

# The Use of NOLM for Investigations of Initial Development of Supercontinuum in Fibers with Anomalous Dispersion<sup>1</sup>

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**Abstract**—We performed a numerical study of the transmission through a nonlinear optical loop mirror (NOLM) of a sequence of solitons generated at the initial stage of the supercontinuum (SC) generation. We found that the NOLM exhibits a selective transmission that critically depends on the amplitude of the input solitons and on the NOLM loop length. The results demonstrate that by properly selecting these parameters the NOLM behaves as an optically controlled switch that allows the transmission of solitons with similar amplitude and width. The results obtained by employing this method are reasonably good and can be used to analyze the soliton formation at the initial stage of SC generation.

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## 1. INTRODUCTION

Supercontinuum (SC) generation in highly nonlinear optical fibers has received great attention after the demonstration of very wide optical spectra excited by an intense optical pulse [1–10]. Since then, several schemes have been investigated for developing broadband sources pumped by a variety of laser pulses. For the femtosecond and picosecond regimes, pump pulses with high peak powers are beneficial in generating SC in short fiber lengths (a few tens of centimeters) [2–6]. In contrast, for the nanosecond and continuous-wave (CW) regimes, the investigations are focused on using power levels of a few watts combined with long fibers for efficient broadband generation [4, 8, 10].

In many experiments reported to date, various nonlinear processes are responsible for SC generation. For femtosecond pulses the dominant effect is related to self-phase modulation (SPM) [5–7]. For picosecond and nanosecond pulses it has been reported that stimulated Raman scattering (SRS) and parametric four-wave mixing (FWM) play an important role in the formation of SC [4, 8, 9]. In the anomalous dispersion regime modulation instability (MI) seeds the spectral broadening. MI causes the breakup of the input pulse leading to the generation of solitons that are shifted to lower frequencies by intrapulse Raman scattering (IRS), contributing to the formation of SC [6, 10].

Because the involved nonlinear processes are very sensitive to experimental conditions, a detailed comparison of experimental results and theory is compli-

cated. Investigations of the SC generation are commonly carried out by solving numerically the nonlinear Schrödinger equation (NLSE) [3, 7, 10]. For a better understanding of the initial process of the SC formation the selective extraction of solitons with similar characteristics such as amplitude and width is desirable. The nonlinear optical loop mirror (NOLM) can be used for this purpose. To the best of our knowledge the use of a NOLM to investigate the initial development of SC was not discussed yet. In this paper we performed a numerical study of the NOLM to be applied for investigations of the soliton formation at the initial stage of SC generation. The NOLM under discussion presents a symmetrical coupler design with highly twisted low-birefringence fiber and a quarter-wave retarder (QWR) inserted in the loop [11]. We investigate the transmission of a sequence of solitons through the NOLM and find that the NOLM exhibits a selective transmission that critically depends on the amplitude of the input solitons before being launched into the NOLM and on the NOLM loop length. The sequence of solitons is formed as a result of pulse breakup when relatively long pulses with initial FWHM duration ( $T_{\text{FWHM}}$ ) of 5 and 100 ps propagate through a standard optical fiber. The results demonstrate that by selecting properly the amplification and the loop length we are able to adjust the NOLM transmission to transmit desired solitons with similar amplitude and width at the NOLM output.

## 2. CONFIGURATION UNDER DISCUSSION

The setup under discussion is shown in Fig. 1. It consists of a NOLM including a symmetrical coupler

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with highly twisted fiber connecting the two output ports of the coupler and a QWR inserted to the loop. The purpose of the QWR is to break the polarization symmetry and the strong twist applied to the fiber produces high optical activity [12] to preserve the optical polarization of each of the counter-propagating beams within the loop.

The principle of the configuration is described as follows. The Standard Fiber is pumped by a relatively long pulse in the anomalous dispersion regime to generate a soliton sequence that contributes to the initial development of SC. The resulting solitons are turned into a circularly polarized beam by the polarization controller (PC), amplified and launched into the NOLM. The coupler splits the input beam into two beams of equal amplitude transmitted through ports 3 and 4 to the loop. We consider that the coupler does not affect the polarization state. The beam transmitted through port 3 keeps its polarization state until it crosses the QWR. The QWR turns this circular polarization into linear polarization and the linearly polarized beam propagates in the clockwise direction until it reaches port 4. For the pulse transmitted through port 4 the initial polarization state is not modified during propagation. As a result, the pulse maintains its circular polarization state until it crosses the QWR. Finally, the linearly polarized beams are recombined again in the coupler and the nonlinear phase difference acquired along the loop determines whether the input beam is transmitted or reflected.

The evolution of the counter-propagating beams in the loop is described by the NLSE used in the following form:

$$\begin{aligned} \frac{\partial A_+}{\partial z} &= \frac{\Delta\beta}{2} \frac{\partial A_+}{\partial T} + i \frac{\beta_2}{2} \frac{\partial^2 A_+}{\partial T^2} + i \frac{2}{3} \gamma (|A_+|^2 + 2|A_-|^2) A_+, \\ \frac{\partial A_-}{\partial z} &= -\frac{\Delta\beta}{2} \frac{\partial A_-}{\partial T} + i \frac{\beta_2}{2} \frac{\partial^2 A_-}{\partial T^2} + i \frac{2}{3} \gamma (|A_-|^2 + 2|A_+|^2) A_-, \end{aligned} \quad (1)$$

where  $A_+$  and  $A_-$  represent the pulse envelope in the right and left circularly polarized states respectively;  $z$  represents the propagation distance; the parameter  $\Delta\beta$  represents the difference in group velocities between the left and right circularly polarized states;  $\beta_2$  is the GVD parameter equal to  $-25.5 \text{ ps}^2/\text{km}$  that corresponds to a dispersion parameter  $D$  of  $20 \text{ ps}/(\text{nm km})$  at  $1550 \text{ nm}$ ;  $T$  represents the physical time in the retarded frame, and  $\gamma$  is the nonlinear coefficient equal to  $1.621 \text{ W/km}$  obtained from the effective area of  $81 \mu\text{m}^2$  and the nonlinear coefficient  $n_2 = 3.2 \times 10^{-20} \text{ m}^2/\text{W}$  for a SMF-28 silica fiber. In this equation we simplify our treatment by excluding the IRS term because its contribution is negligible for the short lengths of the NOLM loop. However, to simulate the soliton sequence in the Standard Fiber we include the IRS term into the NLSE. Equations (1) were solved numerically with the split-

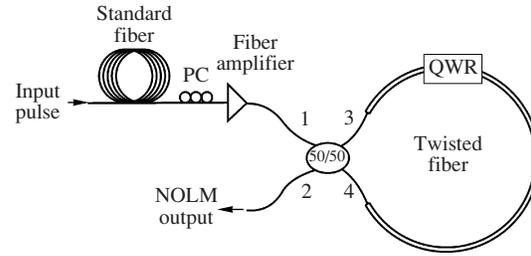


Fig. 1. Setup under discussion.

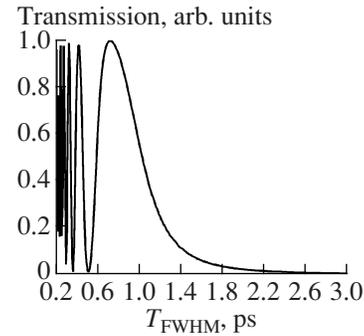
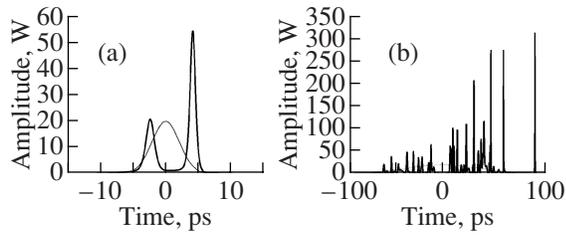


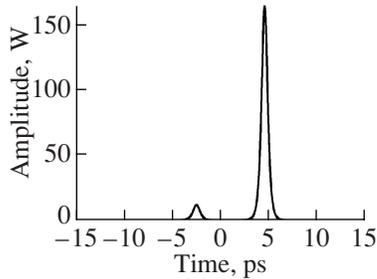
Fig. 2. Transmission of the 37-m NOLM considering linearly polarized solitons at the end of the Standard Fiber amplified by a factor of 3 times.

step Fourier method and the NOLM transmission was analyzed considering different input pulses.

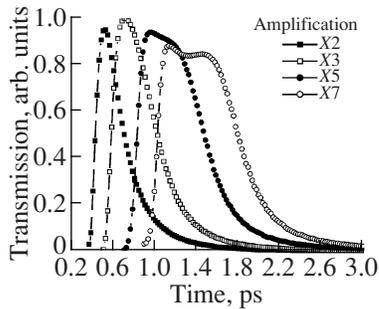
The soliton switching is analyzed considering the solitons resulting from pulse breakup at the end of the Standard Fiber. These solitons cross the PC and their polarization state is turned to circular polarization. At this point the pulses are not solitons since circularly polarized solitons have amplitudes 1.5 times higher than linearly polarized solitons. The Fiber Amplifier makes possible to investigate the case in which fundamental solitons with circular polarization propagate through the NOLM loop. For this case the solitons launched into the NOLM are amplified 3 times. The pulses have amplitude two times higher than that of a circularly polarized solitons and are transmitted through the ports 3 and 4 as a fundamental solitons. The clockwise propagating pulse crosses the QWR and propagates as a linearly polarized pulse with amplitude slightly higher than the fundamental soliton, whereas the counter-clockwise propagating pulse propagates as a circularly polarized soliton. Figure 2 shows the NOLM transmission considering linearly polarized solitons at the end of the Standard Fiber amplified by a factor of 3 times. The solitons have  $T_{\text{FWHM}}$  ranging from 0.2 to 3.0 ps and the NOLM configuration consists of a 37-m fiber length in the loop.



**Fig. 3.** Soliton sequence for the (a) 5 and (b) 100 ps pulses at a distance of 0.53 and 1.86 km in the Standard Fiber, respectively.



**Fig. 4.** Transmitted waveform at the NOLM output by amplifying 3 times the soliton sequence shown in Fig. 3a.



**Fig. 5.** Transmission curves considering different amplification values for linearly polarized solitons at the end of the Standard Fiber.

It can be seen that the transmission oscillates between high and low values for soliton durations ranging from 0.2 to 0.5 ps. For longer solitons the transmission displays a smooth behavior; the transmission increases reaching complete transmission for the 0.72-ps soliton and decays to have low transmission for solitons longer than 2 ps. For applications to the soliton set, the NOLM transmission in the oscillating region results impractical. To avoid this situation, we observe that the maximum transmission corresponds to a loop length of proximately 6 times the dispersion length ( $L_D$ ) of the 0.72-ps soliton, producing the nonlinear phase difference of  $\pi$  necessary to achieve complete transmission. Moreover, high transmission is also obtained for

solitons between 0.59 and 1.00 ps. This property makes possible to adjust the NOLM loop length to achieve complete transmission for a desired soliton and transmit at the NOLM output solitons with similar characteristics.

### 3. NUMERICAL RESULTS AND DISCUSSION

We investigate the soliton formation by using the NOLM configuration shown in Fig. 1. In this configuration an input Gaussian pulse of 20-W peak power is launched into the Standard Fiber where the pulse breakup occurs and a sequence of solitons is formed. Since we deal with relatively long pulses, the pulse sampling requires a very large number of points (typically  $>2^{18}$ ). For this reason we restricted the pulse width ( $T_{FWHM}$ ) to 100 ps. Figure 3 shows the soliton sequence at a distance of 0.53 and 1.86 km for the pulses of 5 and 100 ps, respectively. The fiber length was chosen to produce a time delay in the trailing soliton of one  $T_{FWHM}$  with respect to the time frame. The input pulse is also shown in the figure.

It is clear from Fig. 3 that the soliton formation strongly depends on the pulse width. We first investigate the soliton formation for the soliton sequence shown in Fig. 3a. The waveform consists of two soliton components; the strong pulse has amplitude of 54.4 W and  $T_{FWHM}$  equal to 0.95 ps. For the small pulse the amplitude is equal to 20.8 W and the  $T_{FWHM}$  is equal to 1.55 ps. According to the transmission curve of Fig. 2, we observe that the 0.95-ps soliton has transmission about 10 times higher than the 1.55-ps soliton. So if we amplify this waveform by 3 times before launching into the NOLM we expect at the NOLM output a higher transmission for the 0.95-ps soliton. Figure 4 shows the transmitted waveform at the NOLM output.

According to Fig. 2, for the amplification equal to 3.00 the 0.95-ps soliton has high transmission and solitons longer than 1.55 ps have lower transmission. The pulse is transmitted with a contrast ratio between the highest and the next pulse of 13.5. The strongest pulse has  $T_{FWHM}$  equal to 0.76 ps and amplitude equal to 166 W. On the other hand, since the NOLM transmission is intensity dependent, it changes depending on the amplification of the pulses before being launched into the NOLM. We calculate the NOLM transmission considering different amplification factors between 2 and 7 times for the linearly polarized solitons at the end of the Standard Fiber. The soliton  $T_{FWHM}$  is ranging from 0.2 to 3.0 ps. Figure 5 shows the NOLM transmission. The NOLM includes the 37-m fiber length in the loop.

The amplification of 3 times produces the highest transmission. This amplification causes the transmission of circularly polarized solitons through the NOLM loop achieving a complete transmission. For the other values of the amplification the pulses transmitted through the loop are not solitons and the transmission occurs only for a part of the pulse. However for the val-

ues of amplification presented in Fig. 5 the transmission can be considered high. Another interesting feature that we observe is that the maximum of the transmission is shifted towards longer solitons as the amplification increases. This propriety allows adjusting the NOLM transmission by providing proper amplification to obtain high transmission for the desired solitons. Figure 6 shows the transmitted waveform at the NOLM output for the amplification of 7 times when the soliton sequence shown in Fig. 3a is applied.

The output waveform can be analyzed with the NOLM transmission curves of Fig. 5. For the amplification of 7 times the transmission maximum is shifted towards longer solitons. In this case the amplification is adjusted to obtain low transmission for the 0.95-ps soliton and high transmission for the 1.55-ps soliton. As a result we obtain at the NOLM output the transmission of the 1.55-ps soliton. The transmitted pulse has  $T_{FWHM}$  equal to 0.67 ps and amplitude equal to 273 W. In both cases the compression effect is expected since the beams traveling into the loop have amplitudes higher than the fundamental soliton.

These results demonstrate the potential of the NOLM for analyzing the soliton formation at the initial stage of SC formation. The NOLM selectively relies on selecting properly the amplification and the NOLM loop length to transmit the desired soliton. However for a large number of solitons the transmission of a single soliton is complicated since many of them have similar characteristics such as amplitude and width. Instead of that, we analyze the use of the NOLM to obtain high transmission for solitons with similar characteristics.

We next analyze the soliton formation for the waveform shown in Fig. 3b. The soliton sequence consists of a large number of solitons produced by an input pulse of 100 ps. For this sequence the bigger solitons have  $T_{FWHM}$  around 0.39 ps and amplitude around 310 W. To analyze the soliton transmission we choose a NOLM loop with 10-m fiber length which ensures the highest transmission for the 0.4-ps soliton and calculate the transmitted energy at the NOLM output considering different amplification values for the waveform shown in Fig. 3b. Figure 7 shows the transmitted energy versus amplification.

For amplification lower than 2 the pulses transmitted through the NOLM loop have amplitudes lower than the circularly polarized soliton and as a result the dispersive effect degrades the transmission. For amplifications higher than 2, the pulses at the NOLM loop are almost solitons and the NOLM transmission benefits the bigger solitons which experiment high transmission; the transmitted energy increases linearly until it reaches point A. As the amplification increases, the NOLM transmission is shifted to longer solitons that benefit from higher transmission until they reach point B (amplification of 4.5). At this point we expect the transmission of a large number of solitons since they undergo higher transmission. For further amplification

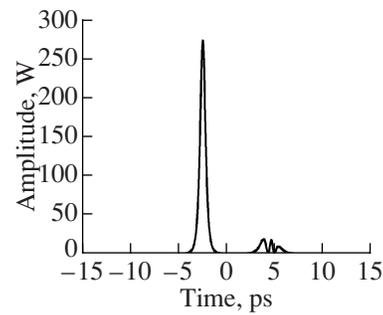


Fig. 6. Transmitted waveform at the NOLM output when the soliton sequence shown in Fig. 3a is amplified 7 times.

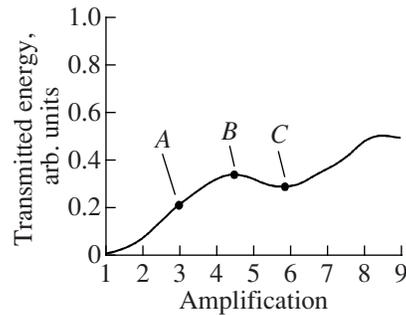


Fig. 7. Transmitted energy versus amplification.

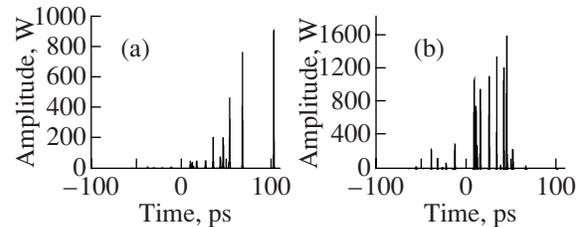


Fig. 8. Transmitted waveforms at the NOLM output by amplifying (a) 3 and (b) 5.8 times the soliton sequence shown in Fig. 3b.

values the transmitted energy is reduced until it reaches point C, this is due to the fact that solitons with shorter  $T_{FWHM}$  undergo low transmission. At this point the transmission of longer solitons is expected. For higher amplifications, the transmitted energy increases until it reaches a value of 0.5. At this point the transmission for the shorter solitons is located in the oscillating part of NOLM transmission; as a result the transmission corresponds to an average of the soliton sequence. Figure 8 shows the output waveforms for values of amplification corresponding to the points A and C in Fig. 7.

These results show good agreement with the transmitted energy curves. It is clear that the amplification and the loop length play an important role to obtain at

the NOLM output the desired solitons. For input pulses with initial duration of a few picoseconds, the pulse breaks into a small number of solitons and the transmission of a single soliton can be exploited. For relatively long input pulses the transmission of a single soliton is complicated because it breaks into a big number of solitons. However by analyzing the transmitted energy at the NOLM output we are able to determine the amplification values at which it is possible to transmit solitons with similar characteristics. The results obtained by employing this method are reasonably good and can be used to analyze the soliton formation at the initial stage of SC formation.

#### 4. CONCLUSIONS

We investigated the use of a NOLM for investigations of the soliton formation at the initial stage of SC formation in fibers with anomalous dispersion. We found that an appropriate amplification and NOLM loop length allows high transmission for the desired solitons and rejecting of the undesired solitons. The selective transmission of solitons through the NOLM demonstrates the potential of the NOLM for analyzing the soliton formation. For relatively short pulses the pulse breaks into a few solitons and the transmission of a single soliton can be exploited. For longer solitons it is possible to transmit solitons with similar characteristics. The results obtained by employing the suggested configuration are reasonably good and can be used to analyze the soliton formation at the initial stage of SC formation.

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