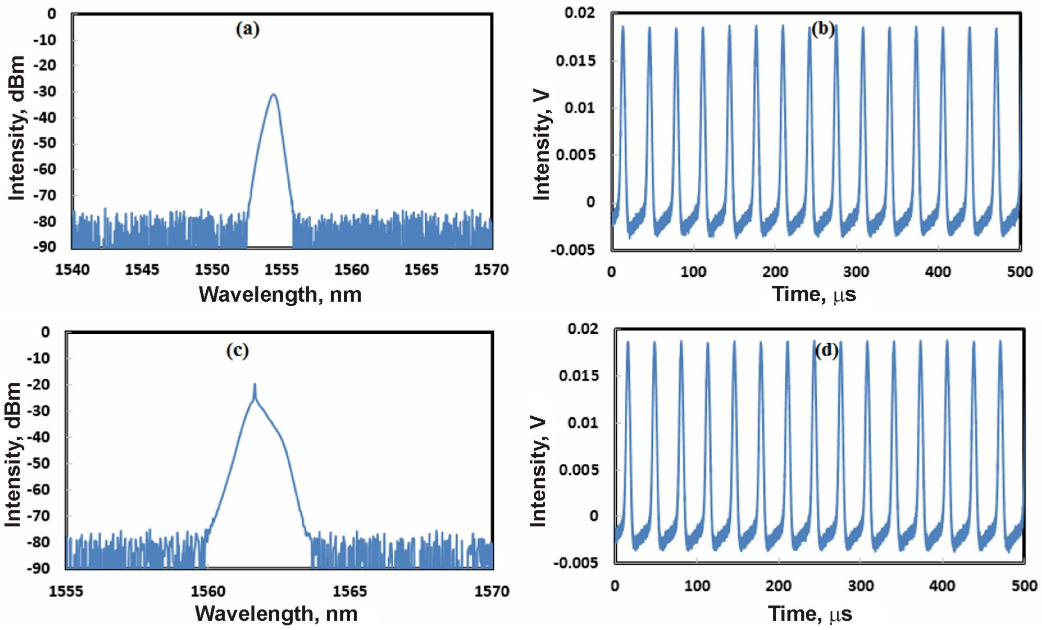

Fig. 6. Q-switching patterns detected at the pump power 96.9 mW: spectra centred at 1555 nm (a) and 1562 nm (c), and time dependences of light intensity observed at 1555 nm (b) and 1562 nm (d).

We have studied the pulse patterns for each of the lasing modes, using a tunable bandpass filter (Newport TBF-1550-1) at the output. When the filter is centred at 1555 nm (see Fig. 6a), a stable Q-switching is observed as shown in Fig. 6b. We obtain the pulse repetition rate 30.0 kHz and the pulse width 5.9 μs at this operating wavelength. Then the filter has been tuned to the wavelength 1562 nm (see Fig. 6c). Again, a stable Q-switching occurs, as displayed in Fig. 6d. The characteristics of the pulses observed at the both operating wavelengths 1562 and 1555 nm are very similar. Moreover, no obvious temporal delay is seen for the Q-switched pulse trains located at different wavelengths. At the pump power 96.9 mW, the repetition rate for the both pulse trains is equal to 30.0 kHz and the pulse width is around 5.9 μs. This testifies that the lasing Q-switched pulses located at the two different wavelengths are temporally synchronized. Synchronization of the pulses obtained at the both lasing wavelengths clearly manifests itself in similarity of the pulse trains shown in Fig. 6b and Fig. 6d.

4. Conclusion

We have demonstrated a successful operation of the dual-wavelength Q-switched EDFL which is based on the MoS_2 SA and the D-fibre. The spectrum of the dual-wavelength Q-switched laser reveals the two peaks centred at 1555 and 1562 nm. The lasing has been achieved in the pump power range 14.9–96.9 mW. In this range, the pulse repetition rate increases from 10.7 to 30.0 kHz and the pulse width decreases from 15.1 to 5.7 μs. Q-switching at the both spectral peaks has been studied using the tunable bandpass filter. Our results testify that, at the both lasing wavelengths 1555 and 1562 nm, our Q-switched laser exhibits the highest repetition rate 30.0 kHz and the narrowest pulse width 5.7 μs at the maximal pump power 96.9 mW. This means that the Q-switched pulses observed at the two operating wavelengths are temporally synchronized and their output characteristics correspond directly to those of the total dual-wavelength Q-switched pulse.

Acknowledgement

We would like to acknowledge financial support of the present study from the University of Malaya through the Grants RU007/2015 and LRGS(2015)/NGOD/UM/KPT.

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Jaddoa M.F., Odah J.F., Ahmad H., Amiri I.S. and Tiu Z.C. 2018. Dual-wavelength Q-switched pulse generation using D-fibre and MoS_2 saturable absorber. Ukr.J.Phys.Opt. **19**: 27 – 32.

Анотація. *Продемонстровано, що генерацію на двох довжинах хвиль для лазера з модульованою добротністю на активованому ербієм волокні можна досягти шляхом використання D-волокна і декількох шарів дисульфіду молібдену як поглинача з насиченням. Для одержання шаруватої структури об'ємний MoS_2 обробляли за методом рідинного фазового відшарування, а для забезпечення тонкоплівкової структури MoS_2 змішували з полівініл-спиртовим полімером. Спектр лазера виявляє два піки з центрами при 1555 і 1562 нм. Модуляцію добротності на обох спектральних піках було вивчено з використанням перестроюваного смугового фільтра пропускання.*