By further increasing the pump current to 355 mA and tuning the PC, combined harmonic mode locking with bound state soliton is observed with period of 13 ns, pulse width of 383 fs and output power of 0.8 mW (Figs. 5(a)-5(d)). The pulse separation is ~3 ps which is ~9 times of pulse duration showing loosely bound soliton [24]. The central dip in the spectrum and spectral symmetry illustrates a π phase shift between the two bound solitons [26]. Anti-phase dynamics of oscillation of the orthogonal polarized SOP leads to CW operation of the output pulse (Fig. 5(d)). Different scenarios could lead to the low DOP of 15% as shown in Fig. 5 (e). For example, three bound states solitons can interleave in time with resulting operation at third harmonic shown in Fig. 5(c). Each of bound state can have different SOP and so averaging over 40 round trips results in low DOP shown in Fig. 5(e). The SOP jumps shown in Fig. 5(f) can be considered as an indication of such scenario. To interpret this more rigorously, a polarimeter with a resolution of a pulse round trip is required. An additional cyclic SOP evolution can be explained as follows. As shown by Akhmediev and Soto-Crespo [36], the eigenstates in a fiber in the presence of linear birefringence and circular birefringence caused by nonlinear self-phase modulation are split into two pairs:

$$S^{(1,2)} = \begin{pmatrix} S_0 \\ \pm S_0 \\ 0 \\ 0 \end{pmatrix}, \quad S^{(3,4)} = \begin{pmatrix} S_0 \\ -\alpha \\ 0 \\ \pm\sqrt{S_0^2 - \alpha^2} \end{pmatrix}. \tag{2}$$

Here S_0 = const and α is determined by the ratio of linear to circular birefringence strength. In mode locked laser, in-cavity polarization controller contributes both into linear and circular birefringence whereas anisotropy induced by pump light is suppressed due to relaxation orientation caused by excitation migration [37, 38]. Mode locked operation changes the active medium anisotropy (both linear and circular) due to polarization hole burning and so the pulse SOP located on a circle as shown in Fig. 5(f). If the beat length in the anisotropic cavity is equal to the round trip and pulse-to-pulse power is constant then pulse SOP is not changed and so vector soliton is polarization locked (Figs. 2(f) and 4(f)). The depth of the hole in orientation distribution of inversion is proportional to the laser power and so with periodical oscillations of the output power (Fig. 5(c)) light induced anisotropy in an active medium will be periodically modulated [37, 38]. If the round trip equals to the rational part of the beat length then SOP after few round trips will slightly deviate from the initial one and can reproduce itself for the period of pulse power oscillations only which is 400 round trips in our case (Fig. 5(f)). Thus, SOP evolution shown in Fig. 5(f) is a superposition of the SOP jumps with precession along the cyclic trajectory on the Poincaré sphere (Fig. 5(f))).

4. Conclusions

Using an in-line polarimeter for erbium doped fiber laser passively mode locked with carbon nanotubes, we demonstrated, for the first time, new types of vector solitons with slowly evolving states of polarization on a time scale of 40-40000 round-trips for tightly, loosely, interleaved and complex bound states. By identifying these new types of unique states of polarization evolving on very complex trajectories, our experimental studies may contribute to new techniques in metrology [5], high-resolution femtosecond spectroscopy [6], high-speed and secure fiber optic communications [7, 11], nano-optics (trapping and manipulation of nanoparticle and atoms [8, 9], and spintronics (vector control of magnetization [10]). It may also open the possibility for creating fundamentally new types of lasers with controlled dynamic states of polarization.

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