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Dynamic evolution of the dissipative soliton in passively mode-locked fiber laser based on black phosphorus as a new saturable absorber

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ABSTRACT

Black phosphorus (BP) is a promising two dimensional (2D) material due to its electronic and optical properties. Hence, we use BP as a new saturable absorber in passively mode-locked (PML) fiber laser to generate dissipative solitons. Numerical simulations show that under the same conditions, the dissipative soliton generated by PML fiber laser based on BP as a saturable absorber has better physical properties than other 2D materials (such as graphene, transition metal dichalcogenides, topological insulators) as a saturable absorber. With the increase of pump power, dissipative soliton requires more pump power to split into multi-soliton, which means PML fiber laser using BP as a saturable absorber generates the dissipative soliton has high nonlinearity tolerance. According to this paper we can find that BP is an ideal saturable absorber and can be used for ultrashort optical pulse generation.

1. Introduction

Ultrafast fiber lasers offer a great number of applications in optical communications, optical sensors, industrial material processing, biomedical diagnostics and frequency metrology [1–6]. In the past decades, it has been demonstrated that the passively mode-locked (PML) fiber laser is a simple and economical way to generate the ultrashort pulse. Compared with the active mode-locked technology, PML fiber laser has many advantages of compactness, simplicity, flexibility and high quality of the output pulse [7–11]. To date, both the artificial saturable absorber [12–14] and real saturable absorber [15–31] were proposed to achieve ultrashort pulses in PML fiber laser. Among them, due to their intrinsic environmental stability and the abundant saturable absorption materials, real saturable absorbers were in widespread use in fiber laser. Semiconductor saturable absorption mirrors (SESAMs) are the most widely used due to their high flexibility and stability. However, SESAMs have drawbacks of high cost and a limited range of optical response, which restrict their applications to a great extent [15,16]. Recently, the newly emerging two-dimensional (2D) materials such as graphene [17–19], transition metal dichalcogenides (TMDs) [20–22] and topological insulators (TIs) [23–25], attracted a lot of attention in ultrafast laser community due to their distinguished advantages such as ultrafast recovery time and easy fabrication. TI has insulating bulky states with indirect band-gap of 0.35 eV and gapless surface states. It had also been successfully applied as an effective saturable absorber [26,27], but has again the drawback of complicated preparation process, which severely limited its applications in optoelectronic devices. Graphene has been a new nonlinear optical material for the generation and modulation of laser pulses, which could find important applications for telecommunications and optical sensing [28–30]. Though it possesses wavelength-independent saturable absorption as a result of the absence of band-gap, the low modulation depth resulted from its low absorption efficiency (2.3% per layer) is not suitable for the pulsed fiber laser [31]. TMDs have a high resonant absorption up to 20%, but the optical response mainly lies in visible range due to a moderate band-gap (1 eV for bulk and 2 eV for monolayer), it is noteworthy that great technological demands for optical communications exist mainly in the infrared wavelength range round 1500 nm (0.8 eV). Hence, the relatively large direct band-gaps corresponding to the visible spectrum range limits their applications in infrared region [32,33].

Fortunately, black phosphorus (BP) as a new member of the 2D materials with band-gap from 0.3 (bulk) to 1.5 eV (monolayer), can bridge the gap between zero-gap graphene and the relatively large band-gap TMDs for infrared photonics and optoelectronics [34,35]. Hence, BP is a very promising material for telecommunication due to its direct band-gap and strong resonant absorption in near-infrared wavelength range. Although BP has attracted enormous attention owing to its unique electronic properties [36–38], ultrafast nonlinear photonic applications relying on the ultrafast photocarrier dynamics as well as optical nonlinearity in BP remain unexplored.

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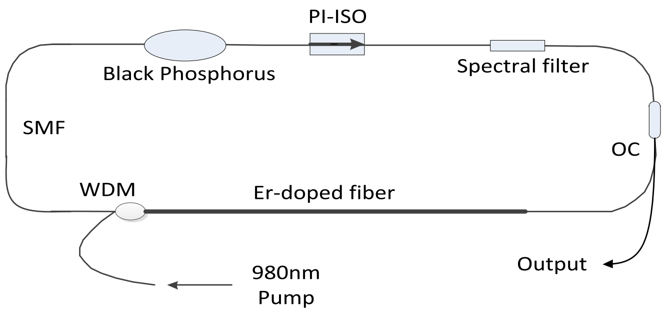

Fig. 1. A schematic diagram of PML fiber laser using BP as a saturable absorber; WDM: wavelength division multiplexer; OC: optical coupler; PI-ISO: polarization-independent isolator.

Table 1
Saturable absorption properties of different 2D materials.

2D materials	Saturation intensity ($MW\ cm^{-2}$)	Nonlinear absorption	
		α_S (%)	α_{NS} (%)
Black phosphorus [34]	6.55	8.1	31.6
Graphene [28]	53.25	2.93	50.05
TMD(MoS_2) [33]	34	4.3	24
TI [23]	12	3.9	67.5

In this paper, we use BP as a new saturable absorber in PML fiber laser to generate dissipative solitons. In order to prove that BP is an ideal candidate for saturable absorber, we also use other 2D materials (such as graphene, TMDs, TIs) as a contrast. Numerical simulations show that the dissipative soliton generated by PML fiber laser using BP as a saturable absorber has better physical properties than other 2D materials as a saturable absorber. With the increase of pump power, the dissipative soliton split into multi-soliton requires high pump power, which means PML fiber laser based on BP as a saturable absorber generates the dissipative soliton can tolerate high nonlinearity.

2. Theoretical modeling

To study the feature and dynamic evolution of the dissipative soliton in PML fiber laser using BP as a saturable absorber, we implement a numerical model that incorporates the most important physical effects such as the saturable absorber, spectral filtering, etc. The schematic diagram of the PML fiber laser is shown in Fig. 1. It consists of a 1.2 m erbium-doped fiber (EDF) and 8.2 m single mode fiber (SMF), filter is a Gaussian spectral filter with 15 nm bandwidth. When the initial pulse propagate through the saturable absorber and the intensity transmission, $T(I)$ is expressed as

$$T(I)=1-\frac{\alpha_S}{1+I(t)/I_{Sat}}-\alpha_{NS} \tag{1}$$

where α_S and α_{NS} are the modulation depth and nonsaturable absorption. $I(t)$ is the instantaneous pulse energy, and I_{Sat} is the saturation

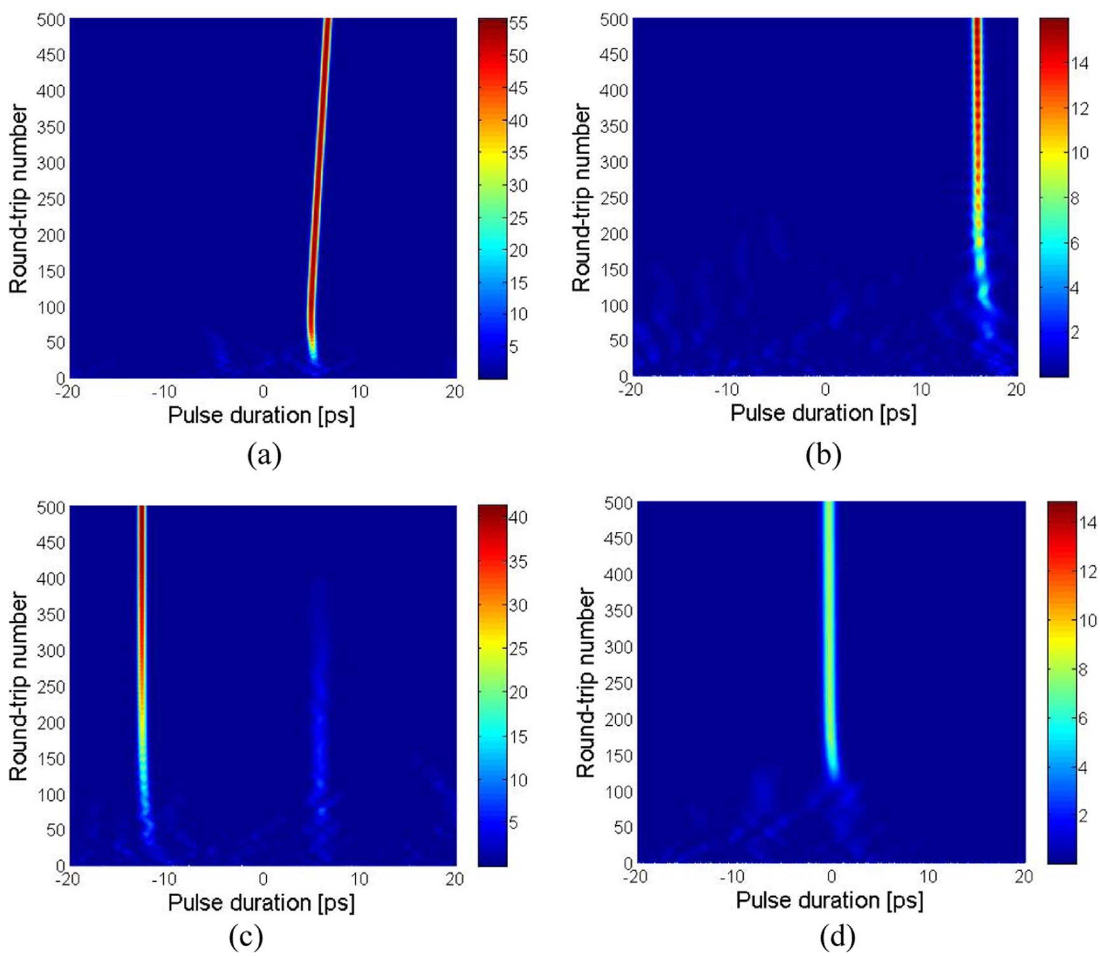

Fig. 2. When g_0=3 m^{-1}, temporal evolution of dissipative soliton in PML fiber laser using different 2D materials as a saturable absorber. (a) BP as a saturable absorber. (b) Graphene as a saturable absorber. (c) MoS2 as a saturable absorber. (d) TI as a saturable absorber.