Generation of Polarization-Locked Vector Solitons in Mode-Locked Thulium Fiber Laser

Volume 10, Number 1, February 2018

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DOI: 10.1109/JPHOT.2017.2789302
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Abstract: In this paper, we report polarization-locked vector soliton (PLVS) generation in a linear thulium-doped fiber laser. The fiber laser was composed of all-anomalous-dispersion fibers, passively mode-locked with a semiconductor saturable absorber mirror. Approximately 1.2-ps single vector soliton pulses centered at 2023.7 nm were generated. Extra “peak-dip” spectral sidebands were clearly visible in the polarization-resolved optical spectra, indicating coherent energy exchange between the two polarization components of the vector solitons. In addition, multiple-PLVS operation modes were experimentally investigated, and our experimental results were confirmed by numerical simulations. To the best of our knowledge, this is the first observation of polarization-locked single vector soliton generation operating in the 2-μm spectral range.

Index Terms: Fiber lasers, mode-locked lasers, fiber nonlinear optics, vector solitons.

1. Introduction

As an attractive platform for investigating solitary wave dynamics, ultrafast fiber lasers have attracted much interest. Scalar, dissipative, and vector solitons have been demonstrated in mode-locked fiber lasers [1]–[3]. The potential applications of vector solitons in nanophotonics [4], [5], high-precision spectroscopy [6], and optical communication capacity expansion based on polarization division multiplexing and the polarization switch [7] have been inspiring more and more studies [8]–[15]. Menyuk theoretically predicted, for the first time, the formation of group-velocity-locked vector solitons (GVLVSs) in optical fibers via the shifting of the central frequencies of two orthogonally polarized components in opposite directions with self-phase modulation (SPM) and cross-phase modulation (XPM) [8]. Other types of vector solitons, such as polarization-locked vector solitons (PLVSs) [9], polarization-rotating vector solitons (PRVSs) [10], and phase-locked black-white vector solitons [11] have also been predicted in weakly linear birefringent fibers. Because of the stringent
requirements on the birefringence properties of the fibers, only GVLVSs have been experimentally achieved in optical fibers [12]. Unlike pulse propagation in a single-mode fiber (SMF), a pulse circulating in a fiber laser is affected by the average cavity parameters of dispersion, nonlinearity, gain, loss, and the cavity boundary condition, instead of by local ones as in propagation fibers. Therefore, the controlling conditions in fiber lasers for pulse generation are simpler than in propagation fibers. Zhao et al. demonstrated GVLVSs in a moderate birefringence fiber laser [13]. PRVSs were obtained by changing the net linear cavity birefringence of the erbium fiber laser [14]. Cundiff et al. reported phase-velocity-locked vector solitons and GVLVSs in a mode-locked erbium fiber laser [15]. The combined effects of the nonlinear index of refraction (SPM and XPM) and coherent energy exchange compensated the birefringence and stabilized the relative phase of the two polarization components. High-order PLVSs and polarization-locked/rotating dissipative vector solitons were also observed in erbium fiber lasers [16], [17].

Ultrafast fiber lasers in the 2-μm wavelength regime have attracted increasing attention in recent years because of the eye-safe nature and variety of industrial and scientific applications, such as laser radar, material processing, medicine, and mid-IR super-continuum generation [18]. Similar vector soliton pulses as in erbium fiber lasers have been observed in thulium-doped fibers (TDFs) or thulium/holium fiber lasers although they exhibit different optical spectra, dispersions, gains, and losses, among others. [19]–[22]. Wang et al. reported the observation of GVLVSs in a TDF laser for moderate cavity birefringence [18]. PRVSs were also observed in TDF lasers, possessing characteristic additional sets of sidebands in addition to the Kelly-sidebands on the spectrum [20], [21]. Recently, a PLVS mode-locked thulium–holmium fiber laser was demonstrated [22]. The solitons generated tended to oscillate within the soliton bunch because of the coexistence of slow and fast absorption of the saturable absorber. To the best of our knowledge, a 2-μm wavelength polarization-locked single vector soliton with soliton sidebands has not yet been observed.

In this paper, we report the generation of stable polarization-locked single vector solitons in a thulium all-fiber laser. The fiber laser was composed of all-anomalous-dispersion fibers and mode-locked by a semiconductor saturable absorber mirror (SESAM). The appearance of “peak-dip” sidebands in the polarization-resolved optical spectra suggests the generation of vector solitons and the coherent energy exchange between the two orthogonally polarized components of a vector soliton. We further investigated the multiple vector soliton operation and associated soliton features.

2. Experimental Setup

To obtain vector soliton pulse emission, we constructed the laser cavity without a polarizer, and all the fibers were weakly birefringent. Fig. 1 shows a schematic of our SESAM mode-locked TDF laser. The fiber laser consists of a pump/signal combiner, output coupler (OC), fiber-based polarization controller (PC), SESAM, and piece of gain fiber. The components are all polarization-insensitive and their polarization-dependent losses are negligible. The gain fiber used in the experiment had a thulium-doped core with a diameter of 10 μm (0.17 NA), surrounded by an octagonal-shaped silica inner cladding with a diameter of 130 μm and NA of about 0.46. The nominal cladding absorption was about 3 dB/m at 793 nm and, hence, a fiber length of about 4.2 m was selected for efficient pump absorption. The pump source was a 793-nm laser diode with a core/cladding diameter of
105/125-μm and fiber pigtail of 0.22 NA. The pump/signal combiner was used to couple pump power into the thulium-doped double-clad fiber. The SESAM (high reflection between 1900 and 2050 nm) was used to initiate mode locking. It had a non-saturable loss of 18%, modulation depth of about 25%, and saturation fluence of about 35 μJ/cm². To avoid residual pump power overdriving on the SESAM, a segment of passive single-clad SMF was spliced to the double-clad fiber and the spliced region was covered with a high-refractive-index matching gel to mode-strip light propagating in the inner cladding. The SESAM was then butt-coupled to the SMF.

A fiber loop mirror was constructed by splicing together two output ports of a 40:60 2×2 fused fiber coupler. A 4.56-m-long fiber loop mirror acted as a partially reflecting mirror and output coupler with variable transmission. A PC was inserted in the loop mirror to modify the output ratio [18] and finely tune the net birefringence of the cavity.

The cavity round-trip length is about 21 m including 8.4 m thulium fiber, 3.6 m SM2000 fiber from the fiber-based PC, 3.7 m SMF-28e fiber pigtail from the pump combiner and 5.3 m SM1950 fiber pigtail from the OC. The anomalous group velocity dispersions for the TDF and SM2000 were estimated to be $-91$ and $-67$ ps²/km [23], respectively. Those of the SM1950 and SMF-28e fibers were estimated to be $-78$ [24] and $-68$ ps²/km, respectively. Therefore, the net cavity dispersion was estimated to be about $-1.67$ ps².

3. Experimental Results

Self-started mode-locking of the TDF laser was directly observed when the pump power increased above the mode-locking threshold (∼1.71 W) with appropriate settings of the intra-cavity PC. Single-pulse operation was achieved by carefully lowering the pump power or finely tuning the paddles of the PC. The optical spectra were inspected using an optical spectrum analyzer (AQ6375, Yokogawa) with a resolution of 0.05 nm. Fig. 2(a) shows a typical optical spectrum of the single-pulse mode-locking operation for an incident pump power of 1.65 W. The central wavelength is 2023.7 nm and the spectral full-width at half-maximum is 3.8 nm, corresponding to a transform-limited pulse width of about 1.13 ps for hyperbolic-secant-shaped solitons. The central peak is smooth and no modulation occurs, indicating single-pulse operation without a bonded pulse [25]. The existence of characteristic Kelly sidebands on the spectrum suggests that the pulse was a near Fourier-transform-limited (FTL) nonlinear Schrodinger equation (NLSE) soliton [26]. Mode-locked pulses were shaped into NLSE solitons in the TDF laser. A commercial autocorrelator (Pulsecheck, APE) was used to record the accurate pulse width [see the inset in Fig. 2(a)]. The single peak of the autocorrelation trace double confirmed the single-soliton operation without a bonded pulse. If a sech² pulse profile is assumed, the actual pulse width was estimated to be ∼1.2 ps. The time-bandwidth product of the pulses is about 0.334, indicating that the pulses approach the transform limit.
Fig. 3. (a) Polarization-resolved optical spectra of the PLVSs. (b) Corresponding pulse traces of the PLVSs along the orthogonal polarization axis.

The inset of Fig. 2(a) illustrates a typical multiple-pulse trace. The pulses are equally spaced by about 101 ns, which agrees with the cavity length of about 21 m. The average output power was about 3.1 mW at 1.65 W of incident pump power. The single pulse energy was about 0.31 nJ. A radio-frequency (RF) spectrum analyzer (N9320B, Keysight Technologies) with a resolution bandwidth of 10 Hz and span of 120 KHz was used to measure the RF spectrum. Fig. 2(b) presents the RF spectrum around the fundamental repetition rate. The pulse repetition rate is about 9.87 MHz, agreeing well with the fundamental cavity frequency of the fiber laser. The signal-to-noise ratio reaches about 60 dB, indicating stable mode-locking. The broader spectrum over a span of 30 MHz [see the inset in Fig. 2(b)] shows no Q-switching instability.

To gain an insight into the PLVS, a fiber-based polarization beam-splitter (PBS) was spliced to the OC pigtail to resolve the two orthogonal polarization components of the laser pulse. The incoming branch and two outgoing branches of the PBS are composed of standard SM1950 fiber and polarization-maintaining fibers (PMF; PM1950, Nufern), respectively. Another in-line PC (PC-2) was inserted just in front of the PBS to compensate the lead-fiber-induced linear polarization change. Each orthogonal polarization component of the PLVSs was monitored using two identical 12.5 GHz photo-detectors (ET-5000, EOT) and was then transmitted to a multi-channel digital oscilloscope (DSOS104A, Keysight Technologies). Fig. 3(a) presents the polarization-resolved spectra of the solitons for an incident pump power of 1.67 W, which exhibit different spectral profiles and sidebands, typical spectral characteristics of vector solitons. The central wavelengths and spectral sidebands are essentially identical, indicating that each polarization component is almost an FTL NLSE soliton. Fig. 3(b) shows the polarization-resolved pulse traces. Uniform intensity distribution pulses were achieved for both polarization components with equal spacings of about 100.6 ns; this agrees with the cavity round-trip of about 20.8 m, suggesting a PLVS operation state. Meanwhile, we observe a sharp peak-dip structure (arrows marking sidebands in Fig. 3(a)) on the polarization-resolved spectra; one polarization component has a peak, while the other has a corresponding dip. The extra sideband characteristics were induced by four-wave-mixing (FWM), i.e., coherent energy exchange between the polarization components of the vector solitons in a fiber laser [27]. Energy exchange can take place at certain wavelengths satisfying the phase-matching condition, implying the formation of vector solitons in the fiber laser. In the experiments, we observed that when tuning the paddles of the intra-cavity PC, the peak-dip sidebands vary sensitively, while there is no remarkable shift for the Kelly sidebands.

Increasing the pump power, multi-soliton states were obtained. The solitons were randomly distributed in the cavity but they were not static. They moved slowly subject to the joint action of attractive and repulsive forces. By finely tuning the pump power and intra-cavity PC, a stable multiple NLSE soliton state could be achieved. Fig. 4(a) shows the pulse traces of either polarization under an incident pump power of 1.69 W. The pulse intensity of either polarization component remains uniform, indicating that the double-pulse vector solitons are phase-locked. For this state, all pulses in
the cavity have almost the same height on the oscilloscope trace, the feature of energy quantization of conventional solitons in fiber lasers. As the separation (~23 ns) between solitons in the twin-pulse soliton bunch [see Fig. 4(a)] is higher than their durations, no direct interaction exists between them. Similar polarization-resolved spectra as those in Fig. 3(a) are observed, except for the variation in positions of the FWM-induced spectral sidebands. The soliton spacing changed with the tuning of the paddles of the intra-cavity PC. A second harmonic mode-locking state, where the separation between the solitons is exactly half of the cavity round-trip time, was also observed. Increasing the pump power did not destroy the polarization-locked state but increased the number of solitons; all vector solitons exhibited almost the same polarization and their polarization features remained unchanged as they circulated in the cavity. Further increasing the pump power, the number of solitons in the cavity increased one by one. The performance of the laser varied with the setting of the intra-cavity PC. Fig. 4(b) shows the evolution of the number of solitons in the cavity as a function of the pump power at a polarization state. The minimum pump power that can support the N-soliton state could be lower than the pump power required for the appearance of the N-soliton state during increasing pump. In other words, hysteresis of soliton formation and annihilation was observed.

4. Numerical Simulations and Discussion

To verify our experimental observations, numerical simulations of the laser performance were carried out based on the coupled Ginzburg–Landau equations (CGLEs) and pulse tracing technique [25]. The pulse propagation in the fiber segments can be described by the following CGLE:

\[
\begin{align*}
\frac{\partial u}{\partial z} &= -i\beta u + \frac{\delta}{\partial t} + k'' \frac{\partial^2 u}{\partial t^2} + i\gamma \left(\frac{1}{3} |u|^2 + \frac{2}{3} |v|^2\right) u + \frac{i}{2} |v|^2 u^* + \frac{g}{2} u + \frac{g}{2} \frac{1}{\Omega_1} \frac{\partial^2 u}{\partial t^2} \\
\frac{\partial v}{\partial z} &= i\beta v - \frac{\delta}{\partial t} - k'' \frac{\partial^2 v}{\partial t^2} + k''' \frac{\partial^3 v}{\partial t^3} + i\gamma \left(\frac{1}{3} |v|^2 + \frac{2}{3} |u|^2\right) v + \frac{i}{2} |u|^2 v^* + \frac{g}{2} v + \frac{g}{2} \frac{1}{\Omega_1} \frac{\partial^2 v}{\partial t^2}
\end{align*}
\]

where \(u\) and \(v\) are normalized envelopes of the optical pulses along two orthogonal polarization axes of the fiber, and \(u^*\) and \(v^*\) are complex conjugates of \(u\) and \(v\). \(2\beta = 2\pi \Delta n / \lambda\) is the wave-number difference between the two polarization modes of the fiber, where \(\Delta n\) is the difference between the effective indices of the two modes and \(\lambda\) is the wavelength in vacuum. \(2\delta = 2\pi \Delta n / 2\pi c\) is the inverse group velocity difference, where \(c\) is the speed of light. \(k''\) is the second-order dispersion coefficient, \(k'''\) is third-order dispersion coefficient, and \(\gamma\) is the nonlinearity of the fiber. \(g\) is the gain of the fiber and \(\Omega_1\) is the gain bandwidth of the laser. For the SMF, \(g = 0\); for the gain fiber, its gain saturation can be expressed as

\[
g = G \exp \left[ - \frac{\int \left( |u|^2 + |v|^2 \right) dt}{P_{sat}} \right]
\]

where \(G\) is the small-signal-gain coefficient and \(P_{sat}\) is the normalized saturation energy.
To simplify the simulation, the fiber loop mirror was modeled as the combination of pulse propagation and the output coupler. The saturation absorption of the SESAM can be described by the rate equation [27]:

$$\frac{\partial l_s}{\partial t} = -\frac{l_s - l_0}{T_{rec}} - \frac{|u|^2 + |v|^2}{E_{sat}} l_s$$

(3)

where $T_{rec}$ is the absorption recovery time, $l_0$ is the initial saturable absorption of the SESAM, and $E_{sat}$ is the absorber saturation energy. The following parameters were used in the simulation: $\gamma = 3$ W$^{-1}$ km$^{-1}$, $P_{sat} = 130$ pJ, $k'' = -0.13$ ps$^3$/km, $E_{sat} = 65$ pJ, $l_0 = 0.25$, and $T_{rec} = 2$ ps. The gain bandwidth $\Omega_1$ is 50 nm, the cavity length is 21 m, and the net cavity dispersion is $-1.67$ ps$^2$.

Stable mode-locked pulses were obtained when $G = 158$ km$^{-1}$ and different optical spectra were found depending on the net cavity birefringence. The intrinsic birefringences for general fibers and PMFs are about $10^{-7}$ and $10^{-4}$, corresponding to beat lengths of about 20 m and 20 mm at 2 $\mu$m, respectively. Physically adjusting the paddles of the intra-cavity PC is equivalent to changing the linear cavity birefringence. In the simulation, the average cavity birefringence was considered. Fig. 5 presents the optical spectra of the numerically simulated vector solitons for the same parameters but different beat length. For a small average cavity birefringence, e.g., $L_b = 10.5$ m (as shown in Fig. 5(a)), both polarization solitons exhibit the same central wavelength. As the birefringence in the cavity increases [see Figs. 5(b) and 5(c)], the central wavelengths offset for the polarization components of the vector soliton. Incoherent coupling between them leads to the generation of GVLVSs. The wavelength offset between the orthogonally polarized components increases with the birefringence. Fig. 5(d) presents the result for strong cavity birefringence. The average cavity birefringence is so large that the group velocities cannot lock together anymore; the pulse is linearly polarized. Therefore, coherently coupled vector solitons can only be generated under weak birefringence (for example, the present case corresponds to a beat length of about 10.5 m).

We reported that a vector soliton bunch was observed in a thulium–holmium fiber laser at the 2–$\mu$m waveband [22]. However, the solitons tended to oscillate within the bunch, subjected to the joint action of attractive and repulsive forces, because of the coexistence of slow and fast
absorption of the saturable absorber. Associated with the oscillation in a bunch, a large width of soliton sidebands was observed. Numerically we found that multiple vector soliton mode could appear with larger pump. When the separation between solitons in the soliton bunch is larger than their durations, no direct interaction exists between them and thus the optical sidebands are relative sharp. In our experiment, the sharp peak-dip sidebands in the polarization-resolved spectra confirm the coherent energy exchange between the orthogonally polarized components of a vector soliton. The combination of coherent energy exchange, SPM, and XPM provides a feedback mechanism critical for the phase locking of PLVSs against external perturbations. To the best of our knowledge, this is the first observation of a polarization-locked single vector soliton in 2-μm fiber lasers.

We noticed that the direct generation of dip-type sidebands was observed in a soliton mode-locked fiber laser [28]. The polarization effect of the microfiber-based WS₂ device contributed to the dip-type sidebands formation, different with that of vector solitons, which is induced by the coherent energy exchange between the orthogonally polarized components. Various 2D materials, such as graphene [29], topological insulator Bi₂Se₃ [30], and WS₂ [31], were used to mode lock fiber lasers. Further studies on the polarization property of the absorption of these materials and the formation of vector solitons in 2D material-based fiber lasers at 2-μm are expected.

5. Conclusion
In this study, we experimentally demonstrated PLVSs in an all-fiber double-clad thulium fiber laser. The fiber laser was composed of all-anomalous-dispersion fibers and mode-locked by a SESAM. Approximately 1.2-ps single vector soliton pulses centered at about 2023.7 nm were generated. Extra “peak-dip” featured sidebands in the polarization-resolved optical spectra indicated coherent energy exchange between the two polarization components of vector solitons. To the best of our knowledge, this is the first observation of polarization-locked single vector soliton generation operating in a 2-μm spectral range. Multiple vector soliton operations and associated soliton features were also investigated. The numerical simulations confirmed our experimental results and further reveal that careful cavity birefringence design can help to construct new types of fiber lasers with controlled dynamical states of polarization. We believe such a PLVS fiber laser may find practical applications in optical communications, novel material processing, nanophotonics, and spintronics.

References


