# Supercontinuum Generation Pump By a Molybdenum Disulfide Based Soliton Mode-Locked Fiber Laser

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## Abstract

In this letter, a highly stable soliton mode-locked Erbium-doped fiber laser (EDFL) is passively obtained using a molybdenum disulfide ($MoS_2$) thin film as a saturable absorber (SA). The $MoS_2$ thin film obtained via electrochemical deposition technique is integrated into an EDFL cavity to generate mode-locked pulses operating at 1.88 MHz with a pulse duration of 3.03 ps. Supercontinuum (SC) light is generated using the proposed soliton mode pulses operating at 1560.4 nm as they are injected into a 100 m long highly nonlinear photonic crystal fiber (HN-PCF) after it is amplified to the output power of 17.8 dBm. The SC light operates in a wavelength range starting from 1360 nm to more than 1750 nm with the intensity above -35 dBm. The proposed supercontinuum laser can be seen as a promising light source for metrology and sensing applications.

*Keywords*: Fiber laser, supercontinuum, molybdenum disulfide, soliton.

## 1. Introduction

Super-continuum (SC) light sources combine the broadband attributes of lamps with the high brightness and spatial coherence of lasers. They have attracted extensive attention in recent years owing to their numerous applications in optical coherent tomography [1], optical communication [2], metrology [3] and sensing [4]. Broadband SC lasers are normally generated through a mode locked laser, which is coupled into a highly nonlinearity fiber (HNLF). The nonlinear mechanisms leading to the generation of SC include stimulated Raman scattering (SRS), four-wave mixing (FWM), self-phase modulation (SPM), cross-phase modulation (XPM), and dispersive-wave generation (DWG) [5]. Since the Raman Effect is self-phase-matched and shifts light to longer wavelength by emission of optical phonons, the SC spreads to longer wavelengths very efficiently. The short wavelength edge arises from four-wave mixing, and often the short wavelength edge is limited by increasing group velocity dispersion in the fiber.

Many works have been performed to understand the phenomenon as well as to implement the intended practical devices. To achieve a wider continuum and higher output power, mode-locked laser system that provides picosecond pulse train with high peak power must be employed as a pump source. Such systems utilizing passive saturable absorber (SA) as a mode-locker have been widely reported over the last decade.

## 2. Methodology

### 2.1. *Fabrication of $MoS^2$ SA*

Within the framework of this experimental investigation, we propose a methodology that leverages the electro-deposition technique. More precisely, the experiment is designed to employ the electrodeposition process for cathodically depositing a molybdenum sulphoselenide film. This deposition procedure will be implemented on tin oxide-coated conducting glass substrates, as well as silicon and/or metal substrates [6]. The electro-deposition technique has undergone thorough investigation, particularly in the fabrication of metallic alloy thin films. As compared to alternative methods, electrodeposition stands out for its scalability and cost-effectiveness. This method is notably advantageous due to its non-vacuum nature and its operation at room temperature [7]. A cyclic voltammetry analysis and the electrodeposition of the thin film are conducted using a three-electrode configuration. The electrolysis cell comprises an ITO-coated conductive film designated as the working electrode (WE), where the deposition of the molybdenum disulfide (MoS2) thin film takes place [8]. In contrast, a graphite rod serves as the counter electrode (CE), and a saturated calomel electrode (SCE) with an Ag/AgCl reference system functions as the reference electrode [9].

## 2.2. *Cavity Characterization*

In this area, we carry out an experimental demonstration of a simplified optical fiber-based supercontinuum source operating a simple mode-locked fiber laser saturating Molybdenum Disulfide ($MoS^2$) as a saturable absorber (SA).

The suggested supercontinuum (SC) laser system is illustrated in Fig. 1, comprising three main keys: the $MoS^2$-based mode-locked Erbium-doped fiber laser (EDFL), an optical amplifier, and a 100-meter-long highly nonlinear photonic crystal fiber (HN-PCF). The mode-locked EDFL utilized a 2.4-meter-long Erbium-doped fiber (EDF) pumped with a 980 nm laser diode serving as the gain medium. The SA was tested by encapsulating the newly developed $MoS^2$ thin film, obtained through the electrochemical deposition technique. We achieved the growth of the $MoS^2$ thin film on a transparent conductive indium tin oxide (ITO) film by functionalizing $MoS^2$ nano-flakes in the presence of monochloroacetic acid. This thin film was integrated into the EDFL cavity to function as a mode-locker.

To enhance the cavity nonlinearity and align the dispersion with the nonlinearity, a 70-meter-long standard single-mode fiber (SMF) with a group velocity dispersion (GVD) of -21.7 ps2/km was incorporated into the cavity. An isolator was employed to maintain unidirectional laser oscillation within the cavity. An 80:20 coupler was utilized to extract 20% of the output laser while retaining 80% of the light within the cavity to sustain the oscillation. The GVD values for both EDF and wavelength division multiplexer (WDM) were approximately 27.6 $ps^2/km$ and -48.5 $ps^2/km$, respectively. The total cavity length amounted to 83 meters, with an anomalous net cavity dispersion of -1.59 $ps^2$. The output from the mode-locked laser was subsequently amplified and introduced into the HN-PCF for generating supercontinuum light.

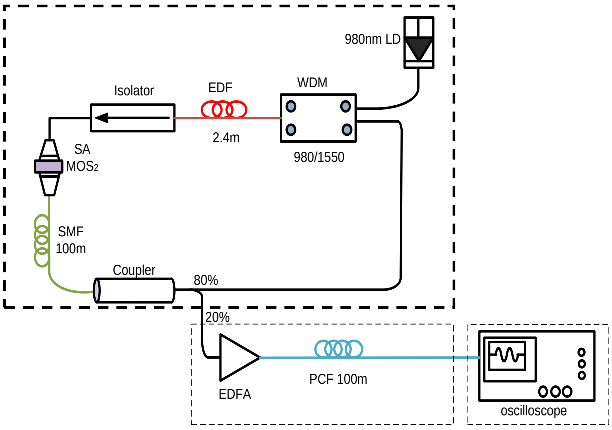

Fig 1. The SC laser system consisting of three main components namely $MoS_2$ based mode-locked laser, optical amplifier, and a HN-PCF spool.

## 2.3. *Mode-Locking of $MoS^2$*

With anomalous net cavity dispersion, fundamental mode locking in the soliton regime is achieved from the EDFL at the pump power of 76.8 mW. By adjusting the pump power up to the maximum pump power of 123.7 mW, the mode-locking state is still preserved. The output spectrum of the output pulses measured by an optical spectrum analyzer (OSA) is depicted in Fig. 2. It centered at 1560.4 nm with a 3 dB spectral width of 2.2 nm. The Kelly sidebands are clearly seen to appear at both sides of spectrum symmetrically, indicating the EDFL operates in conventional soliton mode-locking state. Fig. 3 illustrates the typical pulse train, which has uniform intensity with the interval of two pulses of 536 ns. The pulse period corresponds to the repetition rate of 1.88 MHz, which agrees with the cavity length. The radio-frequency spectrum is measured to study the stability of soliton pulse as shown in Fig. 4. The signal-to-noise ratio (SNR) at the fundamental repetition rate of 1.88 MHz is measured to be higher than 60 dB, which indicates the pulsed laser operates at high stability. Fig. 5 shows the autocorrelation curve, which was obtained by an autocorrelator to measure pulse duration. The full width at half maximum (FWHM) is 4.70 ps, which indicates that the pulse duration is 3.03 ps considering the pulse shape is $Sech^2$.

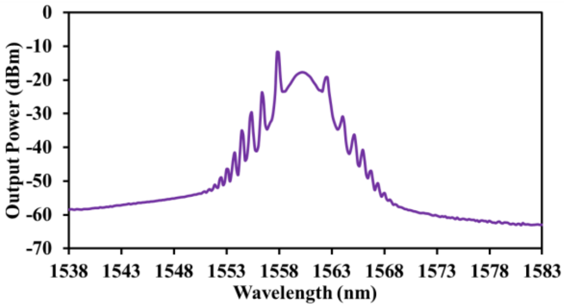

Fig 2. Output Spectrum taken from OSA

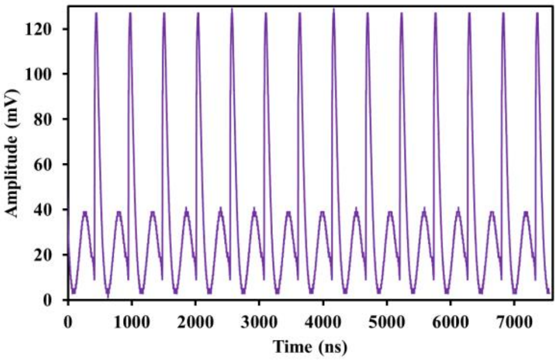

Fig 3. Output measured from oscilloscope

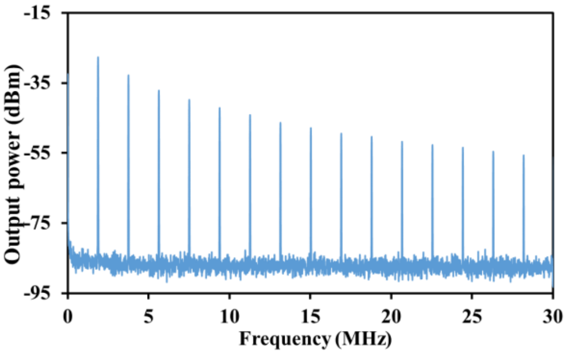

Fig 4. Radio Frequency Output at 30MHz span

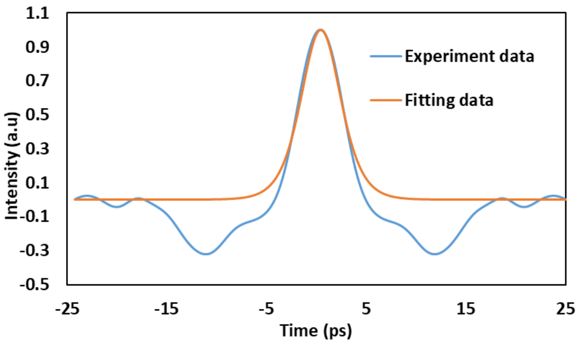

Fig 5. Autocorrelator

The average output power and pulse energy characteristics are shown in Fig. 6. As the pump power increases, both output power and pulse energy increase almost linearly. At the maximum pumping of 123.7 mW, the output power and pulse energy are obtained at 0.79 mW and 0.42 nJ, respectively. To generate SC photons, the soliton laser is amplified by the optical amplifier and then launched into the HN-PCF. The amplifier boosts the signal up to the output power of 17.8 dBm so that it can initiate a spectral broadening in the so-called ‘long pulse’ regime. The HN-PCF used in the experiment has a zero dispersion at 1550 nm with á length of 100 m and nonlinearity coefficient of around 11W$^{-1}$ km$^{-1}$.

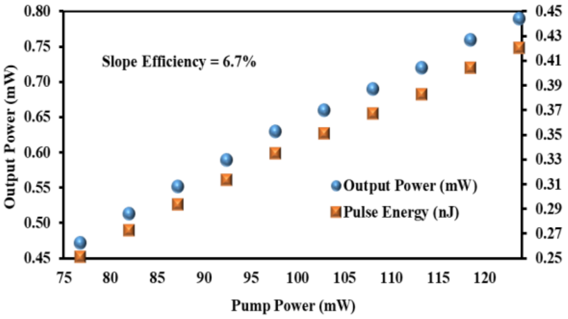

Fig. 6. The average output power and pulse energy at various launched pump power.

## 3. Results and Discussion

### 3.1. *Generation of Supercontinuum Light*

As the soliton picosecond pulses created through saturable absorption of $MoS_2$ are coupled into a HN-PCF, broadband SC photons are generated via various nonlinear mechanisms as shown in Fig. 7. We observe an SC light spanning from 1360 nm up to more than 1750 nm with output power of more than -35 dBm. As the amplified 1560.4 nm soliton pulse laser is injected into the PCF, the SC spreads to longer wavelengths very efficiently due to Raman effect, which is self-phase-matched to allow a shifting of light to longer wavelength by emission of optical phonons. The short wavelength edge arises from parametric four-wave mixing, which breaks up the higher-order solitons to produce frequencies at wavelengths shorter than the zero-dispersion wavelength.

The SC bandwidth can be further expanded by increasing the peak power of the injected pulses. This could be realized by improving the average power as well as compressing the pulse duration of the mode-locked laser. We expect a smaller pulse duration with the improvement of modulation depth and non-saturable loss of the $MoS_2$ SA. The use of an amplifier with higher saturated output power is also expected to further expand the bandwidth as well as improving the flatness and power of SC light.

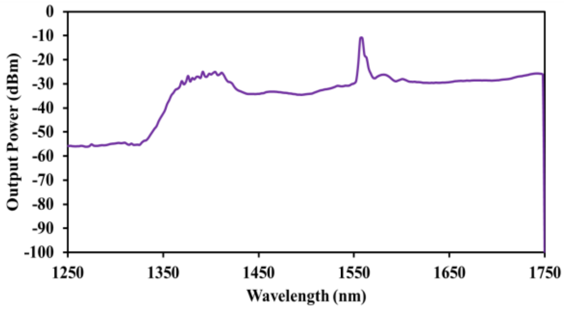

Fig. 7. SC generation due to the injection of the amplified soliton pulses into 100 m long HN-PCF.

From the broader bandwidth SC output, the potential application can be implemented are pulse generation, pulse amplification, pulse compression, metrology, spectroscopy, imaging, telecom and on-chip integration [10].

## 4. Conclusion

In conclusion, our research endeavors have yielded a successful demonstration of broad-spectrum supercontinuum (SC) light generation through the implementation of a newly developed mode-locked Erbium-doped fiber laser (EDFL) utilizing Molybdenum Disulfide (MoS$^2$) as a saturable absorber. The MoS2 thin film, synthesized via the electrochemical deposition technique, was seamlessly integrated into the EDFL cavity. This integration facilitated the generation of mode-locked soliton pulses operating at 1560.4 nm, characterized by a repetition rate of 1.88 MHz and a pulse duration of 3.03 picoseconds. The resultant pulses were subsequently amplified to an output power of 17.8 dBm and introduced into a 100-meter-long highly nonlinear photonic crystal fiber (HN-PCF) to induce SC light. The generated supercontinuum light spans a wavelength range from 1360 nm to beyond 1750 nm. This achievement holds significance in the context of advancing optical sources for applications in diverse fields such as telecommunications, metrology, and sensing.

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## Authors Introduction

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