Microfiber-knot-resonator-induced energy transferring from vector noise-like pulse to scalar soliton rains in an erbium-doped fiber laser

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***Abstract*—We report on scalar soliton rains (SRs) shedding from vector square-wave noise-like pulse (NLP) by introducing a microfiber-knot-resonator (MKR) into an erbium-doped fiber (EDF) laser. The EDF laser has an ultralong cavity of ~3.07 km, resulting in a large net anomalous-dispersion, which facilitates the formation of NLP. Once an MKR was further incorporated, comb-like filtering effect could be clearly observed on the emission spectrum. Apart from that, SRs shedding from the NLP were observed, which resulted from the MKR-induced energy transferring effect from the NLP to SRs. It was further found that the SRs existed only along a particular polarization direction, whereas the NLPs could be found in any pair of orthogonal polarization directions, despite that the peak power might be different depending on polarization. These suggest that the SRs possess scalar feature, whereas the co-circulating NLP is a package of vector pulses. Our results represent the first observation of MKR-induced pulse energy transferring effect and also the first observation of the co-existence of scalar and vector pulses in a single optical system. The related dynamics and mechanisms are analyzed in detail. Besides enriching the dynamics and interactions of optical pulses in fiber lasers, our results extend the applications of MKR to the area of pulse manipulations through spectral tailoring and local nonlinearity engineering.**

***Index Terms*—Optical pulses, Optical resonators, Optical fiber devices, Optical fiber lasers, Optical signal processing.**

I. Introduction

RELYING on rich physical mechanisms and complex dynamics in passively mode-locked fiber lasers, various optical pulses, as well as the related interactions and dynamics, have been explored extensively in past decades. These are still among the hot topics to date, due to the further in-depth studies and the applications of some newly-emerging materials as saturable absorbers (SAs), especially the intensively investigated two-dimensional (2D) materials [1, 2]. Besides several early discovered pulse types, such as conventional solitons, dispersion-managed solitons, dissipative solitons, etc., in recent years, particular attentions have been paid to some long-duration, wave-breaking-free pulses that are formed typically in long-cavity fiber lasers, where considerable accumulatively nonlinear effects can typically be developed due to strong field-confinement of single mode fiber (SMF) and the considerable interaction length. With such a cavity, multiple solitons would be generated due to the well-known area-theorem if the net cavity dispersion falls in the anomalous dispersion regime [3]. Even for the dispersion-managed solitons or dissipative solitons, there are still some upper limits on the single pulse energies and energy quantization still exists [4]-[6].

However, in some cases where a type of peak power clamping (PPC) effect dominates, i.e., the pulse amplitude can be fixed at a roughly constant value. As a remarkable consequence, both the pulse duration and energy can scale with the incident pump power to some unprecedented levels before wave-breaking occurring, if the operation is properly manipulated. So-called dissipative soliton resonance (DSR) is just the most representative regime [7]-[9]. However, not all the square wave or rectangular-shaped pulses can be attributed to such a regime. Detailed studies found that some of them were actually a type of noise-like pulses (NLPs). Although an NLP always shows a rectangular envelop on an oscilloscope, autocorrelation (AC) measurement suggest that it is in fact a tight bunch of many ultrashort pulses [10]-[15].

Despite the lengthy-fiber-induced strong global intra-cavity nonlinearity, some highly nonlinear fiber devices can induce abruptly considerable change on the local nonlinearity. Among them, one interesting device is so-called microfiber knot

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resonator (MKR) [16]-[19]. Its high nonlinearity results from two aspects. One is that it is an extremely-tapered device, which leads to hundreds of times shrinking in cross section. The second is that it is a resonant device, and a certain portion of the optical field within it can circulate for endless times prior to exiting. One interesting issue is how such a device can modify the pulse dynamics in fiber lasers. Although few earlier reports have found some interesting effects due to its incorporation fiber lasers, those were all realized in short cavities with only weak or even negligible nonlinear effects [20]-[22]. Thus, it is still unknown that how such a device can modify the pulse dynamics in circumstances with strong accumulative nonlinearity. From a more general point, it is to say that how the local nonlinearity exerts influences on the global nonlinearity. For that, in this paper, we investigate the MKR-induced effects in an ultralong erbium-doped fiber (EDF) laser. Without MKR, it is found that the EDF laser can deliver typical NLP, whose duration scales continuously with the incident pump power. Once a house-made MKR is incorporated, initially the NLP still follows similar evolution with the incident pump power. However, it is observed that, some soliton rains (SRs) can shed continuously from the NLP, and meanwhile the NLP maintain a constant duration, when the pump power rises above a threshold-like value. Even more interestingly, the SRs are found to be scalar fields while the NLP is a package of vector fields. That is to say that both scalar and vector fields can co-exist and circulate in a single optical system.

II. MKR FABRICATION AND THE EDF LASER CONFIGURATION

The used MKR is shown in Fig. 1(a), where some red light was launched for visibly showing the transmission characteristics of the MKR. The MKR was built by knotting a house-pulled fiber taper fabricated by using a fiber tapering workstation (IPCS-5000, Idealphotonics Inc.). Figure 1(b) shows the tapering waist of the MKR viewed by using a scanning electron microscope (SEM, X-act, Oxford Instruments, Inc.), which gives a measured diameter of ~1.57 µm. The ultra-thin-tapering MKR enables a strong confinement of optical field and thus high local nonlinearity. In our use, the MKR was suspended in air, which can prevent evanescent wave coupling and thus minimize the transmission loss. As measurement, the transmission loss in air is ~2.43 dB. It was further noted that the transmission of the MKR exhibits polarization-dependent characteristics. This results in a power extinction ratio of ~11.56:1, i.e., ~10.63 dB.

Transmission spectrum as shown in Fig. 1(c) was measured by using an ASE source (ASE-FL7004, 1530-1610 nm, FiberLabs Inc.) and an optical spectrum analyzer (OSA, AQ6370C, Yokogawa Test & Measurement Co., Japan) by setting the resolution at 0.02 nm. Figure 1(c) gives a resonance width of ~0.12 nm (estimated at the full width at half maxima, FWHM) and a free spectrum range (FSR) of ~0.61 nm. The further calculated Q factor, finesse, and loop circumference of the MKR are ~13000, ~5.08, and ~216.23 µm, respectively.

As shown in Fig. 1(d), the constructed EDF laser exhibits a typical figure-eight (f-8) structure, which comprises a nonlinear amplifying-loop mirror (NALM), acting as an artificial SA, and a unidirectional ring (UR). In the NALM, a 976 nm laser diode (LD) is used as the pump source. The pump light is coupled into ~80 cm EDF through a fused wavelength division multiplexer (WDM). The EDF (EDF80, OFS) has a dispersion of ~-48 ps/(nm·km) and peak absorption at 1530 nm of ~ 80 dB/m. A three-paddle fiber polarization controller (FPC), noted as FPC-1, is incorporated to adjust the local polarization state (PS). We further use ~35 m highly nonlinear fiber (HNLF) and ~3021 m SMF-28e in the NALM to enhance the accumulative cavity nonlinearity. The HNLF has a core diameter of ~3.55 µm and dispersion of ~1.31 ps/(nm·km) at 1550 nm.

The NALM is connected to the UR through a 3-dB fiber optical coupler (FOC). Unidirectional propagation is enabled by using a polarization-independent isolator (PI-ISO). A 20/80 FOC provides the laser output. The second FPC, i.e., FPC-2, is used to further adjust the local PS in the UR. Except the EDF and HNLF, all other fiber pieces in the EDF laser are standard SMF-28e. The total cavity length is ~3072.8 m, resulting in a net anomalous dispersion of ~-61.9 ps^2 around 1550 nm.

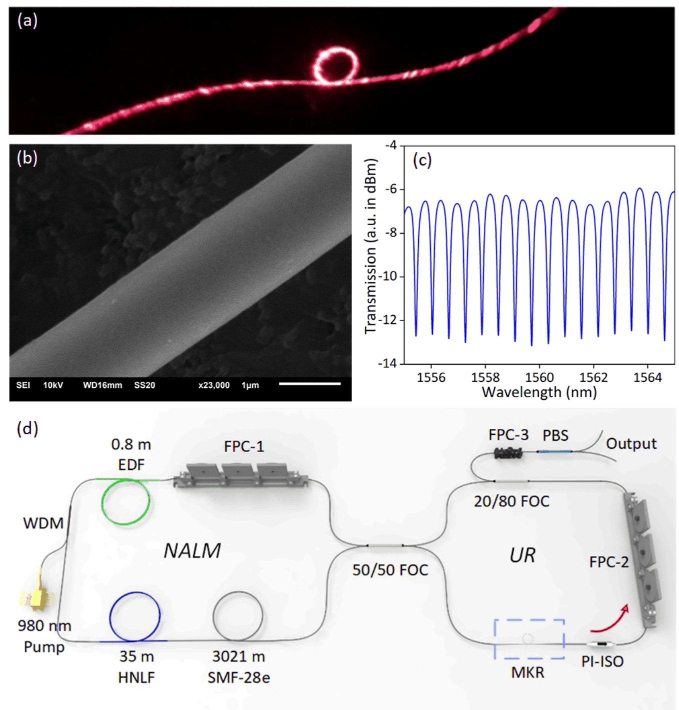

Fig. 1. (a) Photograph of the MKR with propagating red light; (b) SEM around tapering waist of the MKR. (c) transmission spectrum of the MKR. (d) MKR-incorporated f-8 EDF fiber laser.

III. NLP EMISSION CHARACTERISTICS WITHOUT MKR

At first, we carried out an experiment without incorporation of the MKR. A 63 GHz high-speed oscilloscope (DSO-X 96204Q, Keysight Technologies, Inc.) along with a 45-GHz ultrafast-response photodetector (1014, New Focus, Inc.) were employed to real-time monitor the output pulse as fast as possible. Square-wave-shaped pulse could be achieved by adjusting the two FPCs when the pump power increased to ~30.2 mW. With a fixed PS, as the pump power increased from ~74.8 to ~292.9 mW, the pulse duration continuously broadened from ~59.9 to ~246.8 ns, as shown in Fig. 2(a).

Figure 2(b) shows a typical optical spectrum with pump power of ~255.1 mW. The emitted peak wavelength was ~1560.36 nm with a 3-dB bandwidth of ~4.88 nm. Figure 2(c) plots the corresponding detailed radio frequency (RF) spectrum around the fundamental pulse repetition rate, which peaks at ~66.38 kHz with signal-to-noise ratio (SNR) of ~47.3 dB. The RF characteristics through this paper were all measured by using an RF spectrum analyzer (N9320B, Agilent Technologies, Inc) in combination with a photodetector (InGaAs Biased Detector, DET01CFC/M, THORLABS Inc.). The inset of Fig. 2(c) shows an RF trace with 10 MHz span. The RF train and RF spectrum around the pulse repetition rate were recorded with 100 and 10 Hz resolution bandwidth (RBW), respectively.

Considering that the top part of each rectangular-shaped pulse embedded many dense and random spikes, we suspected that the obtained pulse might be a type of NLP. AC measurements were then taken to check that by using an autocorrelator (FR-103HS, Femtochrome Research, Inc.) assisted with a digital oscilloscope (DSO-X3034A, Agilent Technologies, Inc.). The measured AC trace was plotted in Fig. 2(d), when the pump power was ~255.1 mW. As shown, there existed a short pulse with sub-picosecond FWHM that stood on a much longer pedestal, which was a signature of NLP [10]-[14]. This confirmed that our EDF laser was indeed operating in the NLP regime. In general, it is better to use a long fiber cavity for the generation of NLP. Our long fiber cavity can facilitate the accumulation of nonlinearity, which is required by the generation of NLP.

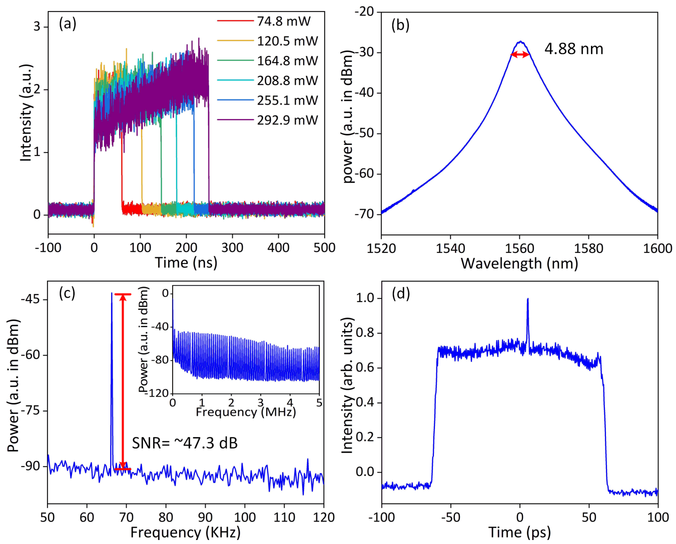

Fig. 2. Square-wave NLP output characteristics without incorporation of the MKR. (a) pulse evolution against pump power; (b) optical spectrum with pump power of ~255.1 mW; the corresponding (c) RF spectrum around the pulse repetition rate; inset: a typical RF train; (d) AC trace.

IV. MKR-INDUCED SOLITON RAIN SHEDDING EFFECTS

The as-prepared MKR was then incorporated in the UR of the EDF laser, as seen in Fig. 1(d). The cavity was thus elongated by ~0.7 m. Similar to the fiber laser without MKR, the NLP broadened almost linearly with the pump power increasing from ~30.2 mW to ~164.8 mW. However, an interesting phenomenon occurred when the pump power increased above ~164. 8 mW. As seen in Fig. 3(a), the duration of the rectangular NLP was maintained at ~190 ns when the pump power increased above ~164.8 mW. Instead of further pulse broadening, there were some dense, burst-like pulses continuously shedding from the NLP. The shedding pulses all moved towards one direction i.e. the left on the oscilloscope. Then they vanished. The higher the pump power, the more pulses shed out and the longer the overall span of these pulses from birth to death, i.e., the longer their life time. It could span to ~9.8 μs when the pump power increased to the maximum limit of the pump source of ~433.1 mW, which took up a considerable portion of the whole repetition period of ~15.4 μs, resulting in to a pulse duty circle of ~63.6%. These shedding pulses can be identified as SRs, considering that there are some similar behaviors with earlier reports on SRs [23]-[25]. But some differences still existed since here they were shed and, in fact, converted from a part of the NLP.

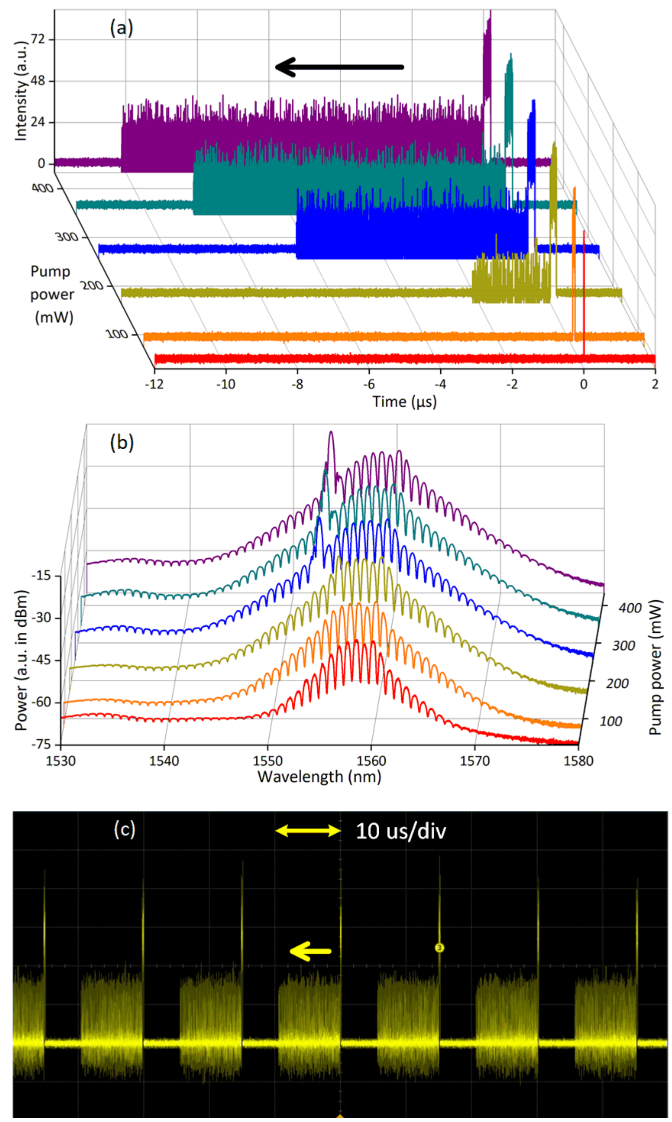

Fig. 3. Pump-power-induced (a) temporal and (b) spectral evolutions; (c) a train of captured NLPs along with shedding SRs when the pump power was ~388.4 mW.

Figure 3(b) plots the corresponding spectral evolution against pump power. The MKR enabled strong modulations on the spectrum. A strikingly rising spectral peak started to stand out from the main spectral profile when the pump power increased above ~164.8 mW when the SRs started to shed from the NLP. It was also noted that the spectral peak shifted from ~1556.1 to 1553.6 nm as the pump power increased from ~164.8 to ~433.1

mW. At the maximum pump power, the 3-dB bandwidth of the spectral peak was ~0.37 nm, which is narrower than the FSR of the MKR (~0.61 nm), probably attributed to the strong rolloff-filtering effect of the MKR as measured in Fig. 1(c). Figure 3(c) shows a captured temporal trace with a span of 100 µs when the pump power was ~388.4 mW.

We also further checked vector characteristics when there were SRs shedding from the NLP. We connected an in-line FPC and a polarization beam splitter (PBS) to the fiber port of the laser output. When the external fiber pigtail's linear birefringence is compensated by the FPC-3, the polarization-resolved characteristics were plotted in Fig. 4. Figure 4(a) show the polarization-resolved temporal characteristics. The rectangular NLP existed in both polarization directions of the PBS, sharing the same pulse duration of ~190 ns, whereas the SRs existed only along the vertical polarization direction. This indicates that the SRs are tightly packaged moving scalar pulses.

Figures 4(b) and 4(c) show the corresponding spectral components along the two orthogonal directions. Both spectral profiles exhibited significant modulations resulted from the comb-like transmission of the MKR. As also noted, the standing-out spectral peak appeared only in one polarizing direction that the SRs just existed.

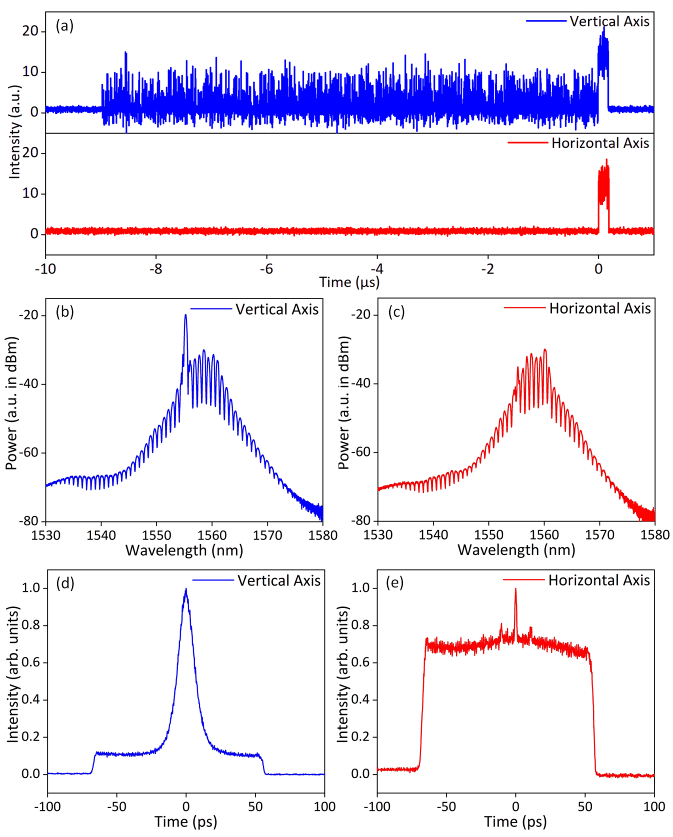

Fig. 4. Polarization-resolved characteristics when there were SRs shedding from the NLP. (a) NLP components in two orthogonal polarizing directions; the corresponding optical spectra [(b) and (c)] and AC traces [(d) and (e)].

The AC trace in the vertical polarization was plotted in Fig. 4(d). A significantly high-rising pulse with an FWHM duration of ~13.6 ps stood out from a wide and low-intensity pedestal. This indicated that the AC trace should be a measurement result of multiple solitons with similar parameters, or a measurement result of SRs. The horizontally polarized AC trace, as plotted in Fig. 4(e), was still a typical NLP.

Here, we would like to mention another point regarding the generation of SRs in fiber lasers. SRs have been reported in various cavity designs, such as unidirectional ring cavities [26, 27] and figure-eight cavities [24]. To the best of our knowledge our fiber laser has the longest cavity length. However, it is difficult to conclude whether it is better or not to use a very long fiber cavity for the generation of SRs.

V. Mechanisms Relating to Scalar SRs

As for the physical mechanisms behind the SRs shedding from the NLP, the dramatically-enhanced local nonlinearity due to the MKR may be a partial answer. The diameter of the fiber taper is only 1.57 µm, noted as d_{taper}, about 1.256% of that of the original fiber. Considering that, for so thin a taper, the propagating optical field might fill the whole cross section, thus we should calculate the nonlinearity using the whole cross section area, rather than only using the tapered core area. The nonlinear parameter γ of a telecommunication SMF at 1.55 µm wavelength is typically 2 W^{-1}km^{-1} [28]. As for the tapered fiber, γ can be calculated by using the following relationship [29]

$$\gamma = \frac{8n_2}{\lambda d_{taper}^2}\left(1-\frac{1}{V^4}\right) lnV \quad (1)$$

where λ is the central wavelength and n_2 is the fiber nonlinear-index coefficient that can be calculated through [30]

$$n_2 \approx [2.507 + 25.25(NA/n_{silica})^2] \times 10^{-20} \text{ m}^2/\text{W}. \quad (2)$$

In it, $n_{silica} \approx 1.444$ near 1.55 µm wavelength, and NA is the numerical aperture. For a fiber taper, the refractive index of the surrounding air cladding is roughly 1. Thus,

$$NA \approx \sqrt{n_{silica}^2 - 1} \approx 1.042. \quad (3)$$

n_2 can then be calculated as $\sim 1.566 \times 10^{-19}$ m^2/W.

V parameter of the fiber taper can be calculated via

$$V \approx \frac{\pi d_{taper}}{\lambda}\sqrt{n_{silica}^2 - 1}\,. \quad (4)$$

Thus, $V \approx 3.315$.

Finally, the calculated $\gamma \approx 387.2$ W^{-1}km^{-1}, which enhanced by ~193.6 times in comparison to the original fiber before tapering. Thus, the MKR results in dramatic enhancement of the local nonlinearity even for a single circulation in the MKR. Further considering the resonant properties of the MKR, the optical pulse can circulate within the MKR for numerous loop-the-loops before it continues to complete a whole cavity roundtrip. Thus, the resulted locally nonlinear effects can experience considerable magnifications.

Benefiting from these, the detailed formation of the SRs can be analyzed as follows. When the pump power was increased to beyond ~164.8 mW, the peak power of the intra-pulse of the NLP was strong enough to trigger the obvious spectrum broadening. At the same time, the dense spectral modulation of the MKR limited the spectrum broadening and instead favored the multiple soliton generation. As the multiple solitons were originated from NLPs, they naturally inhibited instability which behaves as soliton rains. Further pump increase resulted in more soliton shedding, that is, expanding of the temporal span of the SRs.

Besides aforementioned mechanisms attributed to the use of MKR, other possible cause for the formation of SRs through partially depleting the NLP might be the condensed phase achieved by the extension and drift of strong continuous wave (CW) noise background [23]. As previously noted in Figs. 4(a) and 4(b), the soliton rain appeared only when a spectral peak started to standing out from the main spectral profile. This spectral peak was in fact due to some CW components. Despite the spectrally identified CW noise background, the pedestal in Fig. 4(d) covering the whole span of the used autocorrelator should be another indicator.

The physical mechanism for the generated SRs only along one polarization direction should attribute to the polarization dependent loss of the fabricated MKR. As seen in Fig. 4(a), the amplitude of the vertical NLP was higher than that of the horizontal one, whereas they exhibited roughly equal durations. Further taking into account that the shedding SRs also in the vertical direction, the overall amount of the vertically distributed pulse energy was much greater than that with horizontal distribution. These two points indicate that the used MKR indeed has polarization-dependent loss, and the SRs tend to be formed in the polarization direction with less loss. After numerous shaping effects in the MKR, only the SRs in a single polarization, where the MKR has the least loss, can be left, becoming scalars.

Another noted phenomenon is that, although all the SRs are reduced to scalars, the NLP still remains vector characteristics. This is also understandable. It is well known that, in comparison to high peak pulses, the CW or low peak power pulses always experience stronger depletion in fiber lasers when a saturable-absorbing device is incorporated. Here, the NALM acts as the saturable absorber. Thus, considering that the peak power of the formed SRs is indeed lower than that of the NLP, seen in the upper part of Fig. 4(a), and also considering that the transmission loss of the MKR is polarization-dependent, the SRs would preferably appear in the polarization direction that has lower loss. In Fig. 4, it is noted as along the vertical axis that the MKR has the smallest loss. In other polarization directions, the SRs become weaker, and reach the weakest when the polarization direction is orthogonal. From this point of view, the MKR can be also considered as a polarization-dependent absorber. Thus, after repeatedly circulating and reshaping in the MKR, finally the SRs will only appear in the polarization where the transmission loss is the least, i.e., the SRs consequently become scalars. Whereas, due to the higher peak power of the internal sub-pulses of the NLP and the wide pulse duration of the NLP with the random evolution, the polarization-dependent absorption difference would be much weaker. This results in the survival of NLPs along the two orthogonal polarization directions. Thus, the NLP cannot be reduced to a scalar, instead remaining the vector characteristics.

VI. Conclusions

In conclusion, we have experimentally realized scalar SRs shedding away from a vector NLP regime by introducing an MKR device into an ultralong EDF laser. Manipulation on the temporal dynamics was achieved by using the MKR through the spectral tailoring and local nonlinearity management, which potentially paves new ways for the applications of MKR in fiber lasers.

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