Generation of multi-wavelength erbium-doped fiber laser by using $MoSe_2$ thin film as nonlinear medium and stabilizer

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We experimentally demonstrate the application of $MoSe_2$ thin film as a nonlinear medium and stabilizer to generate a multi-wavelength erbium-doped fiber laser. The cooperation of a photonic crystal fiber and a polarization-dependent isolator induces unstable multi-wavelength oscillations based on the nonlinear polarization rotation effect. A $MoSe_2$ thin film is further incorporated into the cavity to achieve a stable multi-wavelength. The laser generates 7 lasings with a constant spacing of 0.47 nm at a pump power of 250 mW. The multi-wavelength erbium-doped fiber laser is stable with power fluctuations of less than 5 dB over 30 min.

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Multi-wavelength erbium-doped fiber lasers (EDFLs) have many applications in optical communications, sensors, and instrumentation. Many approaches have been demonstrated to achieve multi-wavelength lasing at room temperature, such as cascaded stimulated Brillouin scattering[1,2], incorporating a semiconductor optical amplifier and four-wave mixing (FWM)[3]. Furthermore, the nonlinear polarization rotation (NPR) technique is widely used to generate multi-wavelengths due to its simplicity[4,5].

On the other hand, two-dimensional (2D) materials have great nonlinear optical (NLO) responses that can be promising materials for optoelectronics application. Among the different types of 2D materials, transition metal dichalcogenides (TMDs) materials have shown excellent potential as the next generation of 2D materials[6,7]. Basically, TMD materials can split into the following two categories: sulfide-based and selenide-based. The main difference between the sulfide-based and selenide-based TMD materials is the weight of chalcogenide atoms. Selenide-based TMD materials exhibit heavier chalcogenide atoms, which leads to the reduction of the bandgap energies. TMD materials have attracted considerable attention as future optoelectronics materials due to the nature of the layer-dependent optical properties present[8]. Additionally, TMD materials exhibit other useful optical properties, such as high nonlinearity, great ultrafast carrier dynamics, and strong optical absorption[9]. However, most of the studies of 2D materials application only focus on Q-switched and mode-locked laser generation[8,10–12]. Other optical applications using TMD materials are yet to be explored.

In this work, we have proposed and practically demonstrated the application of TMD material as a birefringence medium and stabilizer to generate a multi-wavelength laser. Molybdenum diselenide ($MoSe_2$) is fabricated into a thin film and incorporated into an EDFL cavity to achieve a stable multi-wavelength. To the best of our knowledge, this is the first demonstration of a multi-wavelength EDFL using $MoSe_2$ as a birefringence medium and stabilizer.

In this experiment, few-layer $MoSe_2$ is prepared by the liquid phase exfoliation (LPE) method. The N-methyl-2-pyrrolidine (NMP) solvent for the exfoliation of $MoSe_2$ is mixed with a bulk powder with an initial concentration of 5 mg/mL. The solution is processed with a high-power ultrasonicator for 8 h. The suspension is centrifuged at 3000 rpm for 60 min and the top 2/3 supernatant solution is pipetted out for further characterization. The few-layer $MoSe_2$ solution is then drop casted onto silica wafers to conduct Raman spectroscopy using a Renishaw inVia confocal Raman microscope at an excitation wavelength of 488 nm and 3.5 mW power. As depicted in Fig. 1, the out-of-plane vibration (A_g^1) for bulk $MoSe_2$ is centered at 240 cm^{-1}, whereas the few-layer $MoSe_2$ is centered at 235 cm^{-1}. The peak shift (5 cm^{-1}) of few-layer $MoSe_2$ to the lower region proved that the LPE process has successfully transformed the bulk $MoSe_2$ to few-layer $MoSe_2$. Next, the few-layer $MoSe_2$ solution is further processed to become thin film. The few-layer $MoSe_2$ solution is placed in a bath sonicator for 10 min. Next, 15 mL of the few-layer $MoSe_2$ solution is mixed with 150 mg of polyvinyl alcohol (PVA) dissolved in 15 mL of deionized (DI) water (concentration of 10 mg/mL). The 30 mL solution mixture is stirred and heated continuously at a fixed temperature of 80°C using a magnetic stirrer. The solution is reduced to approximately 10 mL after approximately 6 h. This is followed by drying the remaining solution on a glass substrate in an oven at 80°C for 4 h to obtain the $MoSe_2$ thin film.

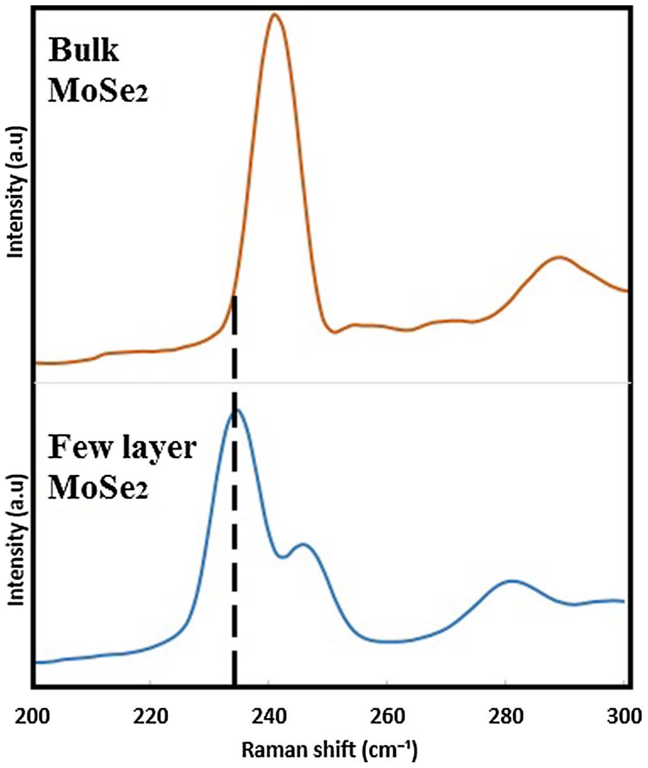

Fig. 1. Raman spectroscopy characterization of the bulk and few-layer $MoSe_2$.

The experimental setup of the proposed EDFL is illustrated in Fig. 2. The ring resonator consists of a 3 m-long erbium-doped fiber (EDF) as the gain medium, a wavelength division multiplexer (WDM), a polarization-dependent isolator (PDI), a polarization controller (PC), a 50 m-long photonics crystal fiber (PCF), a $MoSe_2$ thin film, and 10 dB couplers. The PCF exhibits a group velocity dispersion (GVD) of 90(ps/nm)/km at 1550 nm and a mode field diameter of 9 μm. The EDF used has a doping concentration of 2000 ppm and a GVD parameter of about −21.64(ps/nm)/km. This fiber was pumped by a 980 nm laser diode via the WDM. All of the components and the EDF are connected using the splice technique, whereas the thin film is sandwiched between two pigtails. Unidirectional operation of the ring was achieved with the use of a PDI, while an in-line PC was used to fine tune the linear birefringence of the cavity. The combination of PDI-PCF-PC is used to induced the NPR effect. The output of the laser is collected from the cavity via a 10 dB coupler that retains 90% of the light in the ring cavity to oscillate. The optical spectrum analyzer (OSA) with a spectral resolution of 0.02 nm is used to analyze the spectrum of the proposed multi-wavelength EDFL.

Initially, the $MoSe_2$ thin film is excluded from the cavity. The pump power is fixed at 250 mW (maximum pump power of the photodiode) throughout the experiment. The spectrum is scanned and recorded for every 5 min in a time span of 30 min, as shown in Fig. 3. The light that propagates through the PDI is a linearly polarized light. After propagating through the PC, it become an elliptical polarized light and resolved into two orthogonal polarized light beams. Both polarized light beams are accumulated nonlinear phase shift in PCF due to the high nonlinearity of PCF. The degree of rotation is directly proportional to the light intensity, where the high-intensity light will experience a high degree of phase shift. When the high-intensity light experiences high losses due to the polarization-dependant transmitivity in PDI, mode competition occurs among different wavelengths due to gain saturation in EDF[13]. Therefore, the unstable multi-wavelength oscillation is generated in EDFL as shown in Fig. 3. By incorporating the $MoSe_2$ thin film into the cavity, stable multi-wavelength is generated as shown in Fig. 4. The stable multi-wavelength is scanned and recorded every 5 min in the time span of 30 min. The presence of the $MoSe_2$ thin film in the cavity induced higher birefringence to the cavity. Moreover, the inhomogeneous loss of the $MoSe_2$[14] thin film assisted the suppression of mode competition induced by the homogeneous gain broadening of EDF. Therefore, the stability between the inhomogeneous loss and the mode competition can lead to the generation of stable multi-wavelength[13,15]. Noticed that the peaks of muti-wavelength are not uniform compared to other works which use long single mode fiber

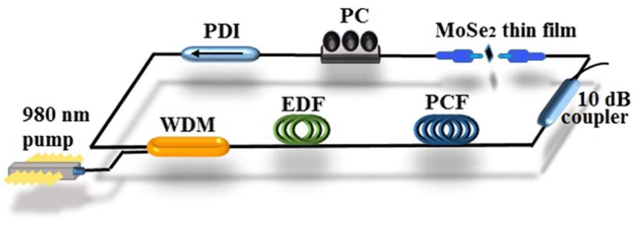

Fig. 2. Schematic diagram of the proposed multi-wavelength EDFL.

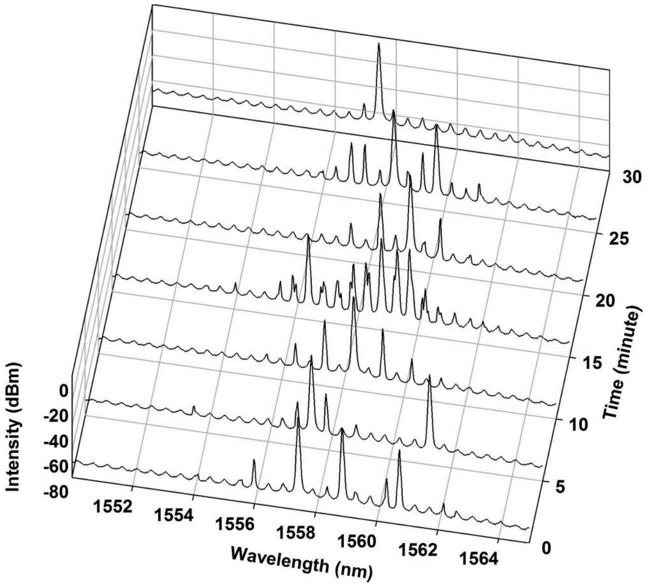

Fig. 3. Spectrum of unstable multi-wavelength EDFL without $MoSe_2$ thin film.

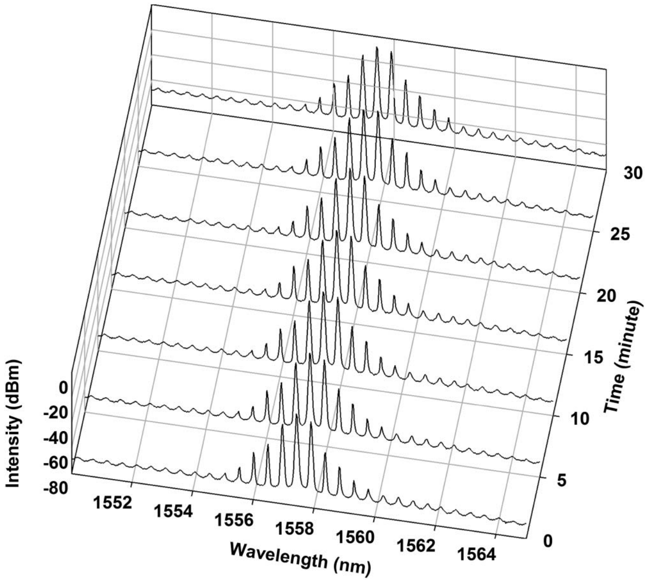

Fig. 4. Spectrum of stable multi-wavelength EDFL with $MoSe_2$ thin film.

(SMF) as birefriengence medium[13]. This is caused by the wavelength dependant loss of $MoSe_2$ thin film[16]. To confirm the wavelength dependent loss of $MoSe_2$ thin film, a tunable laser light source is used to check the loss of $MoSe_2$ thin film from wavelength of 1550–1560 nm with resolution of 0.1 nm. As shown in Fig. 5, the wavelength dependant loss exhibited normal inverse distribution and lowest loss at ~1555 nm. This agrees well with the gaussian modulated peaks pattern in Fig. 4. However, the peak is slightly shifted due to the different $MoSe_2$ thin film sample used in the cavity and wavelength dependant loss measurement.

In Fig. 6, 7 lasings are observed with a constant spacing of 0.47 nm. The free spectral range (FSR) of 0.47 nm is determined by the length and effective group indices of the PCF[17,18]. Furthermore, the average output power is around 2.8 mW at a pump power of 250 mW, which constitutes a laser efficiency of 1.12%. For practical applications, multi-wavelength stability is of vital importance. Fig. 5 also shows the spectral evolution in terms of time.

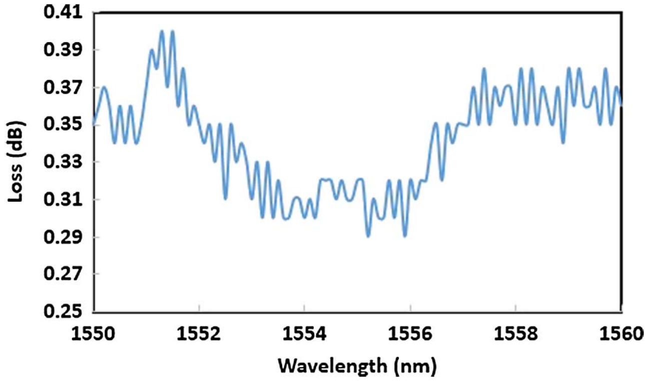

Fig. 5. Wavelength-dependent loss of $MoSe_2$ thin film.

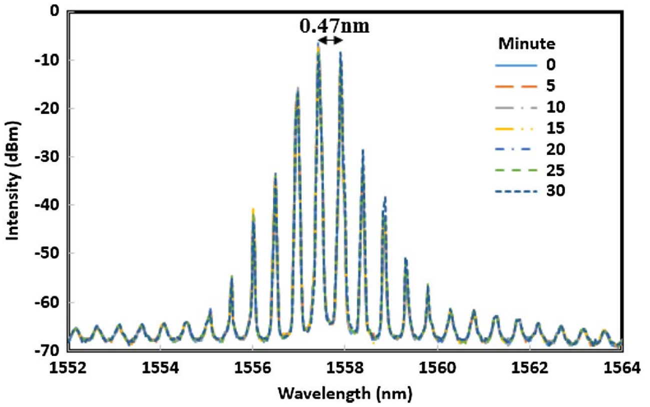

Fig. 6. Multi-wavelength EDFL incorporated $MoSe_2$ thin film.

The output spectrum is repeatedly scanned every 5 min. The multi-wavelength EDFL lases stably, with power fluctuations of less than 5 dB over 30 min. Thermal fluctuations are the main factor that contribute to the operational instability in the conventional EDFL. In the proposed setup, temperature variations and mechanical vibrations were small, as the experiment was conducted in a laboratory; thus, the drift of the spectral profile was minimal.

Throughout the experiment, no Q-switched nor mode-locked generation was observed. In NPR-based multi-wavelength generation, the cavity is operating in a high-loss condition (only low-intensity light propagates through the polarizer). Thus, this condition may interrupt the pulse generation in the cavity.

A multi-wavelength EDFL is demonstrated based on the NPR technique. A 50 m-long PCF is incorporated into the cavity to induce a unstable multi-wavelength oscillation. Furthermore, a $MoSe_2$ thin film is further incorporated into the cavity to achieve a stable multi-wavelength. The laser generates 7 lasings with a constant spacing of 0.47 nm at a pump power of 250 mW. The multi-wavelength EDFL lases stably with power fluctuations of less than 5 dB over 30 min.

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