Exploring New Phenomena in Analogue Physical Simulations through an Optical Feedback Loop in Paraxial Light Fluids

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INTRODUCTION

Advances in optical analogue simulations, particularly those mimicking quantum fluids with paraxial beams of light, have fueled tabletop experiments [1], but limitations arise from the length of the nonlinear mediums. Indeed, a paraxial beam of light propagating through a photorefractive crystal follows a mathematical model similar to the nonlinear Schrödinger equation [2]. Using normalized units and considering that the beam intensity is far from the crystal saturation intensity, the nonlinear Schrödinger equation is written as [3]

$$i\frac{\partial E_f}{\partial \tau} + \frac{1}{2}\nabla_\perp^2 E_f - \left|E_f\right|^2 E_f + i\frac{\alpha}{2}E_f = 0, \quad (1)$$

where α is the crystal absorption and τ is the effective time of the analogue emulation. The maximum propagation distance or analogue effective time allowed by the emulation is estimated as [3]

$$\tau_{max} = k_f \Delta n L_z, \quad (2)$$

where k_f is the beam wavenumber, Δn measures the nonlinear strength, and L_z is the crystal length. Equation (2) highlights the constraint imposed by L_z on the maximum emulation time. This work presents an experimental solution to overcome this physical constraint.

EXPERIMENTAL IMPLEMENTATION

Figure 1 - Illustration of the feedback loop experimental implementation and the steps performed in each passage. A - Simplified experimental setup [3]. B - Three-dimensional representation of the state evolution inside the photorefractive crystal for several feedback loop iterations. C - Optical feedback loop conceptual scheme.

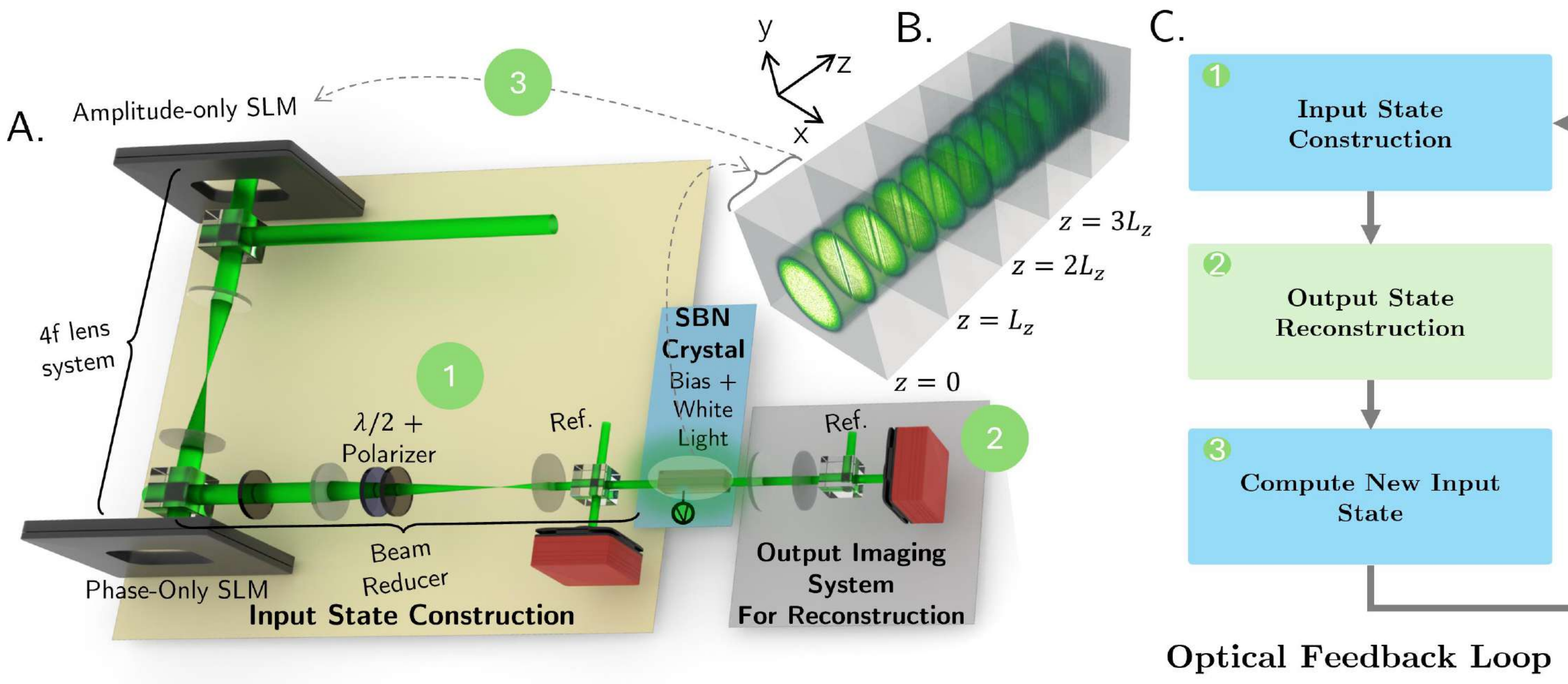
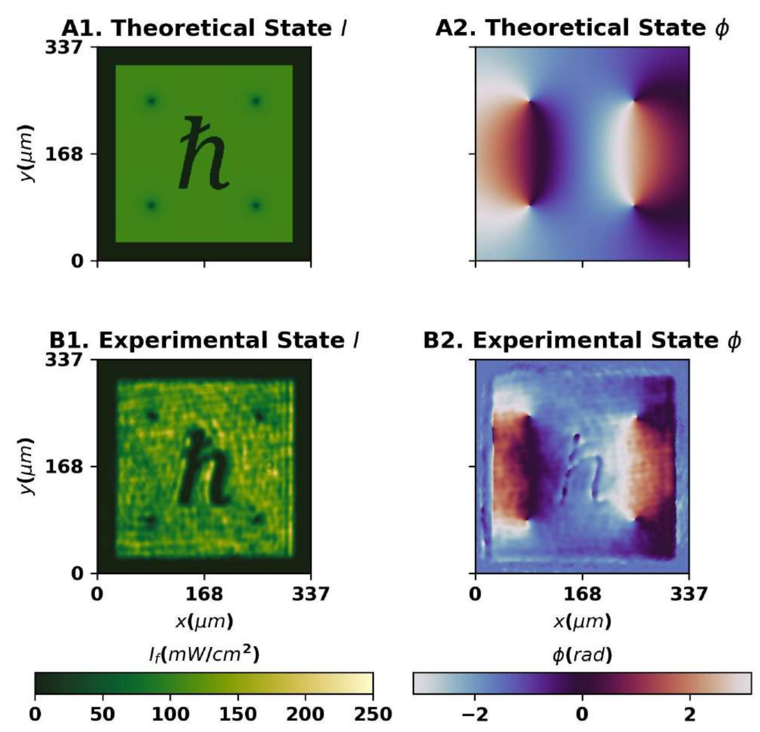


Figure 2 - Generation of arbitrary states: Subfigures A display the numerical state, while Subfigures B show the measured experimental state. This image was taken from [3].



1. The feedback loop uses spatial light modulators to imprint intensity and phase profiles onto the beam. This process involves 4f lens systems to ensure correspondence between the modulators and transport the created state to the entrance of the crystal. In this section, the power is also adjusted to the correct value.

2. The output intensity is measured, and the phase profile is retrieved through off-axis digital holography [4].

3. The amplitude and phase are adjusted to match the spatial light modulators dimensions, with some filtering applied to reduce experimental noise, before restarting the process.

EXPERIMENTAL RESULTS

Vortex Collision and Sound Emission:

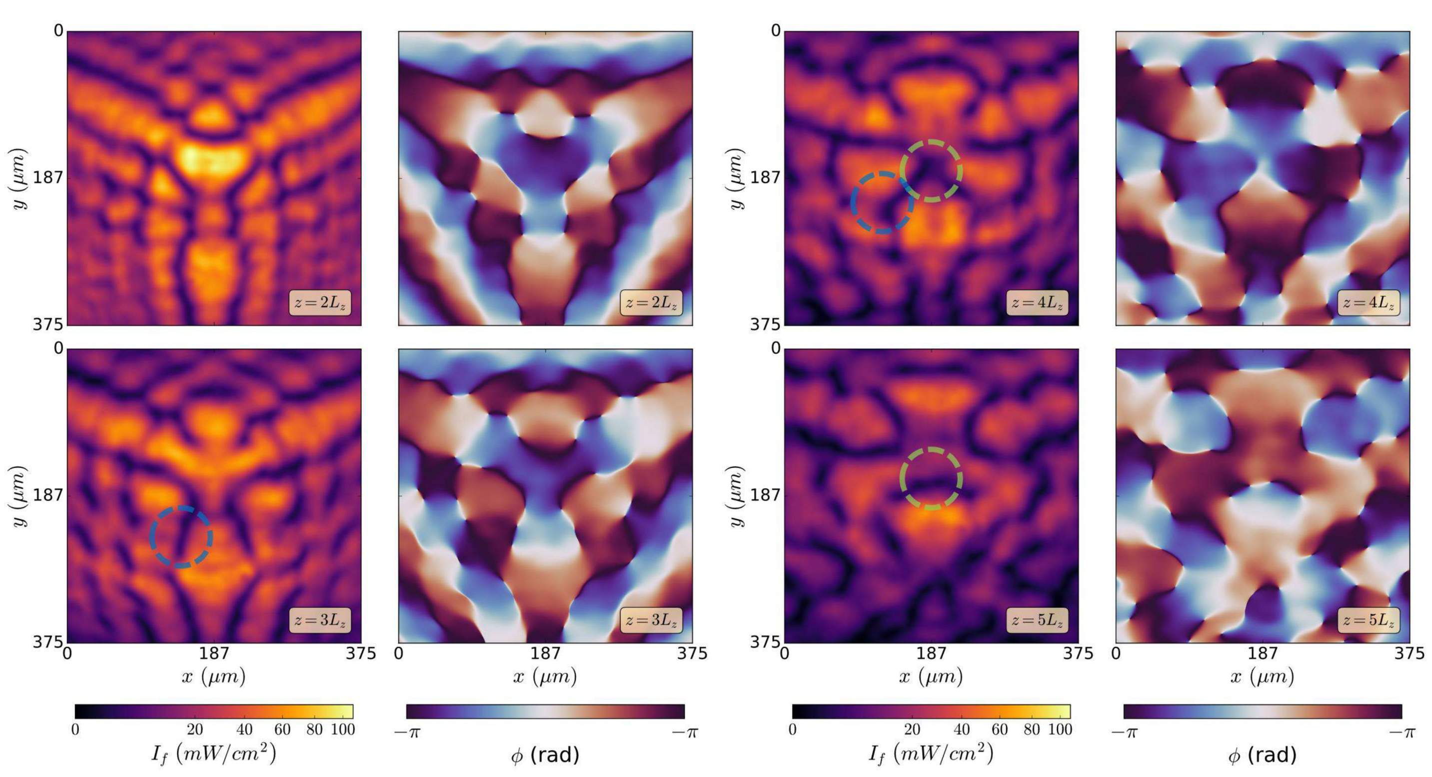


Figure 3 - Experimental results for the collision between three flat-top states. Due to the chaotic dynamics of the state, it is possible to observe the merging between vortices of opposite signals and the subsequent sound emission, indicated by the blue-dashed circles, as well as the generation of vortex pairs due to the collision between wavefronts, indicated by the green-dashed circles.

Multiple Dark Soliton Decay:

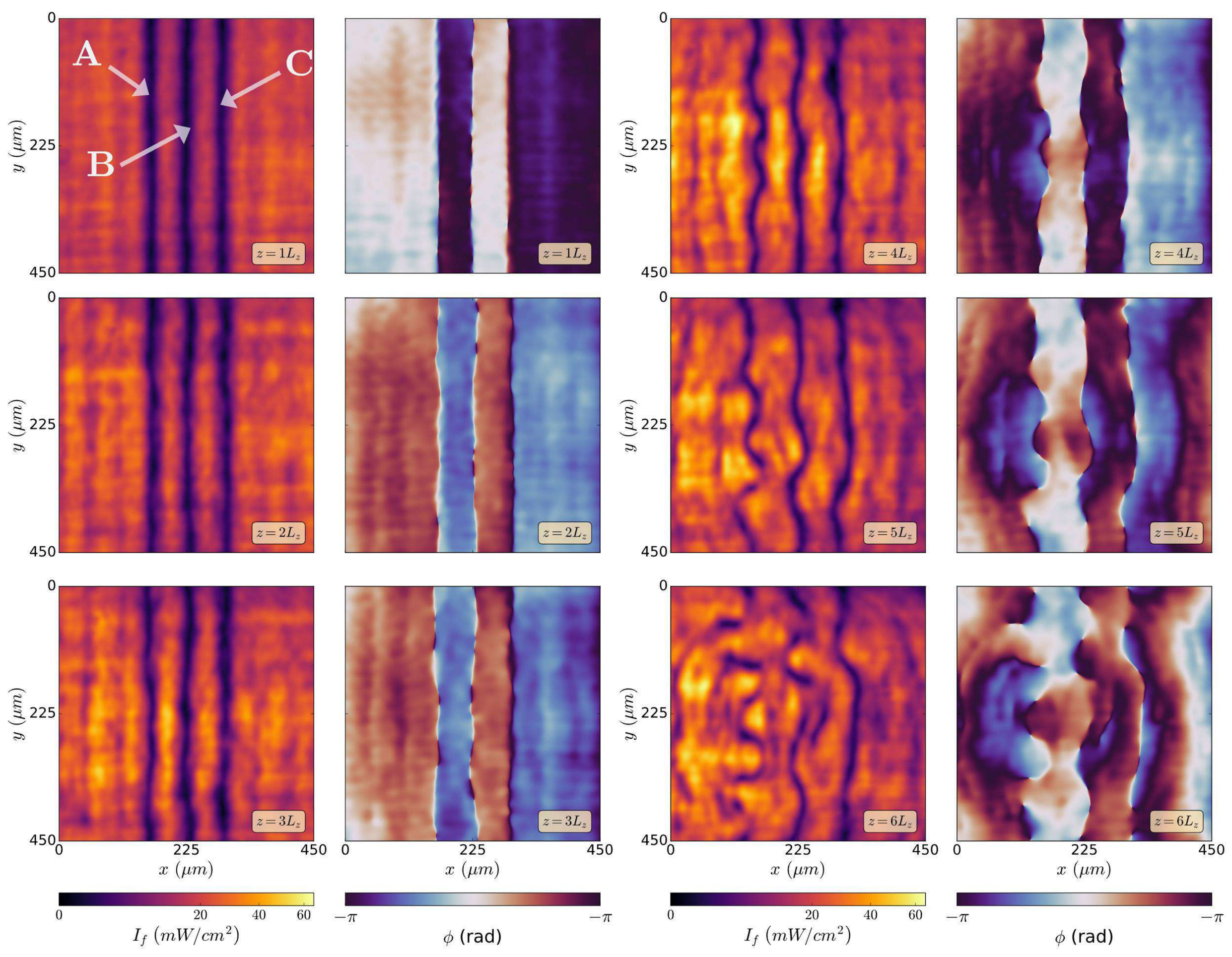


Figure 4 - Experimental results for the decay of multiple dark solitons indicated by the letters A, B, and C. These results disregard the influence of crystal absorption, maintaining a constant input power throughout the passages.

CONCLUSIONS

In this study, we demonstrate the effectiveness of an optical feedback loop in extending the effective time of analogue quantum simulations using paraxial fluids of light, allowing propagation over multiple crystal lengths. Additionally, by exploring collision scenarios and soliton decay, we demonstrated the versatility of the experimental setup, paving the way for further experimental investigations into topics such as quantum turbulence, vortex dynamics, and analogue gravity studies.

REFERENCES

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