Dual-wavelength domain wall solitons in a fiber ring laser

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Abstract: We report on the first experimental observation of dual wavelength domain wall type of dark solitons in a fiber laser made of all normal group velocity dispersion fibers. It was shown that this solitary wave is formed due to the cross coupling between two different wavelength laser beams and consists of localized dip structures separating the two different wavelength laser emissions.

OCIS codes: (060.4370) Nonlinear optics, fibers; (060.5530) Pulse propagation and temporal solitons; (140.3510) Lasers, fiber.

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1. Introduction

Soliton formation in single mode fibers (SMFs) is a well-known effect and has been extensively investigated. It is now well recognized that the dynamics of the formed solitons is governed by the nonlinear Schrödinger equation (NLSE), and bright solitons are formed in the anomalous group velocity dispersion (GVD) fibers, while dark solitons are formed in the normal GVD fibers [1–3]. A fiber laser is mainly made of SMFs. It is natural to anticipate that under appropriate conditions solitary waves could be formed in the single mode fiber lasers. Indeed, both the bright and dark NLSE solitons have been experimentally observed in fiber

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lasers [4,5]. Recently, we also observed a train of dark soliton pulses in an all-normal dispersion fiber laser [6]. Different from reference [5] that reported the first demonstration of high repetition rate (10 GHz) dark soliton pulses, reference [6] investigated a low repetition rate dark soliton pulse train which could be visualized by a commercial oscilloscope other than an auto-correlator.

In addition to the NLSE solitons, recently a new type of optical solitary waves known as the polarization domain wall solitons (PDWSs) was also experimentally revealed in fiber lasers [7]. Formation of PDWSs was first theoretically predicted by Haelterman and Sheppard [8]. It was shown that the cross coupling between the two orthogonal polarization components of light propagating in a dispersive Kerr medium could lead to the formation of a stable localized structure that separates domains of the two orthogonal polarization fields. Cross coupling between waves is a common phenomenon in a wide range of nonlinear physical systems. The experimental confirmation of PDWSs suggests that similar domain wall solitons could also be observed in other nonlinear wave coupling systems [9,10]. Later, Haelterman and Badolo further found that the mutual interaction of two different wavelength optical waves (but the same polarization) could also lead to formation of domain wall solitons, known as dual-wavelength DWSs [11]. In this paper, to the best of our knowledge, we report on the first experimental evidence of a dual-wavelength optical DWS in a fiber ring laser made of all-normal GVD fibers. We show both experimentally and numerically that strong coupling between two different wavelength beams in the fiber laser can result in the formation of DWSs, representing as a stable dark intensity pulse separating the two different wavelength laser emissions.

2. Experimental setup

We used a fiber laser with similar configuration as shown in Fig. 1. Briefly, the cavity is made of ~5.0 m Erbium-doped fiber (EDF) with a GVD parameter of –32 (ps/nm)/km, ~6.1 m dispersion shifted fiber (DSF) with a GVD parameter of –2 (ps/nm)/km. A polarization sensitive isolator was employed in the cavity to force the unidirectional operation of the ring cavity, and an in-line polarization controller (PC) was used to fine-tune the linear cavity birefringence. The laser was pumped by a high power Fiber Raman Laser source of wavelength 1480 nm. A 10% fiber coupler was used to output the signal, and the laser output was monitored with a 2 GHz photo-detector and displayed on a multi-channeled oscilloscope.

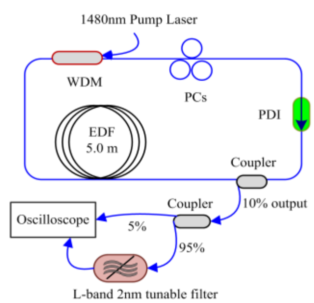

Fig. 1. Schematics of the fiber laser. WDM: wavelength division multiplexer. EDF: erbium doped fiber. PDI: polarization dependent isolator. PCs: polarization controllers.

3. Experimental results

A major difference of the current laser to that of [6] is that in setting up the laser we have intentionally imposed large birefringence into the cavity. Consequently, the birefringence induced multi-pass filter effect becomes very strong and can no longer be ignored for the laser. Under the combined action of the laser gain and the birefringent filter, the laser is forced to operate in a dual wavelength CW emission mode. Figure 2(a) shows a typical spectrum of the laser under dual-wavelength emission. Figure 2(b) and Fig. 2(c) show a typical case of the dark pulse emission of the laser. The dark pulse repeated with the cavity roundtrip time.

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Depending on the laser operation conditions multiple dark pulses could be formed in the cavity. Figure 2(d) shows the measured total output power versus the input pump power of the laser operation. The laser had a threshold pump power of about 90 mW and the laser emission increased almost linearly with the pump power. Under relatively low pumping the laser emission displayed a constant intensity on the oscilloscope trace. However, as the pump power increased to about 260 mW, it was observed that a dark intensity pulse appeared on the laser output. The stronger the pump power, the narrower became the dark pulse, as depicted in Fig. 2(d).

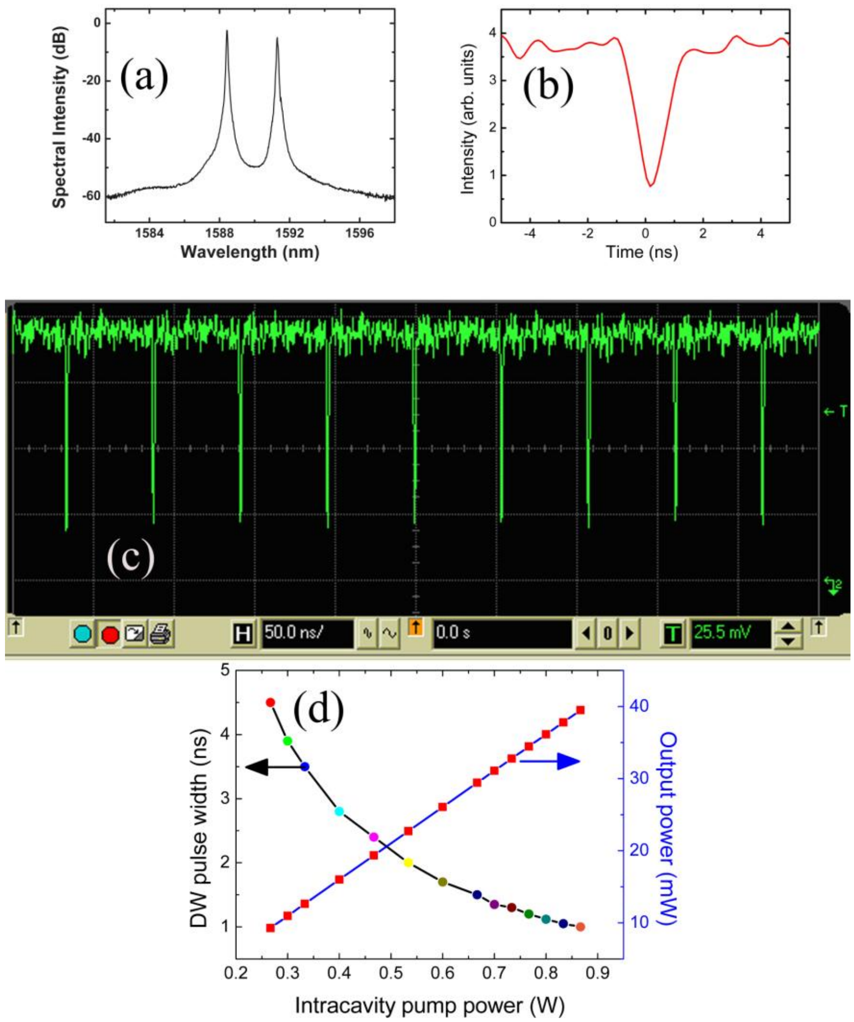

Fig. 2. (a) Spectrum; (b) a magnified figure of the dual-wavelength DWS emission of the laser ; (c) full oscilloscope trace of dual wavelength DWS;(d) FWHM duration and total output power versus pump power.

Tuning the orientation of the intra cavity PC, the band-pass wavelengths of the birefringent filter can be correspondingly shifted. Consequently, the relative strength together with the relative separation of the two different wavelength laser emissions could be altered. Single wavelength laser emission could also be obtained in the laser. However, under single wavelength emission no such dark pulses could be observed, indicating that the appearance of the dark pulses could be related to the coupling of the two different wavelength beams. To

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confirm this hypothesis, we further measured the laser emission at each of the two lasing wavelengths. We used an L-band tunable filter (OFT 320, tuning range: 1570 nm to 1610 nm, filter bandwidth: ~0.1 nm) to separate the laser emissions. Figure 3 shows a result of the wavelength resolved measurement. The laser emission was found to be alternating between the two wavelengths, and the dark pulse always appeared at the position where the laser emission switched from one wavelength to the other. Although wavelength alternation of a fiber laser was reported by P. Le Boudec et al. [12], and it was attributed as a result of the gain competition between the two lasing wavelengths, the appearance of a dark pulse at the wavelength switching position on the total laser emission in our experiment clearly shows that the observed result is not simply due to the gain competition. We note that physically the interaction between two orthogonal incoherently coupled polarization components in birefringent fibers is equivalent to that of two incoherently coupled scale laser fields in a Kerr medium. Given the close resemblance of the observed two wavelength laser emissions to the polarization resolved laser emissions reported in [7], we strongly believe that the observed dark pulses are dual-wavelength DWSs.

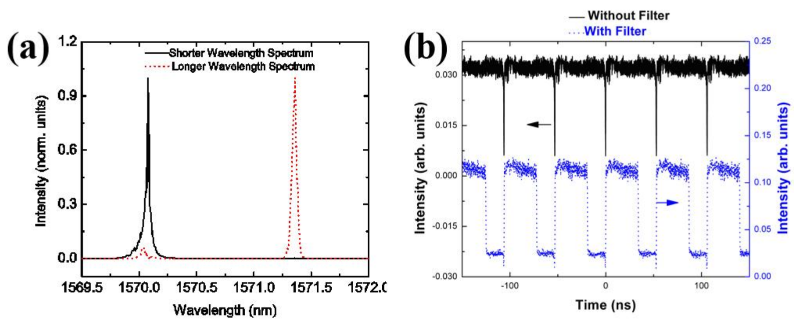

Fig. 3. (a) Wavelength resolved spectra and (b) Oscilloscope trace of the total (upper trace) and one wavelength laser emission (lower trace), measured under pump power ~260 mW.

Under even stronger pumping (~450 mW), a new type of dark pulses could also suddenly appear [6]. These new dark pulses moved with respect to the DWS. Limited by the resolution of our detection system we cannot measure the actual pulse width of the new dark pulses [13], but in contrast with the domain wall type dark pulses, they have different darkness and appeared randomly in the cavity. We had studied previously the NLSE dark solitons in a fiber laser [6]. The observed features of the new dark pulses suggest that they could be the NLSE dark solitons. In our experiment we could control the strength of the laser emission of either wavelength through shifting the filter frequencies. In this way we can suppress the appearance of the NLSE dark solitons on either of the two wavelength laser emissions. Figure 4 shows a comparison on the laser emissions where one of the two-wavelength laser emissions is beyond the NLSE soliton threshold. Figure 4(a) shows the laser emission spectra. The upper (lower) oscilloscope trace shown in Fig. 4(b) corresponds to the spectrum whose longer (shorter) wavelength spectral line has become broadened. Associated with the appearance of the NLSE dark solitons the corresponding laser emission spectrum became further broadened.

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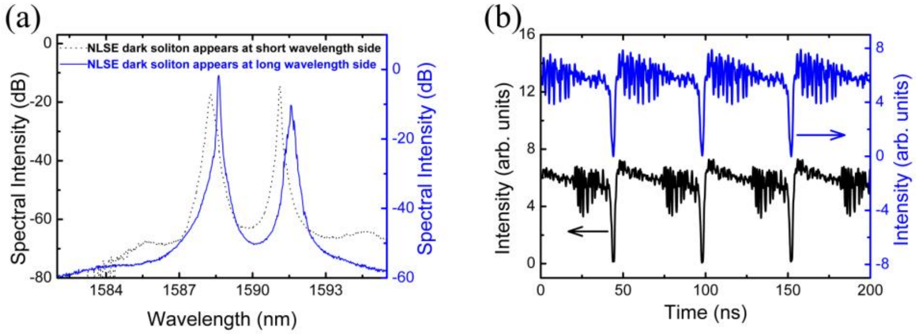

Fig. 4. (a) Spectra and (b) oscilloscope traces of the laser emission with the NLSE dark solitons appeared on emission at one of the wavelengths, measured under higher pump power ~450 mW. The upper (lower) trace corresponds to the spectrum whose longer (shorter) wavelength line is broadened.

4. Numerical simulation

To better understand the dual-wavelength DWS formation in our laser, we have further numerically simulated the operation of our laser under two wavelength emissions. The following coupled Ginzburg-Landau equations were used to describe the light propagation in the fibers [14]:

$$\begin{aligned}\frac{\partial u_1}{\partial z} &= i\beta u_1 - \frac{ik''}{2}\frac{\partial^2 u_1}{\partial t^2} + \frac{k'''}{6}\frac{\partial^3 u_1}{\partial t^3} + i\gamma\left(|u_1|^2 + 2|u_2|^2\right)u + \frac{g}{2}u_1 + \frac{g}{2\Omega_g^2}\frac{\partial^2 u_1}{\partial t^2} \\ \frac{\partial u_2}{\partial z} &= -i\beta u_2 - \frac{ik''}{2}\frac{\partial^2 u_2}{\partial t^2} + \frac{k'''}{6}\frac{\partial^3 u_2}{\partial t^3} + i\gamma(|u_2|^2 + 2|u_1|^2)u_2 + \frac{g}{2}u_2 + \frac{g}{2\Omega_g^2}\frac{\partial^2 u_2}{\partial t^2}\end{aligned} \tag{1}$$

where u_1 and u_2 are the normalized envelopes of the optical pulses along the same polarization in the optical fiber but having different central wavelengths λ_1 and λ_2. $\beta = 2\pi\Delta n/(\lambda_1 + \lambda_2)$ is the wave-number difference between the two optical waves. $\Delta n = n_1 - n_2 \approx 7.16*10^{-9}$ is the refractive index difference between these two waves. k'' is the second order dispersion coefficient, k''' is the third order dispersion coefficient and γ represents the nonlinearity of the fiber. g is the saturable gain coefficient of the fiber and Ω_g is the bandwidth of the laser gain. For undoped fibers $g = 0$; for erbium doped fiber, we considered its gain saturation as

$$g = G*\exp[-\frac{\int(|u_1|^2 + |u_2|^2)dt}{P_{sat}}] \tag{2}$$

Where G is the small signal gain and P_{sat} is the gain saturation energy. Obviously, gain competition between the waves exists. Moreover, we considered the cavity feedback effect by circulating the light in the cavity [14]. We have assumed that the two wavelength beams have the same group velocity and used the following parameters: $\gamma = 3$ $W^{-1}km^{-1}$, $\Omega_g = 16$ nm, $k''_{DSF} = 2.6$ ps^2/km, $k''_{EDF} = 41.6$ ps^2/km, $k''' = -0.13$ ps^3/km, $P_{sat} = 500$ pJ, cavity length $L = 11.1$ m, and $G = 120$ km^{-1}.

A weak dual-wavelength beam with ~2.6 nm wavelength separation and an intensity switching between the two wavelengths was used as the initial condition. We let the light circulate in the cavity until a stable state is obtained. The CGLEs were solved using the split-step method. We found numerically that a stable DWS separating the laser emissions of different wavelengths could indeed be formed in our laser, as shown in Fig. 5. Figure 5(a) shows the domain walls and the corresponding dark DWS calculated. Figure 5(b) shows the optical spectrum of the laser emission. Stable evolution of dual wavelength domain wall could also be identified in Fig. 5(c) and Fig. 5(d).

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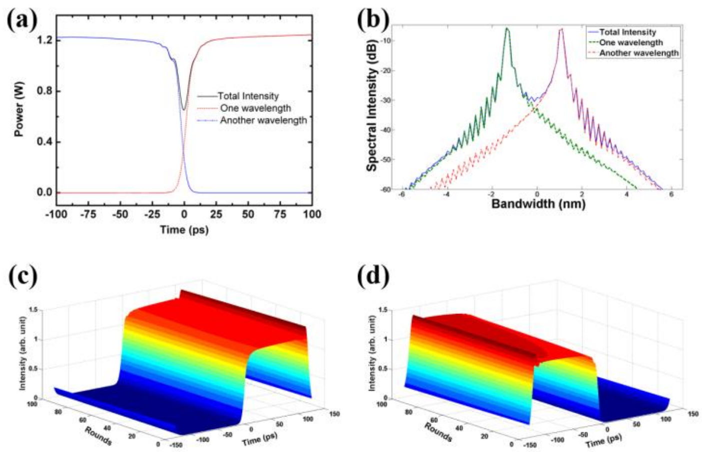

Fig. 5. Dual-wavelength DWS numerically calculated. (a) Domain wall profiles and DWS at a particular roundtrip (b) The corresponding spectrum. Evolution of the dual wavelength domain wall with the cavity roundtrips: (c) one wavelength (shorter wavelength) (d) Another wavelength (longer wavelength).

We have also numerically simulated dual-wavelength DWS formation under various laser parameters. Independent of the concrete laser cavity parameters DWSs could always be obtained. We note that third order dispersion (TOD) impacts dark solitons in the near zero dispersion regime and it could even induce continuum generation by dark solitons [15]. To study the TOD effect, we also deliberately varied the TOD parameter in our simulations and found that the DWS could become temporally asymmetric and even unstable if the TOD was too large. However, since the total cavity dispersion of our laser is far away from the zero dispersion, it only plays a minor role in our experiment. Based on our numerical simulations, we noticed that for the formation of the DWS an initial intensity alternation between the two wavelengths is crucial. Antiphase dynamics between two different wavelength laser emissions was previously experimentally observed in an erbium-doped fiber laser [12]. The numerical result suggests that the gain competition caused antiphase dynamics could also have played a role on the formation of the DWSs in our laser.

5. Conclusion

In conclusion, we have experimentally observed a new type of dark soliton in an erbium-doped fiber laser made of all-normal GVD fibers. It is shown that the formation of the dark soliton is a result of the mutual nonlinear coupling between two different wavelength laser beams and the formed soliton has the characteristic of separating the two different wavelength laser emissions. The features of the soliton suggest that it is a dual wavelength domain wall soliton.

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