

Advanced spatiotemporal manipulation of nonlinear waves and solitons using a recirculating fiber loop

François Copie¹, Pierre Suret¹, Stéphane Randoux¹

1. Univ. de Lille, CNRS, UMR8523 - PhLAM - Physique des Lasers Atomes et Molécules, F-59000 Lille, France

Manipulating and shaping the properties of rapidly varying optical waves is an essential operation with numerous practical applications that is also of fundamental interest for investigating intricate nonlinear processes. In that context, optical fiber systems happen to be extremely versatile platforms that nevertheless suffer major limitations owing to the technical impossibility for the experimenter to interact or even observe the wavefield as it propagates. Recirculating optical fiber loops, historically developed to study long-haul transmissions of solitonic pulses [1] are particularly interesting in this respect as they enable periodic access to the propagating field and have already been used in this sense for instance to stabilize the propagation of solitons [2] or more recently to study optical Bloch oscillations [3] using simple intra-loop modulation techniques. In this work, we developed a new experimental system based on a recirculating fiber loop that enables arbitrary phase modulation of the optical wavefield in both space and time. This generates an effective potential that can be used to greatly manipulate the space-time dynamics of light.

The principle of operation of our experiment is schematically depicted in Fig. 1(a). A 20 ns-long square pulse is injected in a 5 km-long fiber loop. At each roundtrip, a fraction of the circulating field is extracted and directly recorded using a fast sampling oscilloscope enabling the construction of single-shot 2D diagrams of the spatiotemporal dynamics of the signal [Fig. 1(b-c)]. The originality of this system lies in the phase modulation stage embedded in the fiber loop that is synchronized with the circulating field to reshape its dynamics.

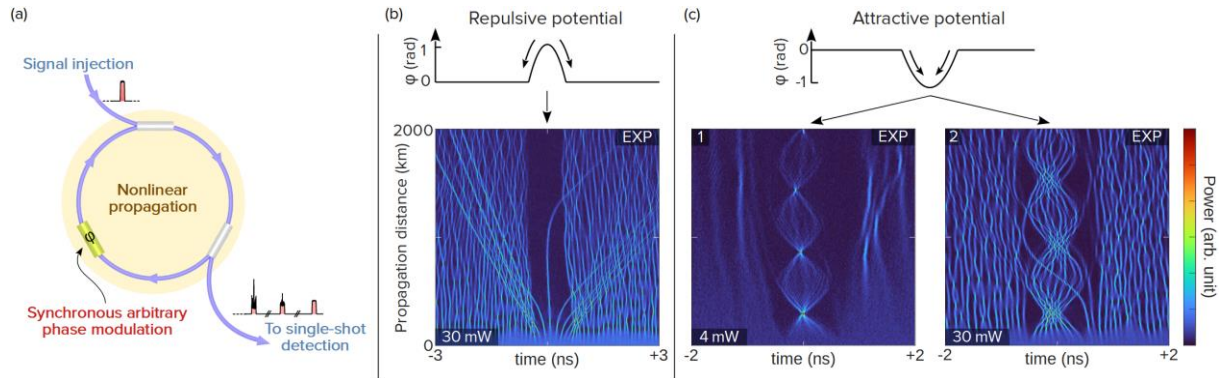


Fig. 1 (a) Principle of operation of the experimental system. (b-c) Experimentally recorded spatiotemporal dynamics of continuous waves undergoing stationary quadratic phase modulations resulting in a repulsive (b) or attractive (c) potential. For large initial power, solitons emerge and are either repelled (b) or trapped (c.2) by the effective potential.

Figure 1(b-c) shows experimental results demonstrating the ability of our platform to manipulate complex nonlinear waves. A quasi-continuous wave input signal experiences spontaneous MI which leads to the complete breakup of the field into an irregular train of pulses followed by a complex spatiotemporal dynamics. However, when coherently applying a stationary quadratic phase modulation localised in time, an effective potential is created that dramatically modifies the spatiotemporal dynamics : When the potential is repulsive, pulses initiated by MI turn into solitons that are repelled, creating a clear void in the place where the phase modulation is applied [Fig. 1(b)] whereas an attractive potential logically confines light in a well in which a remarkable periodic evolution is observed [Fig. 1(c)]. Specifically, the degree of complexity of the observed dynamics increases with the optical power of the continuous wave: while Fig. 1(c.1) shows an almost linear dynamics, solitons emerge at larger power and interact periodically in the harmonic trap resulting in extremely complex interaction patterns [Fig. 1(c.2)].

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 fiber loop. This remarkable capability to shape and control nonlinear waves and even individual optical solitons opens the way to a broad range of original studies largely unexplored so far. Interestingly, this system enables a close analogy to be drawn with the physics of Bose-Einstein condensates.

[1] E. Desurvivre, M. Dignonnet, and H. J. Shaw, “Raman amplification of recirculating pulses in a reentrant fiber loop,” *Opt. Lett.* **10**, 83-85 (1985).

[2] M. Nakazawa, E. Yamada, H. Kubota, and K. Suzuki, “10Gbit/s Soliton data transmission over one million kilometres,” *Electron. Lett.* **27**, 1270-1272 (1991).

[3] H. Chen, N. Yang, C. Qin, W. Li, B. Wang, T. Han, C. Zhang, W. Liu, K. Wang, H. Long, X. Zhang, and P. Lu, “Real-time observation of frequency Bloch oscillations with fibre loop modulation,” *Light Sci. Appl.* **10**, 48 (2021).