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Dark solitons in erbium-doped fiber lasers based on indium tin oxide as saturable absorbers

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ABSTRACT

Dark solitons, which have good stability, long transmission distance and strong anti-interference ability. By using a coprecipitation method, the high quality indium tin oxide (ITO) were prepared with an average diameter of 34.1 nm. We used a typical Z-scan scheme involving a balanced twin-detector measurement system to investigated nonlinear optical properties of the ITO nanoparticles. The saturation intensity and modulation depths are 13.21 MW/cm^2 and 0.48%, respectively. In an erbium-doped fiber (EDF) lasers, we using the ITO nanoparticles as saturable absorber (SA), and the formation of dark soliton is experimentally demonstrated. The generated dark solitons are centered at the wavelength of 1561.1 nm with a repetition rate of 22.06 MHz. Besides, the pulse width and pulse-to-pulse interval of the dark solitons is ~1.33ns and 45.11 ns, respectively. These results indicate that the ITO nanoparticles is a promising nanomaterial for ultrafast photonics.

1. Introduction

In nonlinear systems, solitons can be divided into bright and dark ones [1]. The formation of dark solitons is the same as that of bright solitons, which is an intrinsic feature of the nonlinear light propagation in the normal dispersion regimes [2,3]. Recently, dark solitons as a unique optical phenomenon are widely investigated in nonlinear and ultra-fast optics [4–10]. Compared with the bright solitons, dark solitons have many advantages, such as high stability, long transmission distance, small time jitter and strong anti-interference ability [11]. Thus, dark soliton pulses have wide application potential in the fields of precision measurement, all-optical nonlinear communication and nonlinear optics [12–16].

Dark solitons formed in the erbium-doped fiber (EDF) laser were obtained in Ref. [17] firstly, since then, researchers have explored different saturable absorbers (SAs) based on various nanomaterials for generating dark solitons in the EDF laser. For example, Wei et al. demonstrated dark solitons with WS_2-based SAs in the EDF fiber laser [18]; Liu et al. observed dark solitons in EDF lasers based on Sb_2Te_3 saturable absorbers [19]; Zhao et al. indicated that the generation of L-band bright and dark pulses can be achieved within a graphene-oxide (GO) mode-locked EDF laser [20]. However, all of these 2D materials have an inefficient light-matter interaction. This becomes their bottleneck in the application of the optoelectronic devices [21]. Therefore, a new SAs with strong light-matter interaction, broad saturable absorption region, ultrafast recovery time and cost-effective fabrication for generation of dark solitons pulses is highly desirable and yet to be developed. By analyzing the recent developments on different SAs based on 2D semiconductors, graphene and zero-gap materials of semimetals and topological insulator, we can refer to the stable sequence below to select the SAs: oxide plasmonic nanocrystals > graphene, transition metal dichalcogenides (TMDs) > black phosphorus (BP) and other metal compounds (selenide, telluride, etc.) [22]. Oxide plasmonic nanocrystals will become promising nanomaterials because of their unique properties, such as efficient light-matter interaction, excellent optical nonlinearity, outstanding plasmonic absorption characteristic and mature preparation process [23,24]. So, using oxide plasmonic nanocrystals as SAs is the ideal choice for the formation of dark solitons.

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In our work, indium tin oxide (ITO) as one of oxide plasmonic nanocrystals was employed for dark solitons. To our knowledge, this is the first demonstration that the ITO nanoparticles are used as SAs for dark solitons pulses generation. There are three reasons for using the ITO nanoparticles as SAs. First, the conductive oxides has a lower carrier density, so the plasmonic absorption of ITO in the near infrared region (NIR) has a strong peak and a broad bandwidth [25]. Second, the peak of the plasmonic absorption can be adjusted from 1600 to 2200 nm by changing the concentration of tin doped in ITO [26]. This characteristic endow the ITO an even broader saturable absorption region. Third, recent studies have showed that thin films of the ITO demonstrate large optical nonlinearity. Besides, they report that the ITO have a ultrafast recovery time of about 360 fs [24]. High quality ITO nanoparticles with an average diameter of 34.1 nm was prepared by using a coprecipitation method. By directly dropping ITO colloidal liquid between two fiber connectors in EDF lasers, the dark soliton formation is experimentally demonstrated. A series of optical spectra of dark solitons pulses based the ITO SAs are presented. These results will make great significance for further studies of dark soliton. In addition, this study shows that the ITO is a promising candidate for the ultrafast photonics.

2. Experimental step

2.1. Preparation of ITO nanoparticles

Nanocrystalline ITO powders were obtained by using a coprecipitation method. First, by adding indium into the sulfuric acid, the $In_2(SO_4)_3$ solution was obtained. And then the $In_2(SO_4)_3$ solution

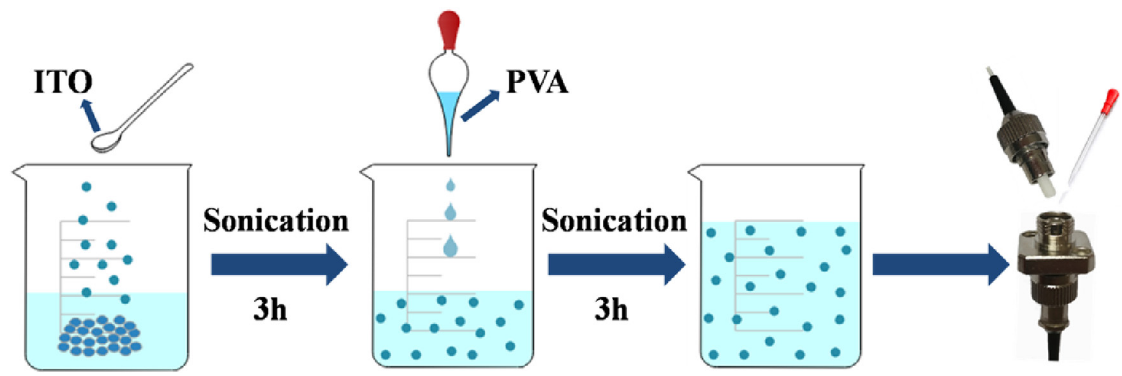

Fig. 1. Fabrication process of the ITO SAs.

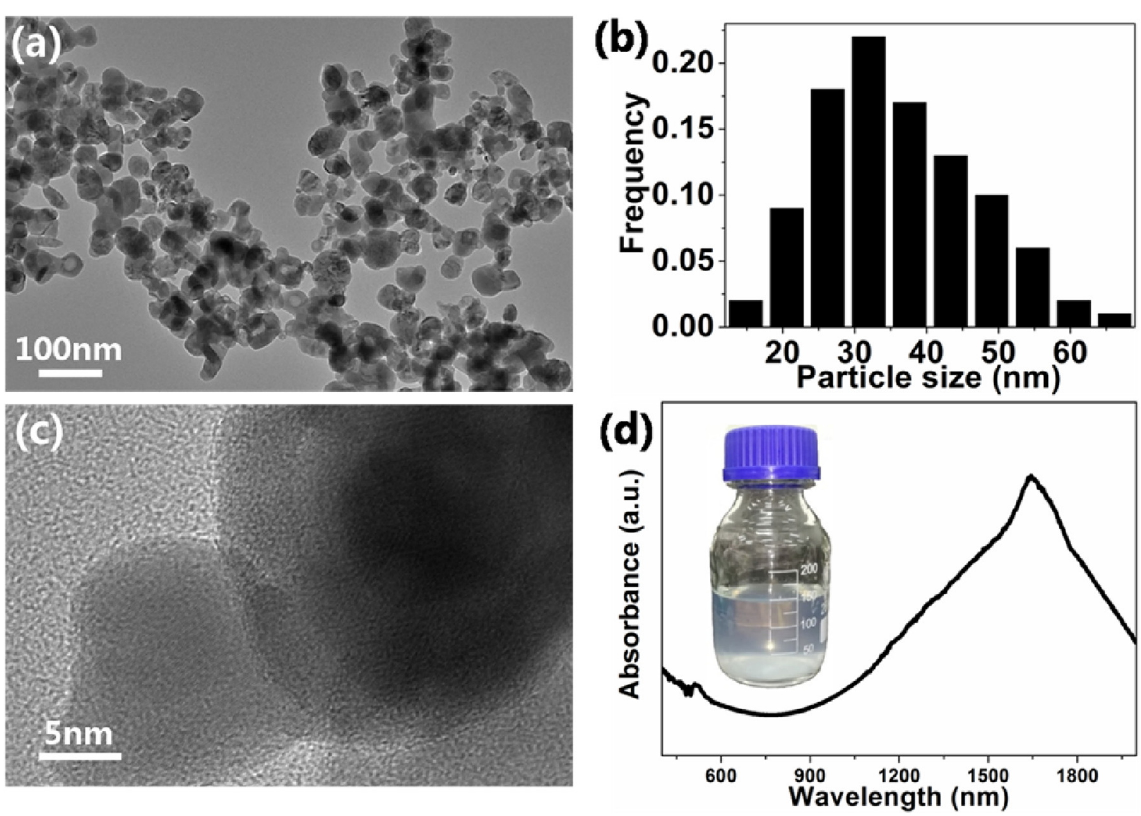

Fig. 2. (a) TEM image of the ITO nanoparticles. (b) The particle size distribution of the ITO nanoparticles from the TEM image. (c) HRTEM image of the ITO nanoparticles. (d) Absorption spectrum of the ITO dispersion solution.