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Phase-space topology of fiber four-wave mixing

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Abstract— We propose and experimentally demonstrate a new experimental testbed enabling the study and control of ideal four-wave mixing interactions in optics. Two approaches are used to reveal the phase-space topology of the underlying nonlinear processes. The first is based on iterated initial conditions in a short fiber segment. The second relies on an experimental dataset that is then processed and analyzed by a neural network.

Keywords—nonlinear photonics, fiber optics, machine learning

Four wave mixing (FWM) arises from the dispersion-mediated energy exchange between discrete evolving frequency components, and is a key physical process of nonlinear science. From a fundamental perspective, the essential features of FWM are most clearly seen in the degenerate case when the system is described by a reduced system of three coupled differential equations [1]. The FWM process then reveals a range of canonical dynamics, including the initial phase of modulation instability, Fermi-Pasta-Ulam recurrence, stationary waves and a separatrix boundary between different dynamical regimes. However although the FWM system has been the subject of many previous theoretical and numerical studies, it remains notoriously difficult to implement in practice due to the cascading of the wave mixing process to generate higher order sidebands in the form of a broadband frequency comb[2, 3].

Here, we address this shortcoming directly through a new experimental technique that has allowed us to characterize near-ideal FWM dynamics in a nonlinear Schrödinger equation system based on optical fiber in the regime of focusing nonlinearity. In order to follow the dynamical interactions between only three evolving frequency components, we use filtering and iterative propagation over a 500-m fiber segment which allows us to focus on the evolution of the key parameters η and ϕ that are the fraction of the total power in the central frequency component and the sideband-pump phase difference, respectively. The problem is therefore experimentally reduced to the generation of a signal with the input properties η_{in}, ϕ_{in} (and a given average power), and to the measurement of the output properties η_{out}, ϕ_{out} . The optical testbed we have developed is made of commercially-available telecommunications components and operates at 1550 nm. A 40-GHz frequency comb resulting from temporal

sinusoidal phase modulation is spectrally processed using a programmable filter that simultaneously eliminates unwanted spectral components, and precisely adjust the ratio η and relative phase ϕ .

In this context, we have developed an experimental approach where iterated initial conditions are sequentially injected in the fiber. By iterating 100 measurements, we emulate the nonlinear propagation over 50 km without suffering from unwanted higher-order effects. Testing different input powers and initial values of η for phase offsets of 0 or π enables us to reconstruct the full dynamical phase space topology, revealing cycles with closed orbits, stationary wave existence, and the system separatrix boundary. We can also retrieve the temporal properties, highlighting characteristic features of multiple Fermi-Pasta-Ulam recurrence. We compare our experimental results with solutions of the canonical differential equation system describing the wave evolution, obtaining excellent agreement.

The second approach we implement takes advantage of the power of machine-learning algorithms that are currently revolutionizing many aspect of photonics [4] including nonlinear fiber optics with prediction of nonlinear reshaping [5] or supercontinuum generation [6]. A set of initial experimental measurements serves here as a basis to train a feedforward neural network. Only a few neurons are required to provide excellent predictions and to retrieve the main aforementioned features of the phase-space topology.

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