Dispersion-managed Tm-doped fiber laser mode-locked with a black phosphorus saturable absorber

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Abstract: We demonstrate an all-fiber Tm-doped mode-locked fiber laser utilizing a black phosphorus saturable absorber. The oscillator delivers self-starting, 139 fs pulses centered at 1859 nm with 55.6 nm spectral bandwidth.

1. Introduction

Ultrafast laser sources at 2 μm spectral region have been extensively investigated due to increasing potential for applications, including in remote gas sensing, biomedical surgeries and longer mid-infrared wavelengths generation [1, 2]. While many saturable absorber (SA) devices for generating pulsed laser emission exist, the field of nanomaterial SAs has gained traction as grapheme [3], semiconducting transition metal dichalcogenides (TMDs) [4] and black phosphorus (BP) [5, 6]exhibit strong intensity-dependent absorption, broadband working wavelength range, ultrafast carrier dynamics and ease of all-fiber integration. Among these 2D material-based SAs, BP has shown a particular interest in recent years due to its unique band structures, i.e. a layer-dependent bandgap covering from 0.3 eV (bulk) to 2 eV (monolayer), making it more attractive over zero-bandgap graphene and large-bandgap TMDs for ultrashort pulse generation at 2 μm. Previous reports have demonstrated BP-based SAs operating in the soliton mode-locking regime with pulse duration limited to sub-picosecond scale [7]. An effective and compact solution to overcome this limitation is to utilize a dispersion management approach, balancing the dispersion and nonlinearity in the cavity [8]. Pulses propagating in the cavity experience breathing in one round-trip time, leading to a significant reduction of the achievable pulse duration. Here, we demonstrate a self-starting mode-locked Tm-doped fiber laser utilizing a BP SA. Through intracavity dispersion management, the BP-based SA produces 139 fs pulses with 55.6 nm spectral bandwidth, representing 5.3 times improvement in pulse duration and 9.5 times in spectral bandwidth compared to previous reports.

2. Experimental setup and results

BP flakes (~3.4 nm, 6 layers) are first exfoliated from bulk crystals using ultrasound assisted liquid phase exfoliation and then uniformly deposited onto an ultrathin polymer substrate by inkjet printing, followed by encapsulation with a 100 nm thick pin-hole free passivation layer [9]. The BP-SA with a measured modulation depth of 20%, saturation intensity of 125 MW/cm^2 [Fig. 1(a)], is inserted into a fiber laser by sandwiching two ~1 mm × 1 mm pieces between two FC/APC fiber connectors.

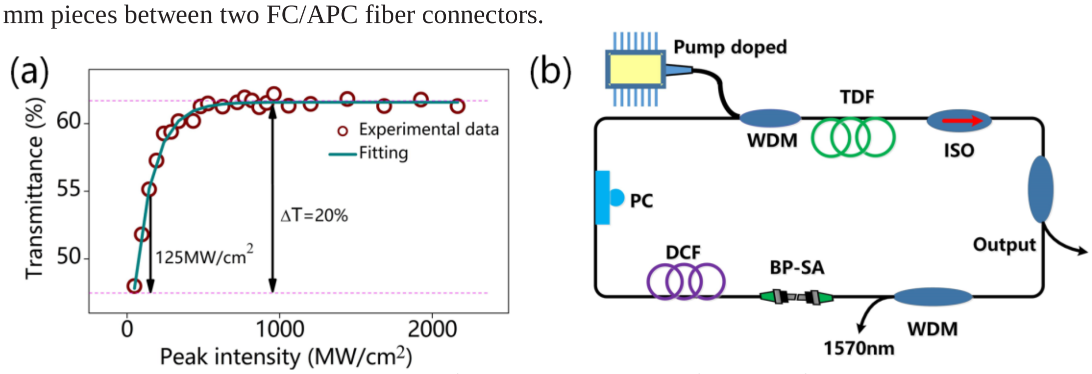

Fig.1. (a) Measured saturable absorption and fit. (b) Schematic diagram of Tm-doped fiber laser using BP-SA

The schematic diagram of the BP-SA based dispersion-managed soliton Tm-doped fiber laser is depicted in Fig. 1(b), including a 1.83 m-long length Tm-doped active fiber (Nufern SM-TSF-9/125), co-pumped by a continuous-wave 1569 nm fiber laser through a 1.1m fused 1550/1900 wavelength division multiplexer (WDM), a 50:50 output coupler, an inline polarization-independent isolator to ensure unidirectional propagation, and a polarization controller (PC) to adjust the intracavity birefrigence. A length of 4 m UHNA4 is used to compensate for intracavity dispersion. The net group velocity dispersion (GDD) of the cavity is estimated as 0.015 ps^2.

Self-starting mode-locking is observed at the fundamental repetition frequency of 20.95 MHz, with a corresponding time interval of 47.4 ns [Fig. 2(a)]. The average output power is 20.4 mW at a pump power of 850mW, corresponding to a single pulse energy of 0.97 nJ. The spectrum is centered at 1859.3 nm with an FWHM (full width at half maximum) of 55.6 nm; Fig. 2(b). Figure 2 (c) shows the fundamental frequency spectrum of the laser output, with a single-to-background background of > 60 dB, without any Aharmonic components, indicating a stable operation of the mode-locking performance. The measured pulse duration of 139 fs is shown in Fig. 2 (d), with a Gaussian fit. The time-bandwidth product is 0.67, indicating that the pulse has a low-Chirp, likely due to the uncompensated high-order dispersion.

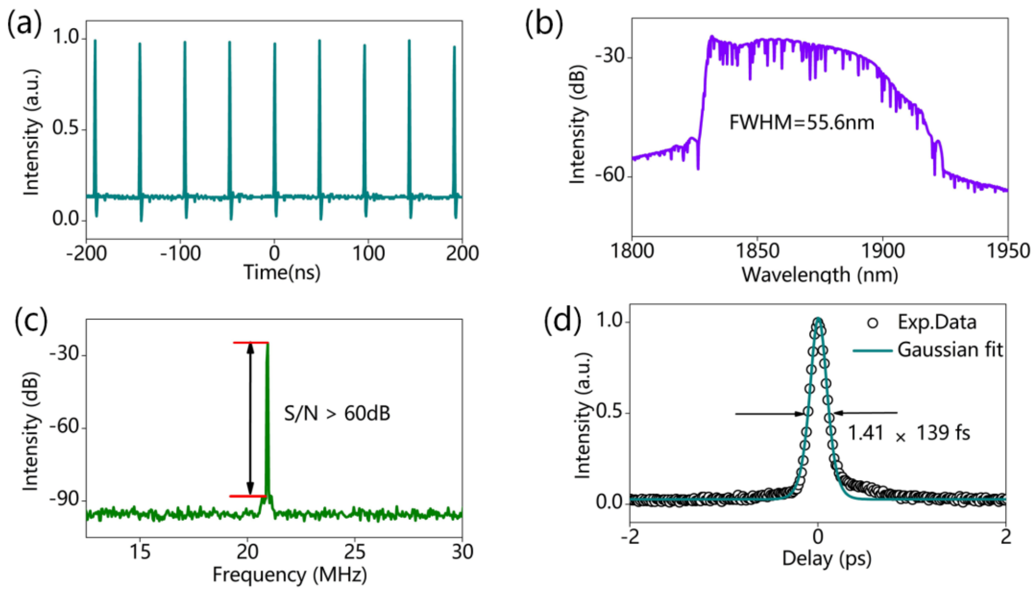

Fig. 2. Output performances of the Tm:fiber mode-locked laser based on a BP-SA. (a) Oscilloscope trace, (b) optical spectrum, (c) autocorrelation trace, (d) fundamental radio frequency spectrum.

3. Conclusion

In summary, we have demonstrated an all-fiber Tm-doped BP-based mode-locked fiber laser, generating self-starting pulses with 139 fs duration, 55.6 nm bandwidth. To the best of our knowledge, this is the shortest pulse with the broadest spectral bandwidth directly from a 2D material-based Tm-doped fiber laser, suggesting the potential for BP and other 2D material-based SAs in femtosecond-pulse laser technology

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5. References

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