Optics and Laser Technology 103 (2018) 354–358

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Generation of dark solitons in Er-doped fiber laser based on ferroferric-oxide nanoparticles

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ARTICLE INFO

Article history:
Received 16 October 2017
Received in revised form 23 January 2018
Accepted 29 January 2018

Keywords:
Dark solitons
Nonlinear optical materials
Ferroferric-oxide nanoparticles

ABSTRACT

The study presents the dark solitons generation in Er-doped mode-locked fiber laser based on ferroferric-oxide (Fe_3O_4) nanoparticles. The D-shaped fiber deposited with Fe_3O_4 nanoparticles is used as the birefringence and nonlinearity device. The dark solitons with repetition rate of 13.5 MHz are obtained in the pump power of 350 mW. The bright-dark soliton pairs are also observed by properly adjusting the polarization state at the pump power of 400 mW. The results in this paper demonstrate that Fe_3O_4 nanoparticles are the promising materials for generating dark solitons in fiber lasers.

1. Introduction

In past few decades, mode-locked fiber lasers have experienced great development due to their important applications in nonlinear optics, fiber optical communication, material processing, and environmental detection [1–3]. In general, there are two types of solitons in mode-locked fiber lasers: bright solitons and dark solitons. If the effective nonlinearity in fiber lasers is attractive, then bright solitons are formed, while dark solitons appear in the opposite case [4,5]. Dark solitons formed as a train of intensity dips in the intensity of a continuous wave background of the laser emission [6]. Compared with bright solitons, dark solitons have the advantages of less sensitive to fiber losses and more stable in the presence of noise, which possesses the potential of long distance communications. Under the perspective view of theoretical point, the dynamics of dark solitons in fiber lasers can be employed by the nonlinear Schrodinger equation [7–11]. The approximating dark soliton solutions can be obtained by a direct perturbation method which treats the loss, gain and filtering terms as perturbations [12]. Mode-locking into single dark soliton and multiple dark pulses have been investigated by using different descriptions for the energy and power of the ring fiber laser system [13]. The first experimental demonstration of dark solitons is in normal dispersion Er-doped fiber (EDF) laser [14], raising the research interests of dark solitons generations [15–17]. The experimental results have confirmed that the dark solitons are an intrinsic feature no matter in net anomalous dispersion or net normal dispersion regime for fiber lasers [18–21].

On the other hand, to achieve passively mode-locking of fiber lasers, the conventional technique of nonlinear polarization rotation (NPR) technique has been used [22]. Due to the disadvantages and drawbacks, the researchers have been exploring high performance saturable absorbers (SAs) with the characters of wavelength independent, high heat dissipation and high laser damage threshold [23–26]. Up till now, various kinds of SAs have attracted great attentions in recent years. Semiconductor saturable absorber mirrors (SESAMs) [27], carbon nanotubes (CNTs) [28,29], graphene [30,31], topological insulators (TIs) [32,33], semiconducting transition metal dichalcogenides (TMDs) [34–36] and black phosphorus (BP) [37] have been experimentally studied. And there have been several experimental demonstrations of dark solitons emission from fiber lasers with these novel nonlinear optical materials [38–40]. However, CNTs SAs are wavelength dependent on their diameters, and can lead to strong nonsaturable losses [28]. For graphene, the absorption is weak, which would decrease the SAs' modulation ability [39]. And the TI SAs are easily saturated over a certain threshold [41]. Most recently, the new functional nanomaterial Fe_3O_4 nanoparticles with a semi-conductive property has emerged as a new type SA can overcome those disadvantages,

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https://doi.org/10.1016/j.optlastec.2018.01.060
0030-3992/

which has a large third-order optical nonlinear susceptibility with a response time in the tens of picoseconds range [42–44]. Generally, in order to make the dark pulse generate easily, a medium with high nonlinearity is required. The imaginary-part of third-order nonlinear susceptibility which is responsible for nonlinear absorption enables Fe_3O_4 nanoparticles as saturable absorber in fiber lasers for pulse generation. On the other hand, the real-part of third-order nonlinear susceptibility of Fe_3O_4 nanoparticles is responsible for optical Kerr effect making Fe_3O_4 nanoparticles as a nonlinear medium [38].

In this work, we propose and demonstrate the generation of dark solitons in Er-doped mode-locked fiber laser based on Fe_3O_4 nanoparticles. The Fe_3O_4 nanoparticles are deposited on D-shaped fiber by optically-driven deposition method, which enables the interaction with the evanescent fields. The modulation depth (MD) and non-saturable losses (NL) of D-shaped fiber deposited with Fe_3O_4 nanoparticles are measured to be 11% and 3.5% respectively. The dark solitons with repetition rate of 13.5 MHz are obtained in the pump power of 350–450 mW range. The bright-dark soliton pairs are also observed by properly adjusting the polarization state at the pump power of 400 mW. Our results prove that the Fe_3O_4 nanoparticles can act as an effective nonlinear optical modulation material and the dark solitons observation might be helpful to design the fiber lasers.

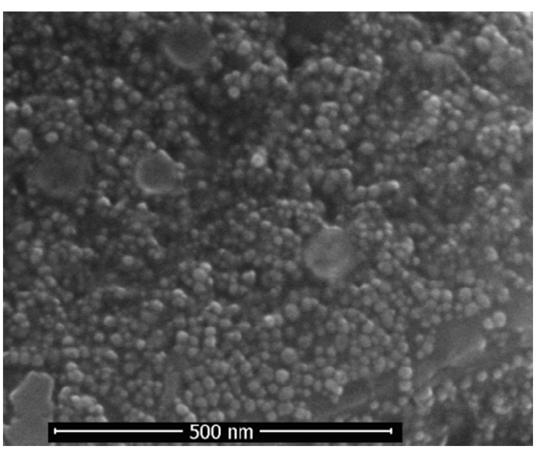

Fig. 1. SEM image of Fe_3O_4 nanoparticles.

2. Fabrication of Fe_3O_4 nanoparticles

The Fe_3O_4 nanoparticles used in our experiment are dispersed in N-Methylpyrrolidone (NMP) solution to form the homogeneous suspension after the ultrasonic and centrifugation processes. The nanoparticles are characterized by a scanning electron microscope (SEM), as shown in Fig. 1. It is observed that the Fe_3O_4 nanoparticles have near spherical shape. The sizes of nanoparticles are measured as 30–50 nm. The parameters of prepared D-shaped fiber are as follow. The distance from the fiber core boundary to the D-shaped surface is optimized 2 μm. The interaction length of D-shaped area is estimated to be 10 mm. So we think that there exist weak polarization dependent losses. However, it does not influence the dark solitons mode-locking operation. The D-shaped fiber can work as a polarizer, combined with polarization controller, can make fiber laser operate in a proper state with enough nonlinear effect for easily mode locking operation [45]. The evanescent field of D-shaped fiber is shown in Fig. 2, implying it can achieve efficient interaction with Fe_3O_4 nanoparticles. Based on this scheme, it can enhance the nonlinear modulation effect. The Fe_3O_4 nanoparticles are deposited to the surface of the D-shaped fiber by optical trapping effect as long as the injecting laser passes through the fiber. The insert loss of the D-shaped fiber deposited with Fe_3O_4 nanoparticles mainly depends on the power leakage from the fiber core. What is more, the D-shaped fiber can be easily incorporated in the all-fiber laser cavity without splice loss. As most of the power intensity distributes in fiber core, only a small part of optical power leaks from the fiber, so the inset loss can be deduced in a very small value.

The linear transmission of D-shaped fiber deposited with Fe_3O_4 nanoparticles is measured from 1400 nm to 1700 nm. As depicted in Fig. 3(a), the transmission spectrum of Fe_3O_4 nanoparticles is very flat and the transmission is as high as 85.9% at 1560 nm. The nonlinear optical properties are investigated by the balanced twin-detector measurement technique [34]. A femtosecond pulse laser (central wavelength: 1560 nm, pulse duration: 500 fs, repetition rate: 30 MHz) is used as the source. As can be seen from Fig. 3 (b), the MD and NL are evaluated to be 3.5% and 11%.

3. Experimental setup

The schematic diagram of EDF laser is depicted in Fig. 4. The ring laser oscillator cavity consists of a gain fiber, a wavelength division multiplexer (WDM), a polarization independent isolator (PI-ISO), optical coupler (OC), a polarization controller (PC) and the Fe_3O_4 nanoparticles SA. A 4 m long EDF with absorption coeffi-

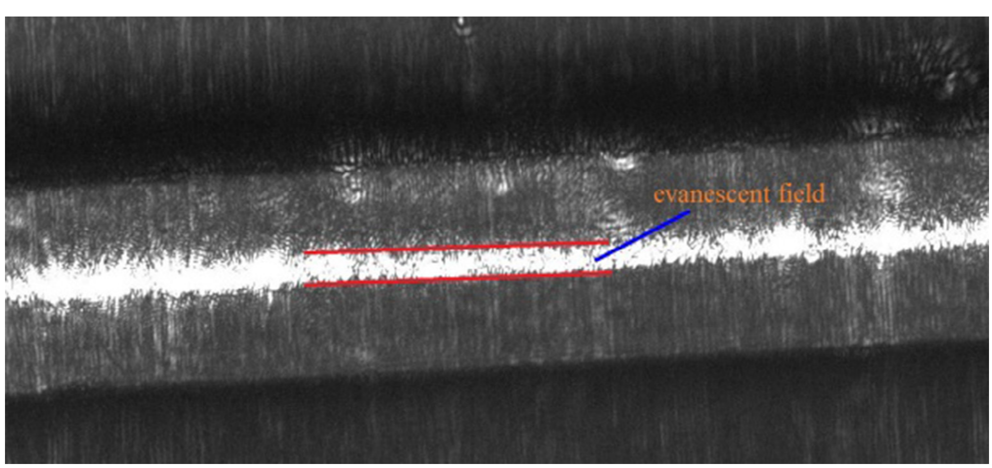

Fig. 2. The microscopic image of the D-shaped fiber.