Development of an Optical Feedback Loop for Paraxial Fluids of Light

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Abstract: This work introduces an optical feedback loop employing off-axis digital holography and spatial light modulators to overcome limitations imposed by the finite length of nonlinear optical materials in analogue experiments with paraxial fluids of light. By reconstructing the output state at the medium's entrance, this approach extends the effective emulation time, enabling access to intermediate states, and facilitates the exploration of complex dynamics that typically require extended emulation times.

Experimental Implementation

Motivation

Advances in optical analogue simulations using paraxial light beams to mimic quantum fluids have enabled tabletop experiments [1, 2], but they are limited by the length of the nonlinear medium. In photorefractive crystals, paraxial beams follow a model equivalent to the nonlinear Schrödinger equation [2, 3]

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

where α is the crystal absorption and τ is the effective time. The maximum effective analogue time scales with the crystal length ($\propto L_z$), thereby limiting the range of observable dynamics.

Figure 1 - Illustration of the feedback loop. A - Simplified experimental setup [4]. B - Three-dimensional representation of the state evolution.

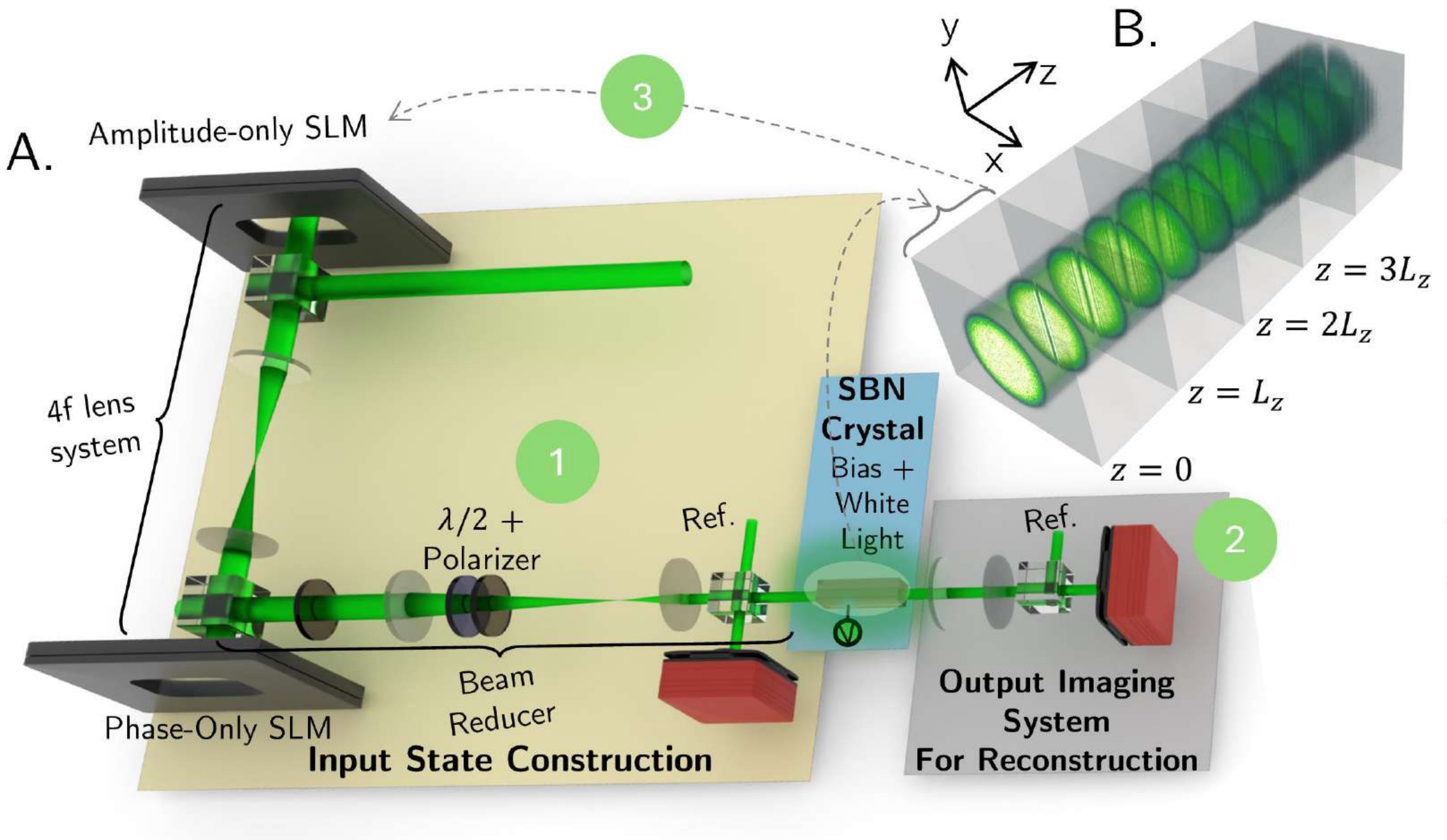
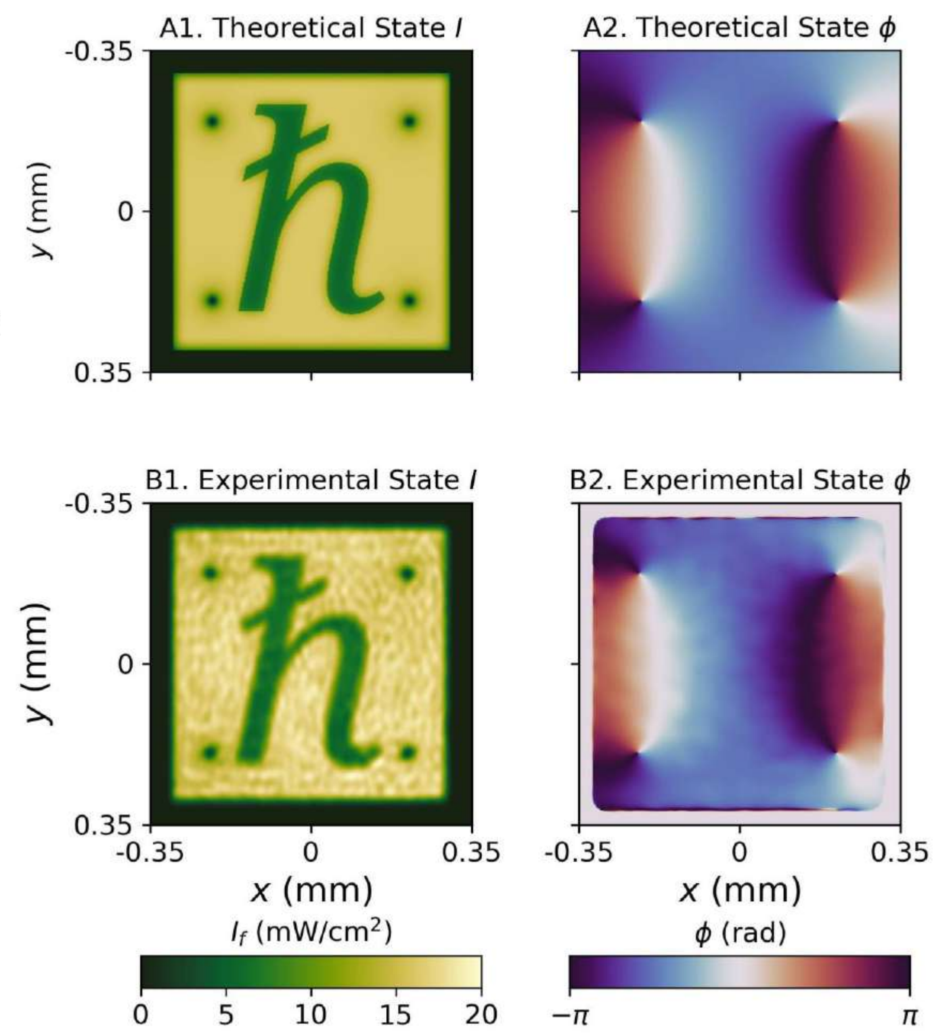


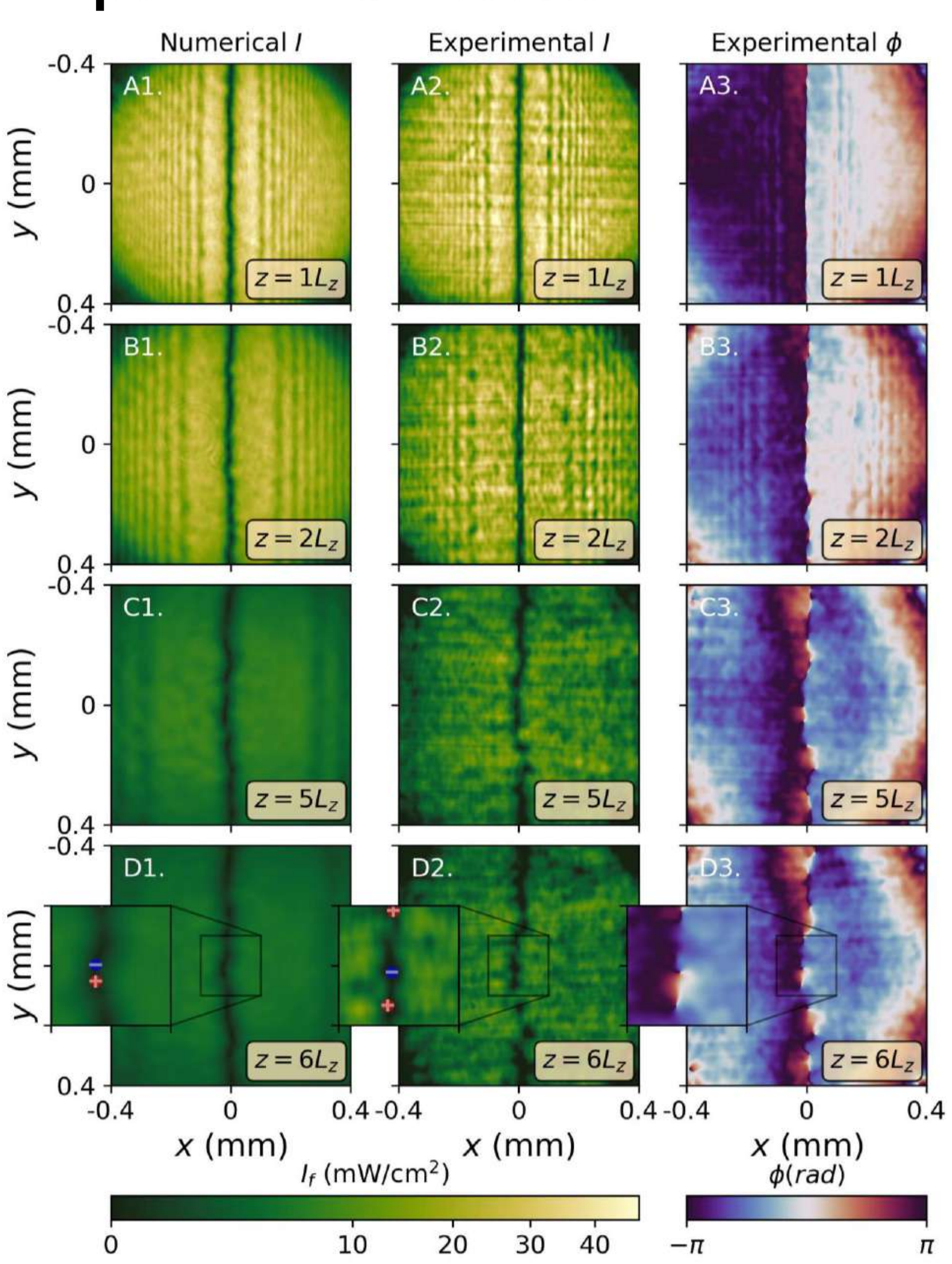
Figure 2 - Generation of arbitrary states: Subfigures A - numerical state. Subfigures B. Experimental state with $\mathcal{F} \approx 0.98$.



Fidelity

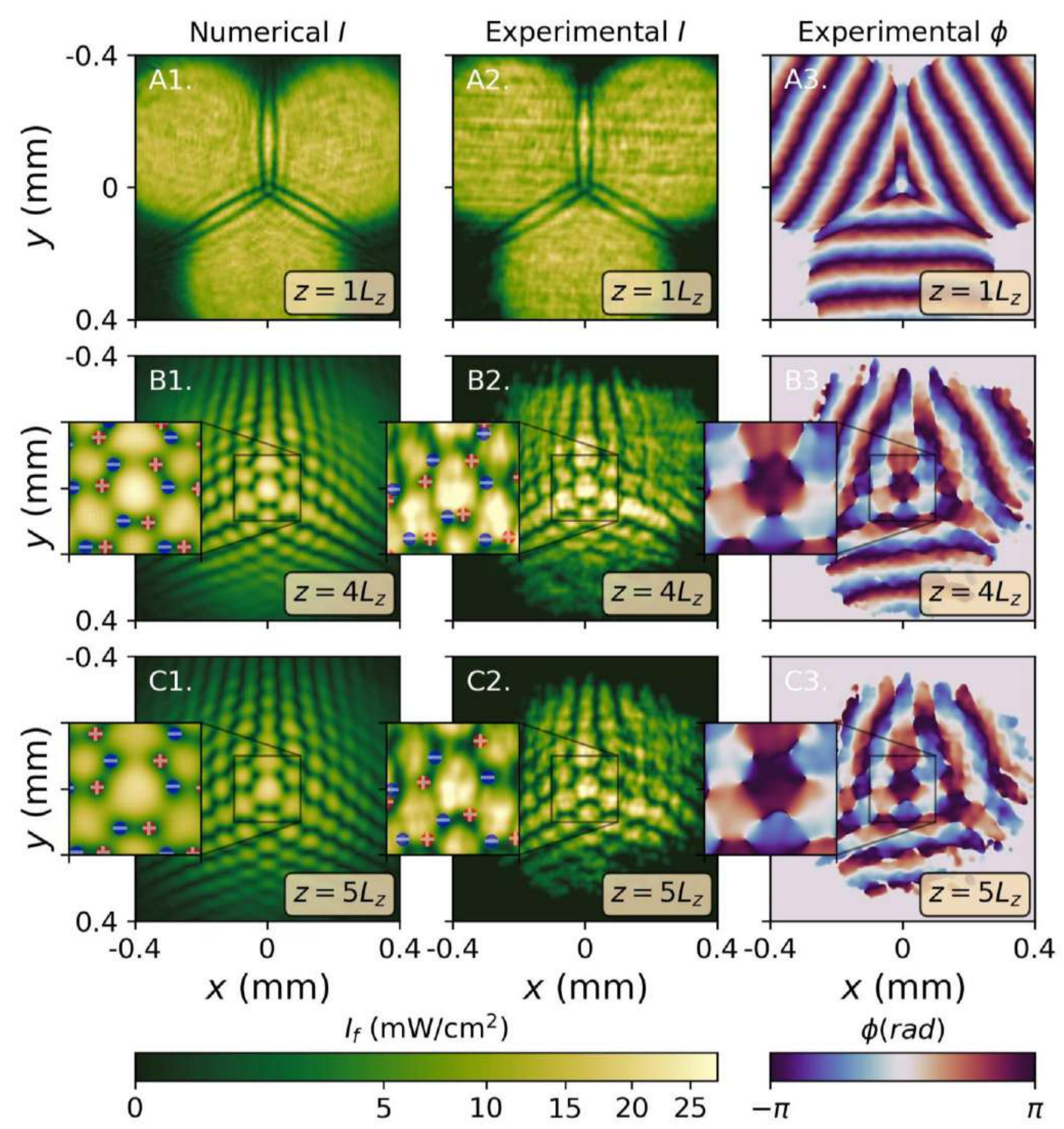
To access the quality of the created states we use the overlap integral [5] $\gamma = \frac{1}{\sqrt{P_{in}P_{in,exp}}}\int E_{in}^* E_{in,exp}\,dxdy$, where the fidelity $\mathcal{F} = |\gamma|^2$ measures the agreement between the experimental and theoretical states.

Experimental Results



Dark Soliton Decay

Figure 3 - Experimental results showing the decay of a dark soliton for 6 passes through the crystal. Initially, the formation of shock waves is observed, followed by their expansion. The dark soliton then undergoes the characteristic snake instability, eventually decaying into vortex pairs.

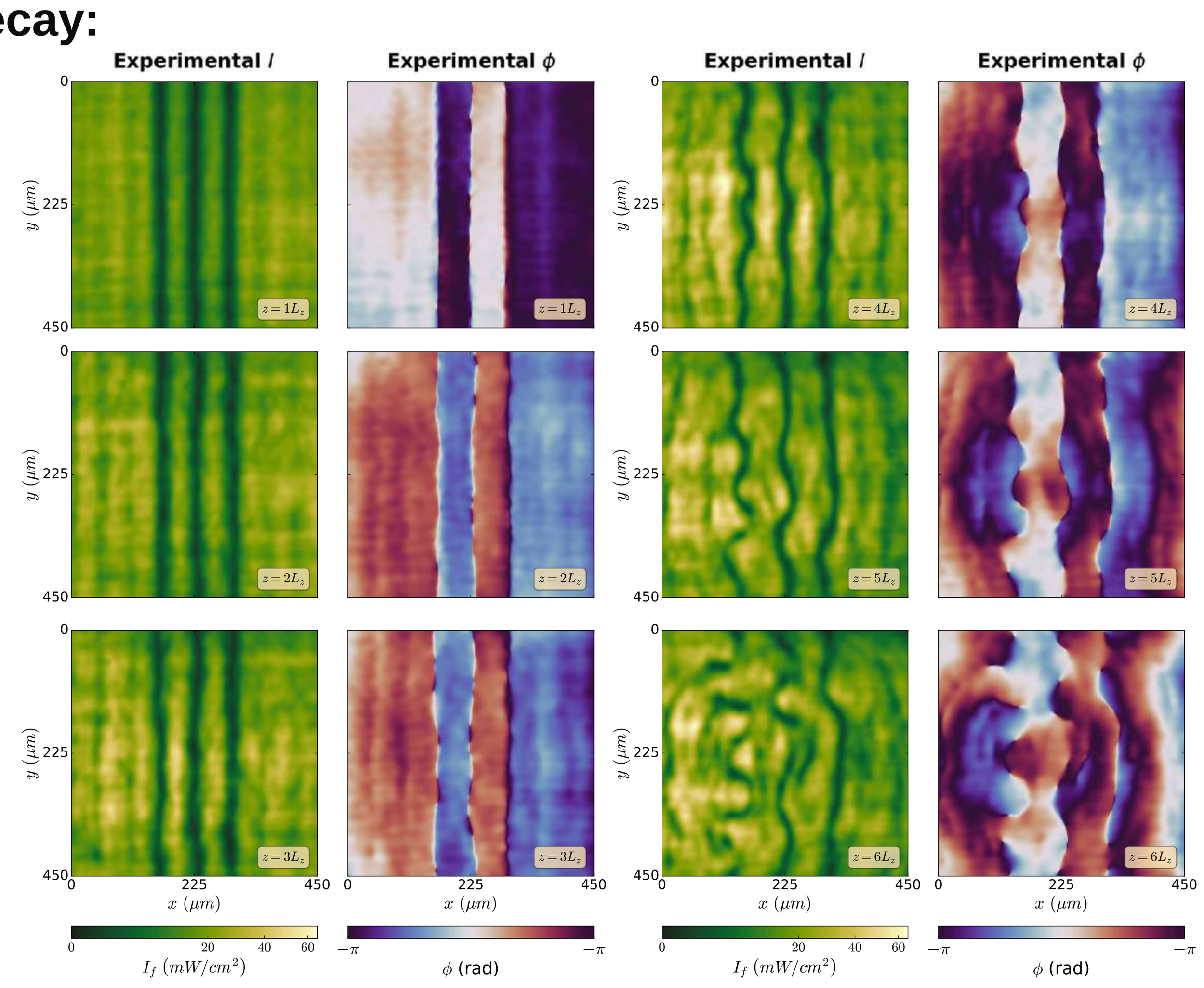


Flat-top Collision

Figure 4 - Experimental results of the collision between three flat-top states after 5 passes through the crystal. The interaction leads to the formation of a polygonal structure composed of multiple vortices in the center.

Multiple Dark Soliton Decay:

Figure 5 - Experimental results for the decay of multiple dark solitons. These results disregard the influence of crystal absorption, maintaining a constant input power throughout the passages.



Conclusions

- The feedback loop extends the effective emulation time, up to 6 propagation lengths, revealing previously inaccessible dynamics.
- Enables exploration of complex phenomena like quantum turbulence and analogue gravity with non-trivial initial conditions.
- Anisotropic effects may cause deviations in the current implementation, but isotropic media could improve the accuracy of the emulations.

References

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