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Effects of nanomaterial saturable absorption on gain-guide soliton in a positive group-dispersion fiber laser: Simulations and experiments

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ABSTRACT

In recent years, several kinds of nanomaterials have been discovered, and successfully used as saturable absorbers (SAs) for passively mode-locked fiber lasers. However, it is found that most of nanomaterials-based SAs cannot stably generate gain-guide solitons in positive group-dispersion fiber lasers, which is urgently expected to fully understand the inherent reasons. In this paper, we numerically and experimentally investigate the effects of nanomaterial saturable absorption (e.g. modulation depth and saturation optical power) on gain-guide soliton in positive group-dispersion Er^{3+}-doped fiber laser (PGD-EDFL). By numerically solving the Ginzburg–Landau equation, the evolutions of both the mode-locked optical spectrum and pulse duration as a function of modulation depth and saturation optical power are analyzed, respectively. In experiment, we firstly prepare five nanomaterial SAs with the similar insertion loss, which have the different modulation depth from 1.80% to 23.36%, and the different saturation optical power from 8.8 to 536 W. We then perform the experimental comparison by incorporating the five SAs in a same PGD-EDFL cavity, respectively. The experimental results are in good agreement with the numerical ones. Our result reveals that: (1) a low modulation depth cannot support the formation of gain-guide soliton, (2) as the modulation depth increases, the spectral bandwidth of gain-guide soliton increases, the pulse duration decreases and the pulse chirp becomes large, (3) the saturation optical power has the weak influences on the gain-guide soliton performances.

1. Introduction

Passively mode-locked fiber lasers (PMLFLs) have attracted great interest owing to their widespread applications, including spectroscopy, medicine, telecommunications, biomedical imaging, optical sensing and material processing [1–6]. Compared with other types of mode-locked lasers (e.g. Ti:sapphire [7], laser diodes [8], Yb:KGW [9], Nd:YVO_4 [10]), PMLFLs are more compact, lower cost, user-friendly, maintenance-free and high spatial beam quality [11]. In general, passive mode-locking in fiber laser is usually established through a saturable absorber (SA) [12–22], such as dyes [12,13], transition-metal-doped crystals [14], semiconductor saturable absorber mirrors (SESAMs) [15], nanomaterials [16–28] and other artificial SAs [29–32] (e.g. nonlinear polarization rotation and nonlinear optical loop mirror). Among them, nanomaterials are the most popular SAs in recent years because of their advantages of high-performance, easy-fabrication and low-cost.

Over the past decade, several kinds of nanomaterials have been successively discovered as potential SAs. In 2003, Set et al. reported the carbon-nanotubes (CNTs) passively mode-locked Er-doped fiber laser [19]. In 2009, graphene was found to possess the excellent saturable absorption in ultra-broadband spectral region [17], and this triggered a worldwide upsurge in research interest of two-dimensional materials as optical SAs. Topological insulators (TIs) with the ultrahigh modulation depth were demonstrated as the effective SAs in 2012 [20]. Subsequently, transition metal dichalcogenides (TMDs) were revealed as broadband SAs [21]. In 2015, black phosphorus as a new and attractive SA was also reported due to its excellent properties (e.g. high carrier mobility, thickness-dependent optoelectronic response and mechanical properties) [16]. In 2016, both of few-layer perovskite [33] and C_3N_4 [34] for passive mode-locking have been presented as well. It should be noted that all of these nanomaterial-based SAs have already been used to

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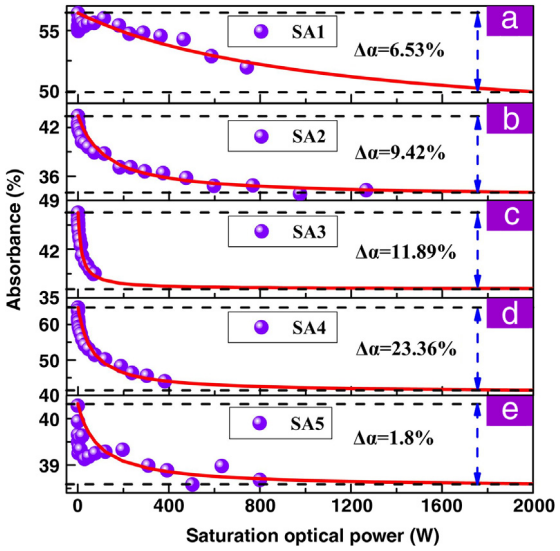

Fig. 1. The measured power-dependent absorption curves of the five SAs, respectively.

successfully obtain passive mode-locking in fiber lasers, which therefore manifests the important contribution of nanomaterial-based SAs for the ultrafast fiber laser.

In general, fiber laser cavity with negative dispersion can generate traditional soliton [35,36], based on the balance of negative dispersion and self-phase modulation [37–40]. However, the soliton pulse energy is usually limited to < 1 nJ. In order to boost pulse energy, one of most effective methods is to generate gain-guide soliton by adjusting fiber laser cavity in the positive dispersion regime, therefore generating high-energy, large-chirp and ultrashort pulses [41–43]. However, it was usually found that gain-guide soliton in positive-dispersion fiber laser is difficultly realized by most of the nanomaterial-based SAs. Therefore, there are always strong motivations to understand the effects of saturable absorption parameters on gain-guide soliton in positive group-dispersion fiber laser. Although Jeon et al. numerically studied the minimum modulation depth of SA for stable passive mode-locking [44], the systematical investigation of SA parameters' effects on gain-guide soliton has not yet been performed, and the corresponding experimental confirmation has not been done in particular.

In this paper, we numerically and experimentally investigated the influences of nanomaterial saturable absorption (both the modulation depth and saturation intensity) on gain-guide soliton in positive group-dispersion Er-fiber laser. Five nanomaterial-based SAs were firstly fabricated with different modulation depth from 1.80% to 23.36%, the saturation optical power from 8.8 to 536 W and the insertion loss of 34%–49%. By solving the Ginzburg–Landau equation (GLE), then we numerically simulated the effects of SA's modulation depth and saturation optical power on gain-guide soliton. At last, we performed the experimental studies of gain-guide solitons in a positive-dispersion Er-doped fiber laser using the as-prepared five nanomaterial SAs, respectively, and further compared the experimental results with theoretical ones.

2. Five nanomaterial-based SAs and their characteristics

In this work, we fabricated five nanomaterial-based SAs using either CNTs or graphene. Our graphene was prepared by the solution-based route (details described in Ref. [45]). Initially, natural graphite powder was chemically oxidized and exfoliated under ultrasonication to obtain the graphene-oxide aqueous suspension, and then it was reduced by hydrazine/ammonia solution to produce few-layer graphene. Polyvinyl alcohol (PVA) powders were further dissolved in the graphene solution by ultrasonication. The single-wall CNTs used in our work were grown by laser ablation technique. The CNTs with four different concentrations were then dispersed into host-polymer polyvinyl alcohol (PVA), respectively. At last, five kinds of freestanding nanomaterial-polymer films could be obtained by drying the graphene-PVA and CNTs-PVA solutions, respectively.

Table 1
The measured parameters of five SAs.

	Type	ΔT or $\Delta\alpha$	T_0	α_0	P_{sat}
SA 1	CNTs	6.53%	43.59%	49.88%	536 W
SA 2	CNTs	9.42%	65.55%	34.07%	115 W
SA 3	CNTs	11.89%	52.73%	36.38%	18 W
SA 4	CNTs	23.36%	35.19%	41.57%	59 W
SA 5	Graphene	1.80%	59.70%	38.52%	8.8 W

The as-prepared nanomaterial-PVA films were sandwiched by two fiber ferrules, and therefore five kinds of fiber-compatible SAs were successfully obtained finally. The saturable absorption characteristics of the five SAs were measured by a balanced twin-detector measurement system (described in Ref. [46]). The results are shown in Fig. 1, and the power dependent absorption curves are fitted by the following equation:

$$\begin{aligned}\alpha &= \alpha_0 + \Delta\alpha \Big/ \left(1 + \frac{P}{P_{\text{sat}}}\right) \\ &= 1 - T_0 - \Delta T \cdot \left(1 - \frac{1}{1 + P/P_{\text{sat}}}\right)\end{aligned} \tag{1}$$

where α_0, T_0, $\Delta\alpha$ (ΔT), P_{sat} represent non-saturation loss, initial transmittance, modulation depth and saturable optical power, respectively. P is the pulse peak power. The detail parameters have been measured and listed in Table 1. The modulation depths of the as-prepared five SAs cover from 1.80% to 23.36%, and the saturation optical power has a broad distribution from 8.8 to 536 W.

3. Numerical simulations

In this section, the GLE is used to simulate the effects of SA's modulation depth and saturation optical power on passively mode-locking performances. We neglect the influence of SA's recovery time on passively mode-locked in our work, because the ultrafast recovery time of most nanomaterial-based SAs is about sub-100 fs [47] or sub-picosecond.

3.1. Theoretical model

In order to fully compare with our experiment, we used the simulation numerical model of passively mode-locked fiber laser as same as our experimental configuration. As seen in Fig. 2(a), the laser cavity consists of 6.6-m erbium-doped fiber pumped by a 976 nm laser diode through a 980/1550 nm wavelength division multiplexer (WDM), optical isolator (ISO), 10/90 optical coupler (OC), fiber-compatible SA, polarization controller (PC) and 3.6-m single mode fiber (SMF-28, Corning inc.). The parameters of each component are listed in Table 2. The total cavity length is ~12.2 m, corresponding to a free spectral range of ~17 MHz. The net cavity dispersion is about 0.0324 ps^2. In order to understand the propagation model, an equivalent model has been given in Fig. 2(b), and the last thing is to calculate the pulse evolution of each part separately in Fig. 2(b).

We use the GLE to simulate pulse propagation in the laser cavity. Considering most of important physical effects including group velocity dispersion (GVD), self-phase modulation and saturated gain with a finite bandwidth, the GLE describes as follow:

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = \frac{g}{2}A + i\gamma|A|^2 A + \frac{g}{2\Omega_g^2}\frac{\partial^2 A}{\partial t^2} \tag{2}$$

where,

$$g = \frac{g_0}{1 + P_{\text{avg}}/P_{\text{sat,g}}} \tag{3}$$

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