Dynamics control in four-wave mixing processes in optical fiber

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Abstract. A nonlinear interaction of waves in a dispersive medium manifests itself in a four-wave mixing process that can be described as an evolution of waves' parameters on a phase plane in a form of closed orbits. Here we propose a method to control these trajectories and to switch from one state to another in an optimal manner by implementing an abrupt change of the average power. The method is confirmed experimentally by the reconstruction of a fundamental four-wave mixing dynamics in an idealized model using iterative propagation in a short segment of fiber.

1 Introduction

The nonlinear Schrodinger equation is a basis of nonlinear fiber optics. In the focusing regime of propagation, the four-wave mixing (FWM) process can explain a broad range of observations such as modulation instability, generation of ultrashort high-repetition pulse trains, parametric amplification… In its simplest configuration, FWM involves the interaction of three waves (a strong continuous wave pump and two other components located symmetrically on both sides of this pump) with exchange of energy and phase variation. The dynamics of this system is of recurrent nature and can be depicted as closed orbits in reduced coordinates on a phase plane. The trajectories follow unique paths depending on the initial energy distribution and dephasing between the three waves as well as the average power [1]. Hence, it is impossible to link two states unless they belong to the same orbit. Here we seek to remove this fundamental limitation by introducing an approach based on an abrupt change of the average power. If it is done at a relevant point on the phase plane the switching allows an efficient transition between the two desired states.

2 Idealized four-wave mixing

1.1 Theoretical background

An ideal FWM assumes that nonlinear interaction occurs solely between the pump ψ_0 and the two spectral lines $\psi_{\pm 1}$ at $\pm\omega_m$ (with $\omega_m = 2\pi f_m$ being the modulation frequency). To describe the dynamics, one may use reduced parameters: the relative spectral amplitude $\eta = |\psi_0|^2 / \sum|\psi_i|^2$ and the relative phase $\phi = \phi_{-1} + \phi_1 - 2\phi_0$ with ϕ_i being the phase of each spectral line. In this case the evolution of spectral lines with propagation distance can be described by the one-dimensional conservative Hamiltonian [1]:

$$H = 2\eta\left(1-\eta\right)\cos\phi + \left(\Omega^2+1\right)\eta - \frac{3}{2}\eta^2, \quad (1)$$

$$\frac{\partial\eta}{\partial\xi} = \frac{\partial H}{\partial\phi} \quad \text{and} \quad \frac{\partial\phi}{\partial\xi} = -\frac{\partial H}{\partial\eta}. \quad (2)$$

Here the $\Omega^2 = sign(\beta_2)(2\pi f_m)^2/(|\beta_2|/\gamma P_0)$ is a nonlinear mismatch parameter with P_0 being the average power, β_2 and γ - the second-order dispersion and the nonlinear coefficient of a fiber, respectively. $\xi = z/(\gamma P_0)$ is the normalized distance.

To characterize the dynamics, the evolution of η and ϕ can be put on a phase plane: ($\eta\cos\phi$, $\eta\sin\phi$). There exist two families of solutions following the recurrent orbits, that are divided by a separatrix [1, 2].

1.2 Experimental setup

In order to remain in the framework of the ideal FWM without any new cascaded spectral component, we developed a devoted experimental setup presented in Fig. 1 which relies on standard components of the telecommunication industry [3]. We generate a comb at 40 GHz from a continuous wave (CW) laser modulated by a phase modulator, which is then shaped in the frequency domain to reach the desired η, ϕ. The signal is amplified by an erbium-doped fiber amplifier (EDFA) to reach P_0 and then propagates in a single-mode fiber (β_2 = -8 ps^2 km^{-1} ; γ = 1.7 W^{-1} km^{-1}). By using a limited length of optical fiber (500 m), we avoid cascaded interactions as well as spurious additional nonlinear effects. The level of dissipation is negligeable. The output relative amplitude is measured with an optical spectrum analyser (OSA), and the phase is obtained from relative sinusoidal beating of two filtered signals measured on a high-speed sampling oscilloscope. After the output η, ϕ are measured, the input is updated, and the process is repeated

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continuously, so that a complete trajectory can be reconstructed. Note that an alternative design of this setup has been developed to benefit to machine-learning approaches [4].

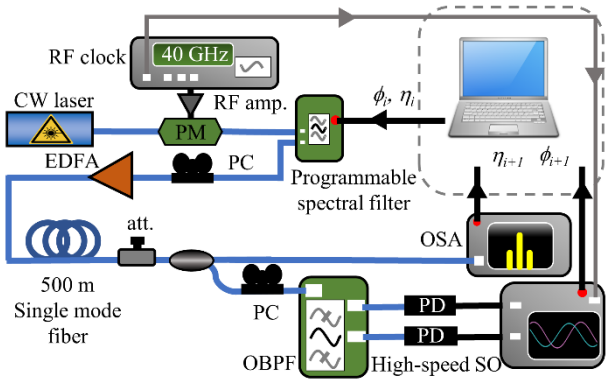

Fig. 1 Experimental setup. PC – polarization controller, Att. – attenuator, OBPF – optical band pass filter, PD – photodiode, RF amp. – radiofrequency amplifier.

3 Trajectory control

3.1 Principle

Early experiments in fiber optics or hydrodynamics have already explored the idea of an abrupt change of the medium properties to freeze the longitudinal evolution of a breathing wave [5,6]. Indeed, depending on the fiber characteristics the orbits would have different shapes and the normalized mismatch parameter Ω in Eq. (1) will change. Therefore, Ω represents a key control parameter [7] which change will enable a control of dynamics and states transitions. In our approach, instead of varying the fiber properties, we choose the average power as a the degree of freedom and we do not restrict ourself to targeting a stationary state.

If there are no limitations in reachable values of Ω, any two points on the phase plane can be connected by a single abrupt change of this parameter. In practice, however, experimental conditions limit the control: we consider fixed fiber characteristics, and the input power is restricted in order not to damage the equipment. In our case, only values $\Omega^2 \in$ [-2.51 : -0.95] can be reached.

To make a state transition, first, we select the input η_{IN}, ϕ_{IN} and the output η_{OUT}, ϕ_{OUT} points we want to connect. Then, using a Hamiltonian conservation, we find all reachable states for both points within the given limits of Ω. Out of this range of reachable states we find an optimum, i.e. an intersection point that allows to connect input and output on the shortest propagation length. To change the Ω we adjust the input power accordingly in the intersection point.

3.1 Experimental demonstration

Two examples of experimental demonstrations are presented in Fig. 2 (solid lines ; dashed lines represent ideal close orbits for the input and output powers). We confirm that with a single change in the average power, the trajectory can cross the separatrix and switch to another type of dynamics (panel (a)). The transition takes 11 km with a switching taking place after 6.5 km.

It is also possible to control the orbits within the same family of solutions (panel (b)). Here a trajectory starting on the right side makes a transition to the inner orbit after power increase by 1 dB.

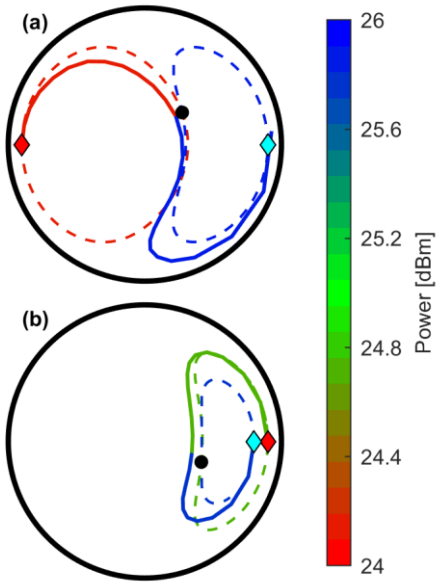

Fig. 2 Experimental trajectories that connect (a) η_{IN} = 0.90, ϕ_{IN} = π and η_{OUT} = 0.90, ϕ_{OUT} = 0, (b) η_{IN} = 0.90, ϕ_{IN} = 0 and η_{OUT} = 0.80, ϕ_{OUT} = 0, by an abrupt power change. The colour depicts value of input average power that is used for each part of the trajectory.

Conclusion

We have conceptually and experimentally demonstrated that an abrupt change of the average power allows tailored manipulation of the ideal FWM dynamics and can help to connect two states that are not part of the same orbit [8]. This switching technique is robust to small deviations from the ideal simulations. The results follow well the numerical predictions, and the theoretical estimation of the switching point is accurate.

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