

# Spatiotemporal observation and manipulation of nonlinear optical waves in single-shot using a recirculating fiber loop

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**Abstract:** We present experiments realized in a synchronously phase-modulated recirculating fiber loop demonstrating the possibility to manipulate the spatiotemporal dynamics of nonlinear waves. Temporal quadratic phase modulations are shown to either expulse or trap solitons.

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Manipulating and shaping the properties of rapidly varying optical waves is a basic operation which is crucial for some of the most practical applications ranging from laser surgery to telecommunication. For the latter, optical fiber is now predominantly used and also happen to be an extremely versatile medium for fundamental investigations of intricate nonlinear processes with important implications in a broad range of transverse fields including hydrodynamics and quantum physics. In this context, a major limitation of experiments based on the propagation in optical fibers lies on the technical impossibility for the experimenter to interact or even observe the wavefield as it propagates. The recirculating optical fiber loop configuration, historically developed to study long-haul transmissions of solitonic pulses [1], actually partially circumvent this constraint and has recently proven to be a powerful experimental platform to observe and investigate complex spatiotemporal dynamics induced by nonlinear processes such as modulation instability (MI) [2-3]. This configuration is particularly interesting in this respect as it enables periodic access to the propagating field and has already been used in this sense to stabilize the propagation of solitons [4] or more recently to study optical Bloch oscillations [5] using intra-loop modulation techniques. However, the reported extent of control over the dynamics of nonlinear structures remains rather limited.

In this work, we report experiments performed in a recirculating fiber loop in which a synchronous phase modulation stage is embedded enabling remarkable manipulation of the spatiotemporal dynamics of optical waves. As a demonstration, we investigate how repulsive and attractive temporal quadratic phase modulations act as potentials that dramatically modify the scenario of spontaneous MI by the expulsion of solitons in one case or by strongly forcing their interactions in the other.

The experiments conducted in this work are based on a recirculating optical fiber loop configuration the principle of operation of which is schematized in Fig. 1. An arbitrary shaped input signal (20 ns-long square pulses, 50 Hz repetition rate in the present case) is generated via fast electro-optic modulation of a single frequency laser (1555 nm). The input signal is coupled in a 5 km-long fiber loop mostly comprised of standard single mode fiber.

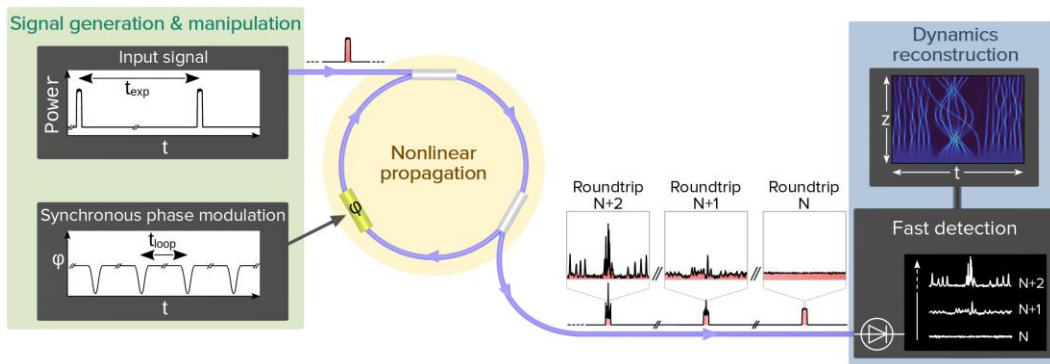


Fig. 1. Principle of operation of the phase modulated recirculating optical fiber loop. In the present work:  $t_{\text{exp}} = 20\text{ms}$ ,  $t_{\text{loop}} \approx 25\mu\text{s}$ .

At each roundtrip, a fraction of the circulating field is extracted and directed towards the detection system composed of a fast photodiode and sequentially triggered fast sampling oscilloscope leading to an overall bandwidth of  $\sim 32$  GHz. Raw data, consisting in a succession of segments (one per roundtrip), are numerically processed to construct the single-shot 2D diagram of the spatiotemporal dynamics of the input signal in the reference frame

travelling at the group velocity of the carrier frequency. In order to achieve long propagation distances, roundtrip losses are compensated via counter-propagating distributed Raman amplification (not shown for clarity) leading to effective power losses of the order of  $10^{-7}\text{m}^{-1}$ . The originality of the experimental setup presented here lies in the phase modulation stage embedded in the fiber loop that is synchronized with both the input signal and the roundtrip time of the circulating field in order to act coherently from one roundtrip to the other.

To demonstrate the ability of our experimental platform to manipulate complex nonlinear waves, we designed an experiment where a static (i.e. constant from one roundtrip to the other) temporal quadratic phase modulation is coherently applied to the circulating field. Results are illustrated in Fig. 2 as single-shot 2D spatiotemporal diagrams. Setting the input signal as a quasi-continuous wave (long square pulses), spontaneous MI is triggered, leading to the complete breakup of the field into an almost regular train of pulses followed by a complex spatiotemporal dynamics. When coherently applying a repulsive potential limited in time, pulses initiated by MI turn into solitons that are repelled creating a clear void in the place where the phase modulation is applied [Fig. 2 (a)]. On the contrary, an attractive potential logically confines light in a well in which a remarkable periodic longitudinal evolution is observed [Fig. 2 (b-d)]. Specifically, the presented spatiotemporal diagrams exhibit dynamics with a degree of complexity that increases with the optical power of the continuous wave: Figure 2(b) shows a linear dynamics while for larger power, a few solitons emerge and collide periodically due to the harmonic nature of the trap [Fig. 2 (c)]. The number of solitons trapped in the well increases with power eventually resulting in extremely complex interaction patterns [Fig. 2 (d)].

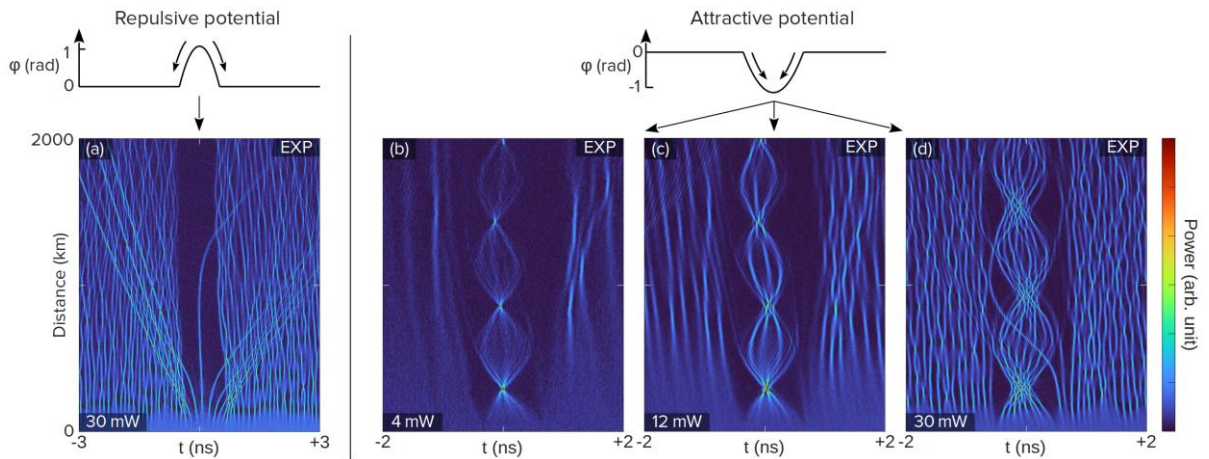


Fig. 2. Experimental spatiotemporal diagrams of the dynamics of quasi-continuous waves subject to a phase modulation localized in time. A synchronous quadratic phase modulation is applied at each roundtrip over a duration of 1 ns leading to an effectively repulsive (a) or attractive (b-d) potential. (b-d) Same attractive trap applied to quasi-continuous waves of increasing power.

In conclusion, we developed a new experimental platform that enables highly reconfigurable manipulation of the spatiotemporal dynamics of nonlinear structures thanks to a synchronous phase modulation stage integrated to a recirculating optical fiber loop. With this system, we report single-shot observations of the expulsion and trapping of multiple solitons using simple potentials. This new capability to control nonlinear optical pulses opens the way for a vast range of original experimental studies largely unexplored so far. Interestingly, this system enables a close analogy to be drawn with the physics of Bose-Einstein condensates.

## References

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