Unlocking New Dynamics in Paraxial Fluids of Light with an Optical Feedback Loop

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What are paraxial fluids of light?

And why are paraxial fluids of light important in current research?

$\Downarrow$

Analogue Simulations

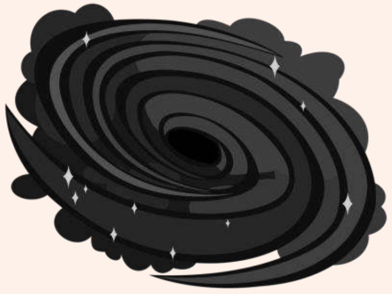
Optical Analogues For Physical Simulations

Physics, nowadays, is **interested** in **systems** that **hard** or **impossible** to **experiment with**.

A **black hole** is perhaps the **best example** of this!

We can use **systems** that have a **similar mathematical description** for **emulating them**.

Systems governed by a similar mathematical model



Black hole

Water drain

Study black holes
with a **water drain**

The water black hole image adapted from arXiv:1801.08473

Optical Analogues

The application of analogue simulations

Analogue Simulations → **Physical systems emulating other real phenomena or mathematical models!**

Optical Analogues
Analogue simulations with light

Analogue simulations with **light** are perhaps the **most successful example** of this **branch**.

Light systems offer **great opportunities**:

- ✓ **Parallelization**
- ✓ **High-speed** capabilities
- ✓ **Low-power** requirements
- ✓ **Precision control** of the **amplitude** and **phase** profiles.
- ✓ Allow **recovery** of the **experimental amplitude** and **phase** profiles.

Analogue systems created with **light** for **emulating** **<u>Quantum Fluids</u>**.

Optical Analogues
Quantum Fluids of Light

Quantum fluids are **hydrodynamical systems** that **exhibit quantum effects**, such as superfluidity or quantum turbulence.

Quantum fluids of light tries to **emulate these systems** with **light.**

Optical Analogues

Quantum Fluids of Light

Systems governed by a similar mathematical model

Quantum Fluid

$$\underbrace{i\hbar\frac{\partial\psi(\vec{r}_\perp,t)}{\partial t}}_{\text{Time}} + \left[\underbrace{\frac{\hbar^2}{2m}\nabla_\perp^2}_{\text{Mass}} \underbrace{+ V_{ext}(\vec{r}_\perp,t)}_{\text{External potential}} \underbrace{+ g\left|\psi(\vec{r}_\perp,t)\right|^2}_{\text{Interactions}} \underbrace{+ i\gamma}_{\text{Losses}}\right]\psi(\vec{r}_\perp,t) = 0 \rightarrow$$

Vortex nucleation due to a defect

They **support macroscopic quantum effects**.

The BEC image was adapted from 10.1088/1367-2630/ac8656.

Optical Analogues
Quantum Fluids of Light

Systems governed by a similar mathematical model

Quantum Fluid

$$\underbrace{i\hbar\frac{\partial\psi(\vec{r}_\perp,t)}{\partial t}}_{\text{Time}} + \left[\underbrace{\frac{\hbar^2}{2m}\nabla_\perp^2}_{\text{Mass}} \underbrace{+ V_{ext}(\vec{r}_\perp,t)}_{\text{External potential}} \underbrace{+ g\,|\psi(\vec{r}_\perp,t)|^2}_{\text{Interactions}} \underbrace{+ i\gamma}_{\text{Losses}}\right]\psi(\vec{r}_\perp,t) = 0 \longrightarrow$$

Vortex nucleation due to a defect

<u>However</u>, they require **low-temperatures** and **expensive experimental setups**.

Accessing all the **fluid properties**, such as the <u>velocity field</u>, is **difficult**.

The BEC image was adapted from 10.1088/1367-2630/ac8656.

Optical Analogues

Quantum Fluids of Light

Systems governed by a similar mathematical model

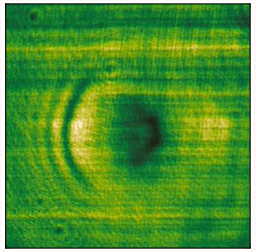
Vortex nucleation due to a defect

Quantum Fluid

$$i\hbar\frac{\partial\psi(\vec{r}_\perp,t)}{\partial t} + \left[\frac{\hbar^2}{2m}\nabla_\perp^2 + V_{ext}(\vec{r}_\perp,t) + g\left|\psi(\vec{r}_\perp,t)\right|^2 + i\gamma\right]\psi(\vec{r}_\perp,t) = 0$$

Paraxial Fluid of Light

$$i\frac{\partial E(\vec{r}_\perp,z)}{\partial z} + \left[\frac{1}{2k_0n_0}\nabla_\perp^2 + k_0V_{ext}(\vec{r}_\perp,z) + k_0 g\left|E(\vec{r}_\perp,z)\right|^2 + i\frac{\alpha}{2}\right]E(\vec{r}_\perp,z) = 0.$$



Time | Mass | External potential | Interactions | Losses

<u>Paraxial fluids of light</u> are **suitable physical system** <u>capable</u> of **emulating quantum fluids**.

The BEC image was adapted from 10.1088/1367-2630/ac8656.

Optical Analogues

Quantum Fluids of Light

Systems governed by a similar mathematical model

Vortex nucleation due to a defect

Quantum Fluid

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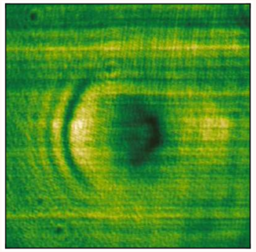
$$\updownarrow$$

Paraxial Fluid of Light

$$i\frac{\partial E(\vec{r}_\perp,z)}{\partial z} + \left[\frac{1}{2k_0 n_0}\nabla_\perp^2 + k_0 V_{ext}(\vec{r}_\perp,z) + k_0 g\,|E(\vec{r}_\perp,z)|^2 + i\frac{\alpha}{2}\right]E(\vec{r}_\perp,z) = 0.$$



Time | Mass | External potential | Interactions | Losses

More generally, <u>Paraxial fluids of light</u> are:

Physical Emulators of the **Nonlinear Schrödinger equation**.

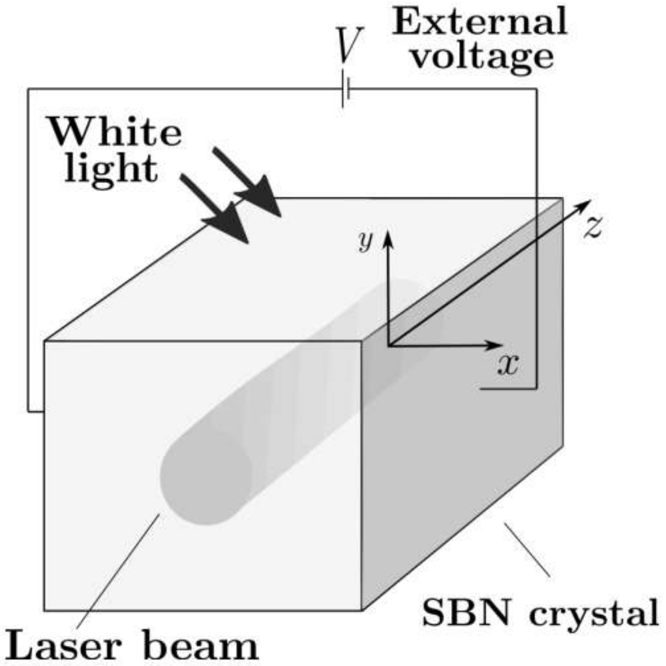
The BEC image was adapted from 10.1088/1367-2630/ac8656.

Paraxial Fluids of Light

How can we use a photorefractive crystal to emulate quantum fluids?

A **light beam propagating** in a **photorefractive crystal** can be described by the following model:

$$i\frac{\partial E_f}{\partial z} + \frac{1}{2k_f n_e}\nabla_\perp^2 E_f + k_f \Delta n_{max} \frac{|E_f|^2}{|E_f|^2 + I_{sat}} E_f + i\frac{\alpha}{2} E_f = 0$$



$\Delta n_{max} \propto V_{Ext}$

$I_{sat} \propto$ White light

Figure 1 – Photorefractive crystal. Image adapted from "Fluids of light in a nonlinear photorefractive medium", Omar Boughdad, 2020.

Paraxial Fluids of Light

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The **z coordinate plays** the **role** of an **effective time**.

The **analogue fluid** is **two-dimensional**.

Each **slice along** the **propagation direction** (z-axis) **represents** the **fluid** at **different moments** in **time**.

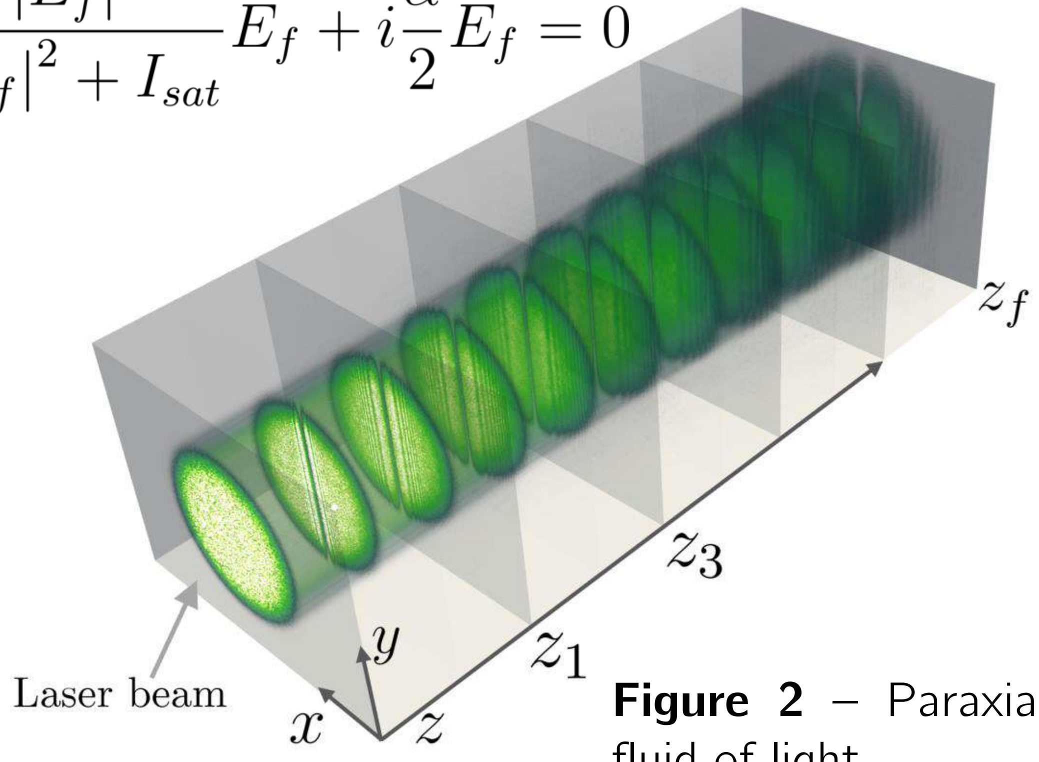

Figure 2 – Paraxial fluid of light.

Paraxial Fluids of Light

How can we use a photorefractive crystal to emulate quantum fluids?

A **light beam propagating** in a **photorefractive crystal** can be described by the following model:

$$\underbrace{i\frac{\partial E_f}{\partial z}}_{\text{Time}} + \underbrace{\frac{1}{2k_f n_e}\nabla_\perp^2 E_f}_{\text{Effective mass}} + k_f \Delta n_{max} \frac{|E_f|^2}{|E_f|^2 + I_{sat}} E_f + i\frac{\alpha}{2} E_f = 0$$

Paraxial Fluids of Light

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The **nonlinearity mediates** the **photons interactions**.

These **must be repulsive** for the **system** to **behave** as a **fluid**.

Defocusing regime of the **nonlinear material**.

Paraxial Fluids of Light

How can we use a photorefractive crystal to emulate quantum fluids?

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Paraxial Fluids of Light
Experimental implementation

Figure 3 – Experimental setup

We start by **considering** a **collimated laser beam**.

Paraxial Fluids of Light

Experimental implementation

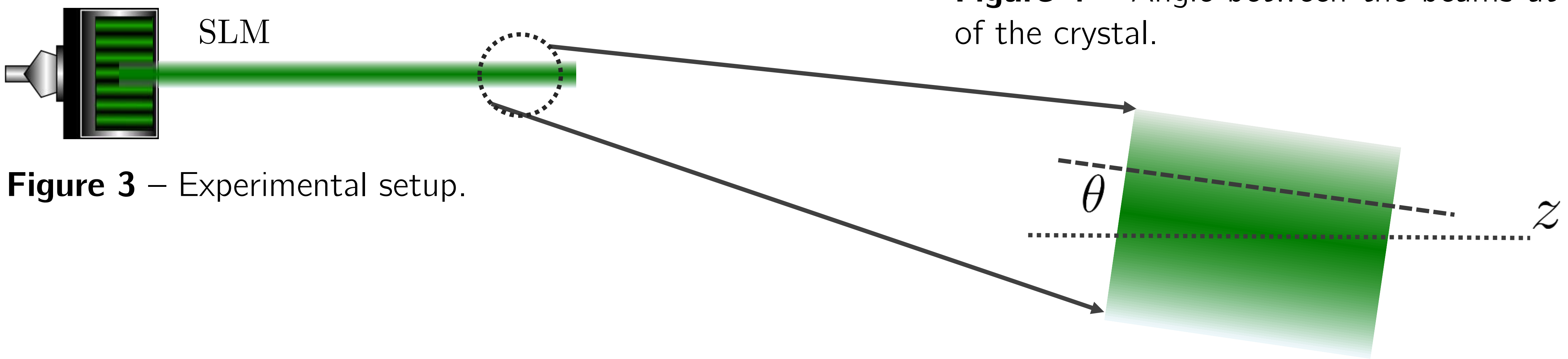


Figure 4 – Angle between the beams at the input of the crystal.

Figure 3 – Experimental setup.

Analogue fluid velocity $\vec{v} = \dfrac{1}{k_f n_e} \nabla_\perp \phi$

$$\vec{v} = \frac{1}{k_f n_e} \nabla_\perp \phi \quad \xrightarrow{\text{Uniform velocity}} \quad v \approx \frac{\theta}{n_e}$$

The analogue **fluid velocity** <u>corresponds</u> to the **angle** between the beam and the **propagation direction**.

This **angle** is **controlled** with an **SLM.**

Paraxial Fluids of Light
Experimental implementation

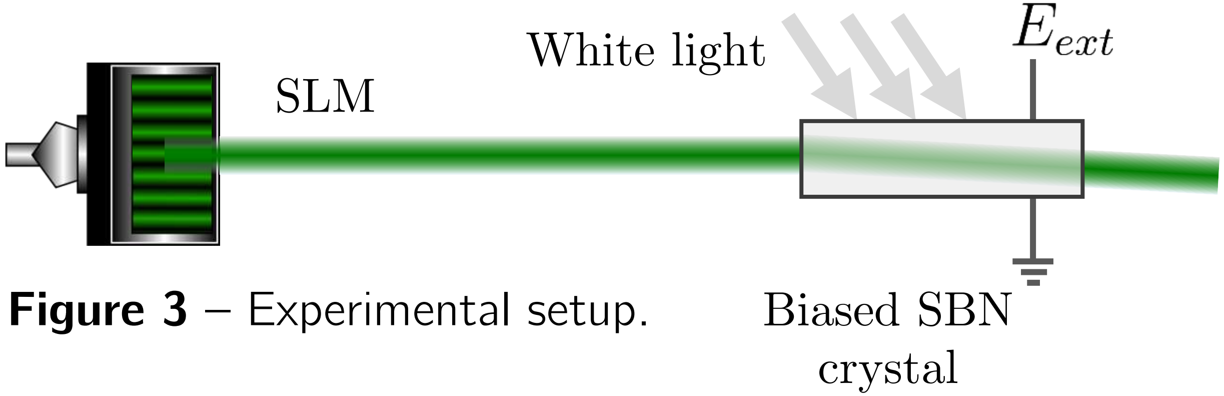


Figure 3 – Experimental setup.

The **beam propagates inside** the **crystal**.

Paraxial Fluids of Light

Experimental implementation

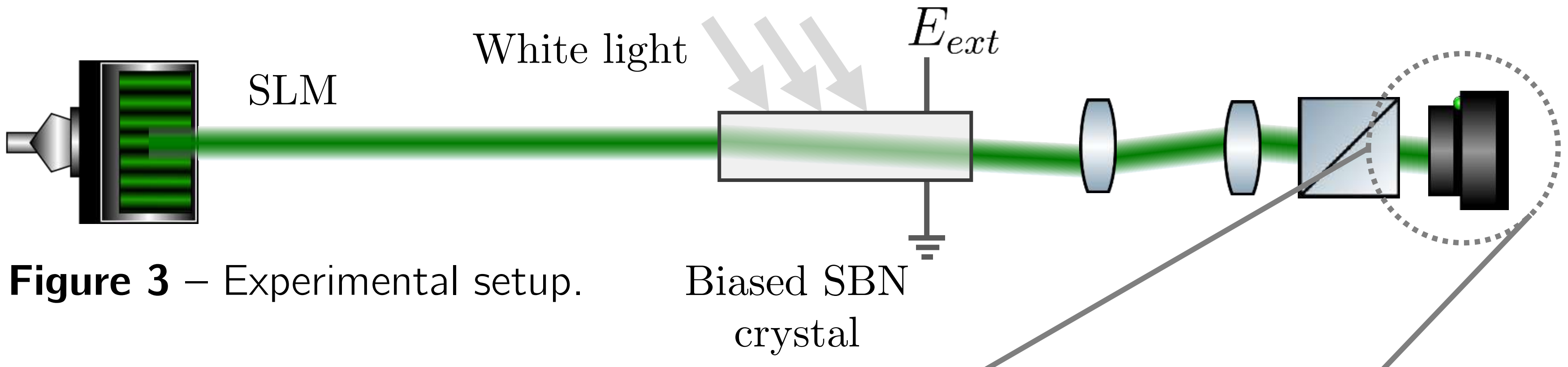


Figure 3 – Experimental setup.

The **output** is **imaged** into a **CMOs camera**.

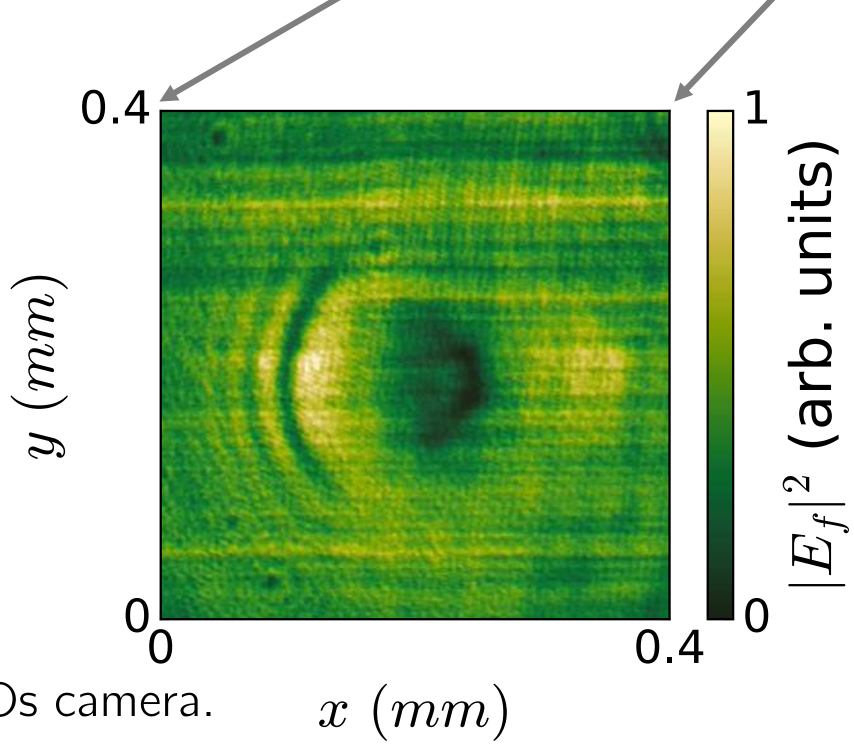


Figure 5 – Output measured by the CMOs camera.

Paraxial Fluids of Light

Experimental implementation

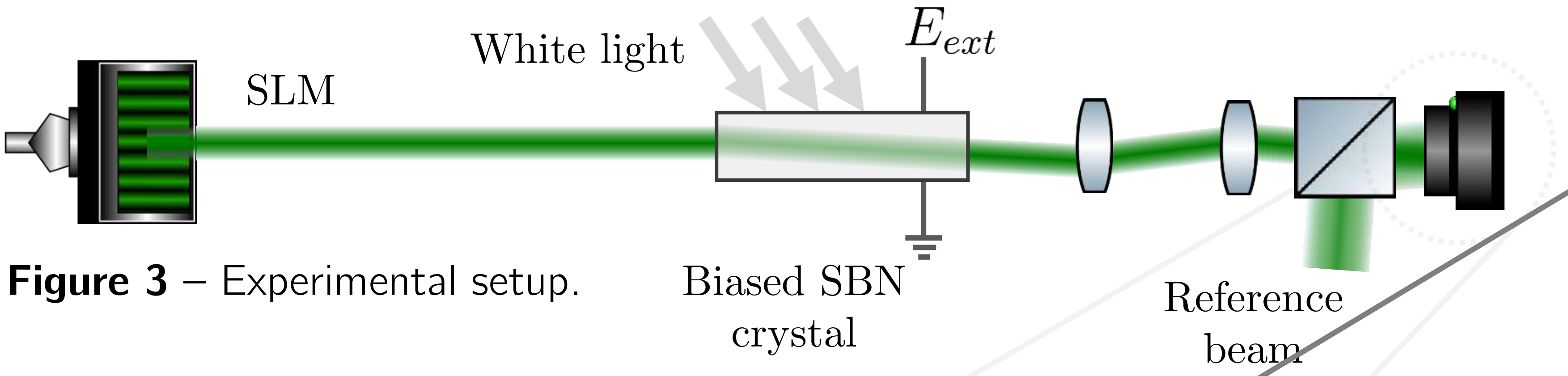


Figure 3 – Experimental setup.

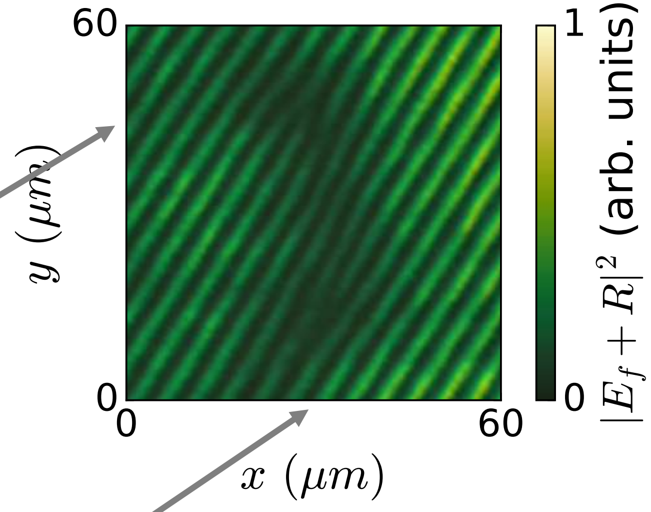


Figure 6 – Interferogram.

With a **reference** beam is **possible** to **reconstruct** the **phase** of the beam

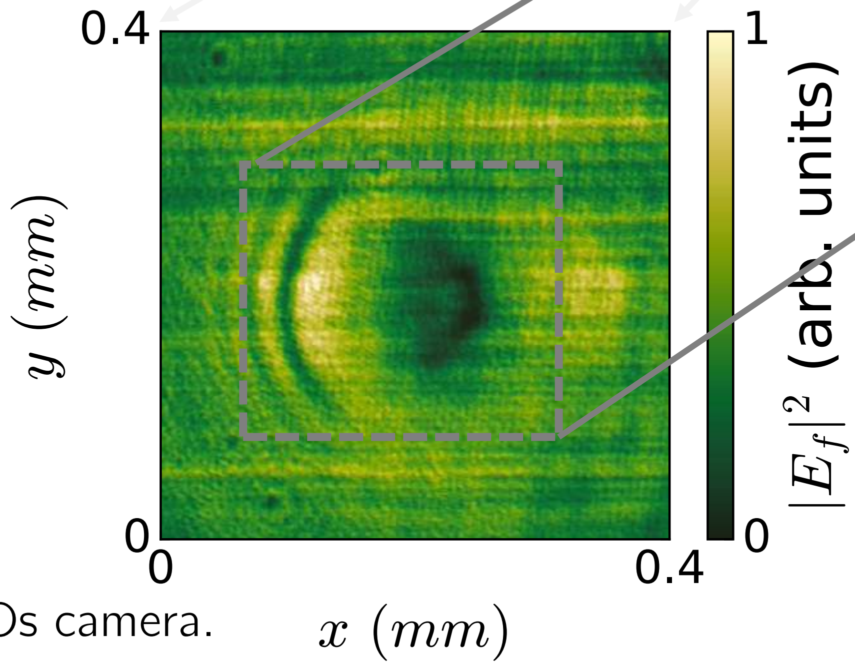


Figure 5 – Output measured by the CMOs camera.

Paraxial Fluids of Light

Experimental implementation

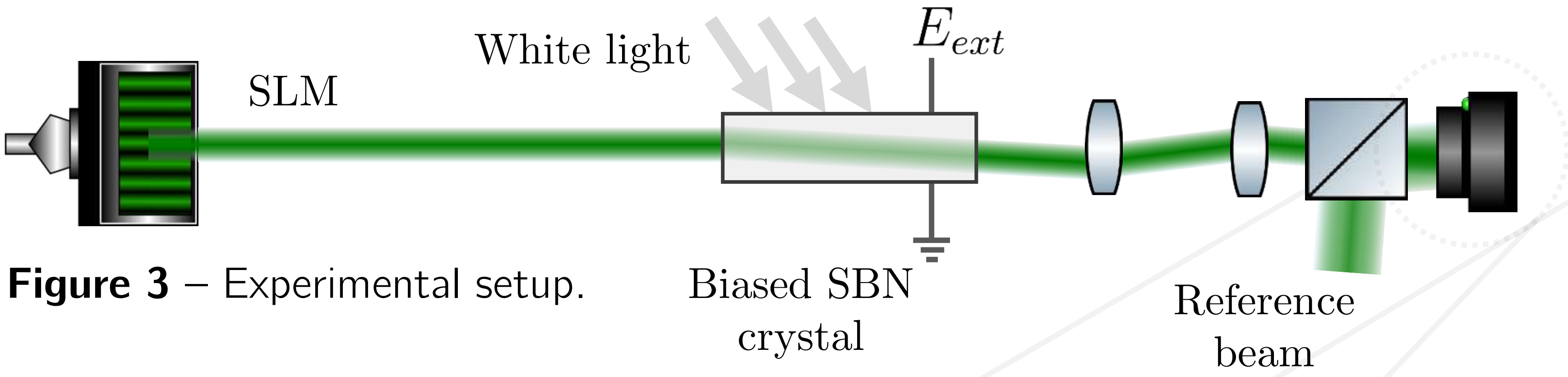


Figure 3 – Experimental setup.

With a **reference** beam is **possible** to **reconstruct** the **phase** of the beam

<u>Off-axis Digital Holography</u>

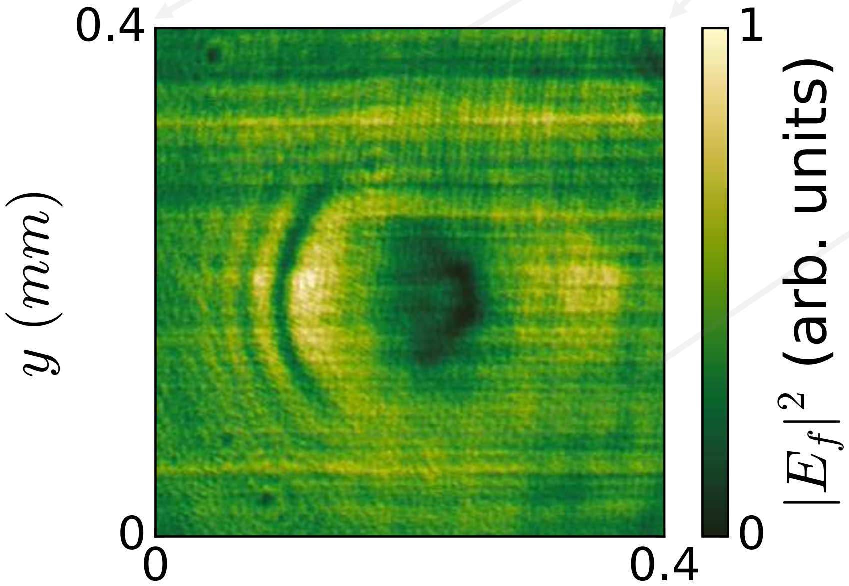
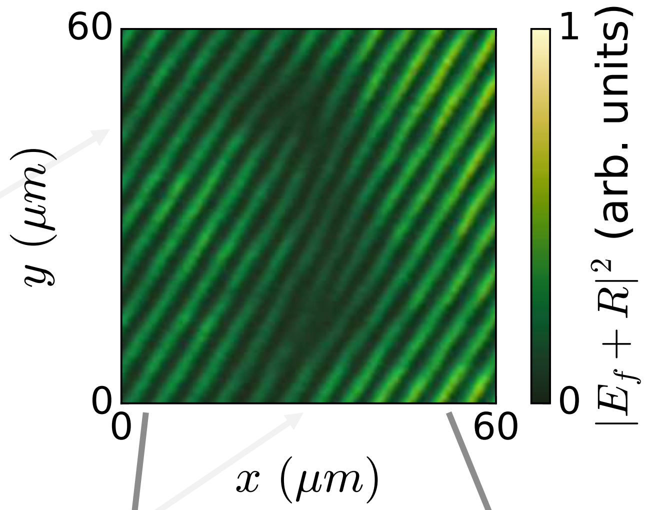


Figure 5 – Output measured by the CMOs camera.

Figure 6 – Interferogram.



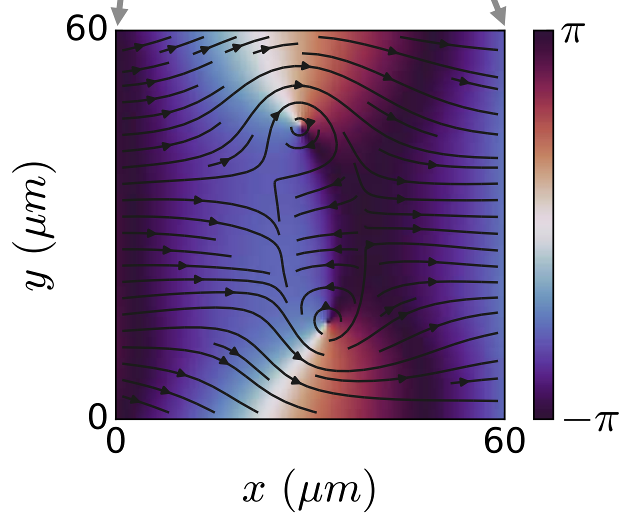


Figure 7 – Phase of the output.

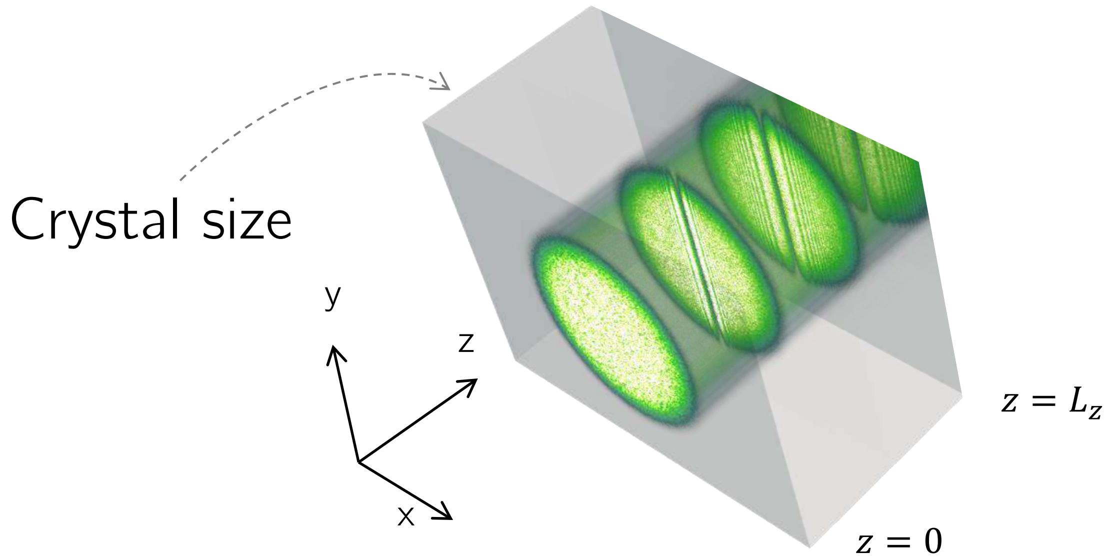
Optical Feedback Loop in Fluids of Light

Motivation

The **size** of the **nonlinear optical medium** **limits** the **emulation time!**

Remember: $i\frac{\partial E_f}{\partial z}$ **Time** is **mapped** along the **z-axis**!

Time

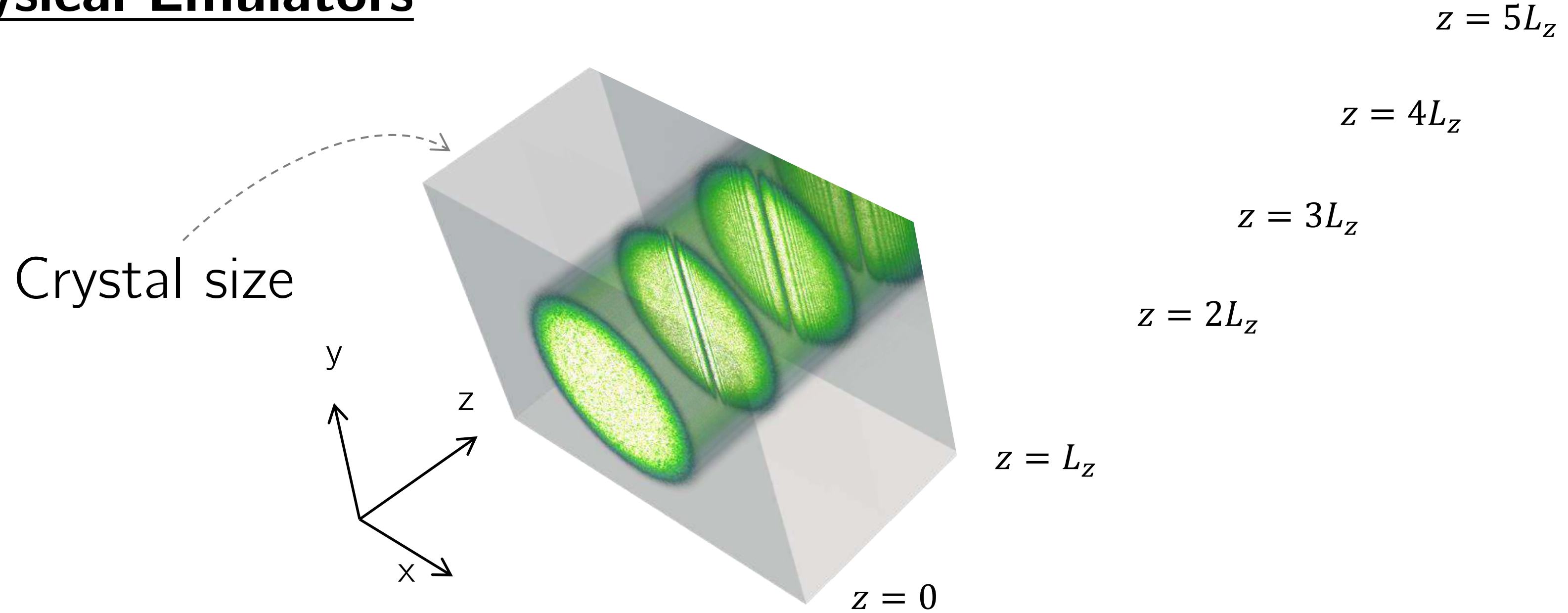


Optical Feedback Loop in Fluids of Light
Motivation

The **size** of the **nonlinear optical medium** **limits** the **emulation time!**

Motivation: Extend the **emulation beyond** the **size** of the **medium** and **probe** the **intermedia states**.

Versatile Physical Emulators



Optical Feedback Loop in Fluids of Light

Experimental implementation

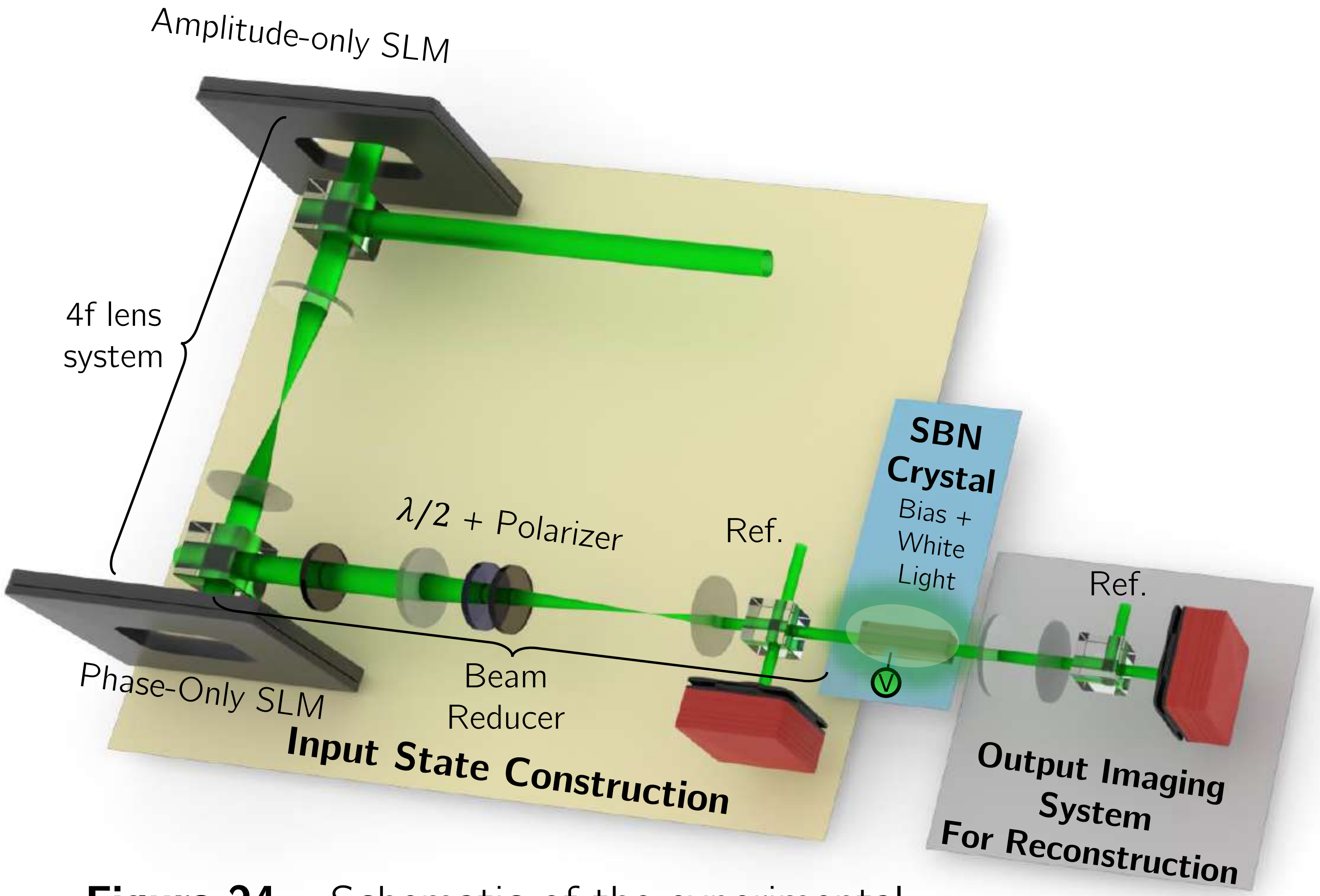


Figure 24 – Schematic of the experimental scheme used to implement the optical feedback loop.

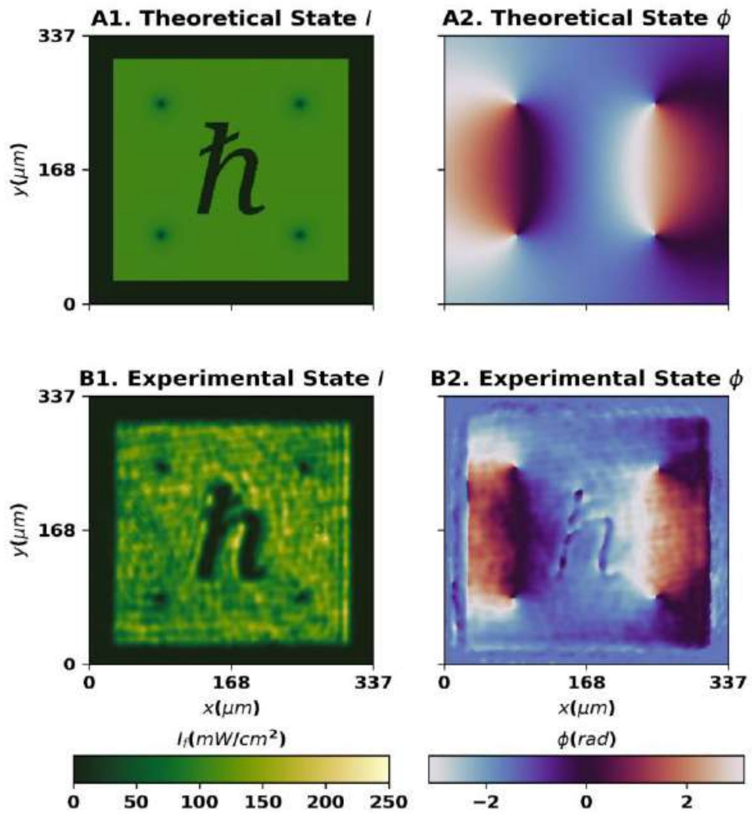


Figure 25 – Arbitrary state generation.

Tiago D Ferreira et al. arXiv:2312.12336 (2023)

Optical Feedback Loop in Fluids of Light

Experimental implementation

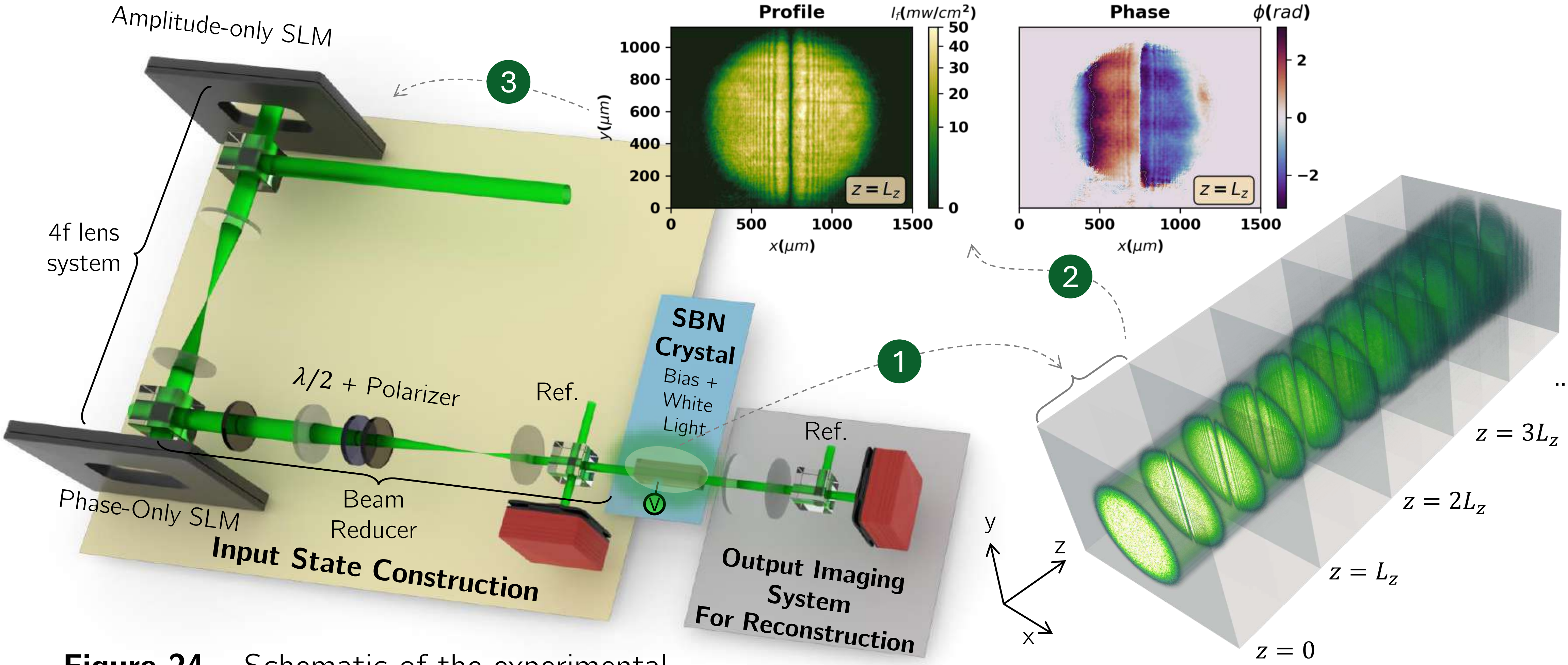


Figure 24 – Schematic of the experimental scheme used to implement the optical feedback loop.

Tiago D Ferreira et al. arXiv:2312.12336 (2023)

Optical Feedback Loop in Fluids of Light

Experimental results: Dark Soliton decay and shock waves expansion

Old method!

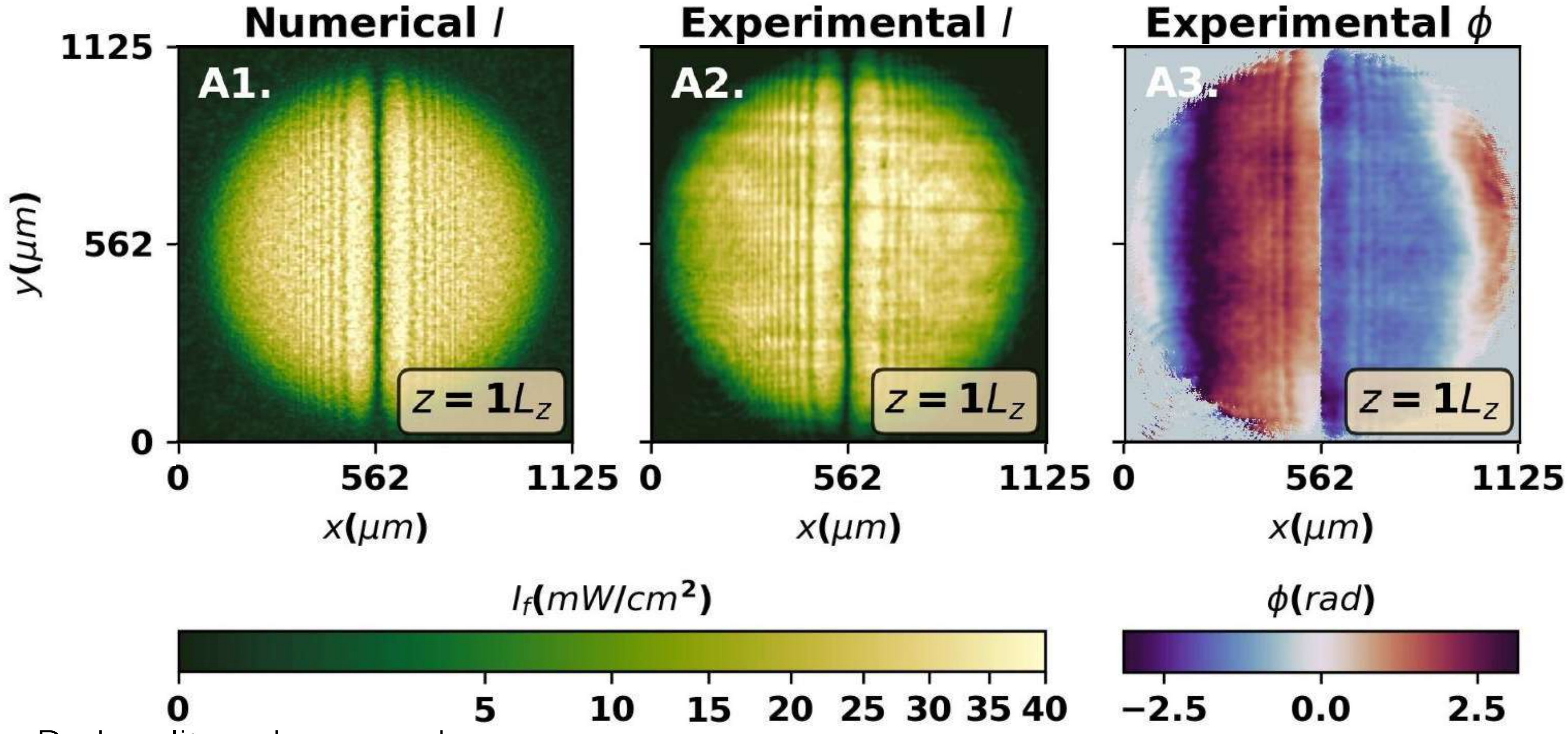


Figure 26 – Dark soliton decay, snake instability, and shock waves expansion.

Tiago D Ferreira et al. arXiv:2312.12336 (2023)

Optical Feedback Loop in Fluids of Light

Experimental results: Dark Soliton decay and shock waves expansion

Feedback Loop for 5 passages!

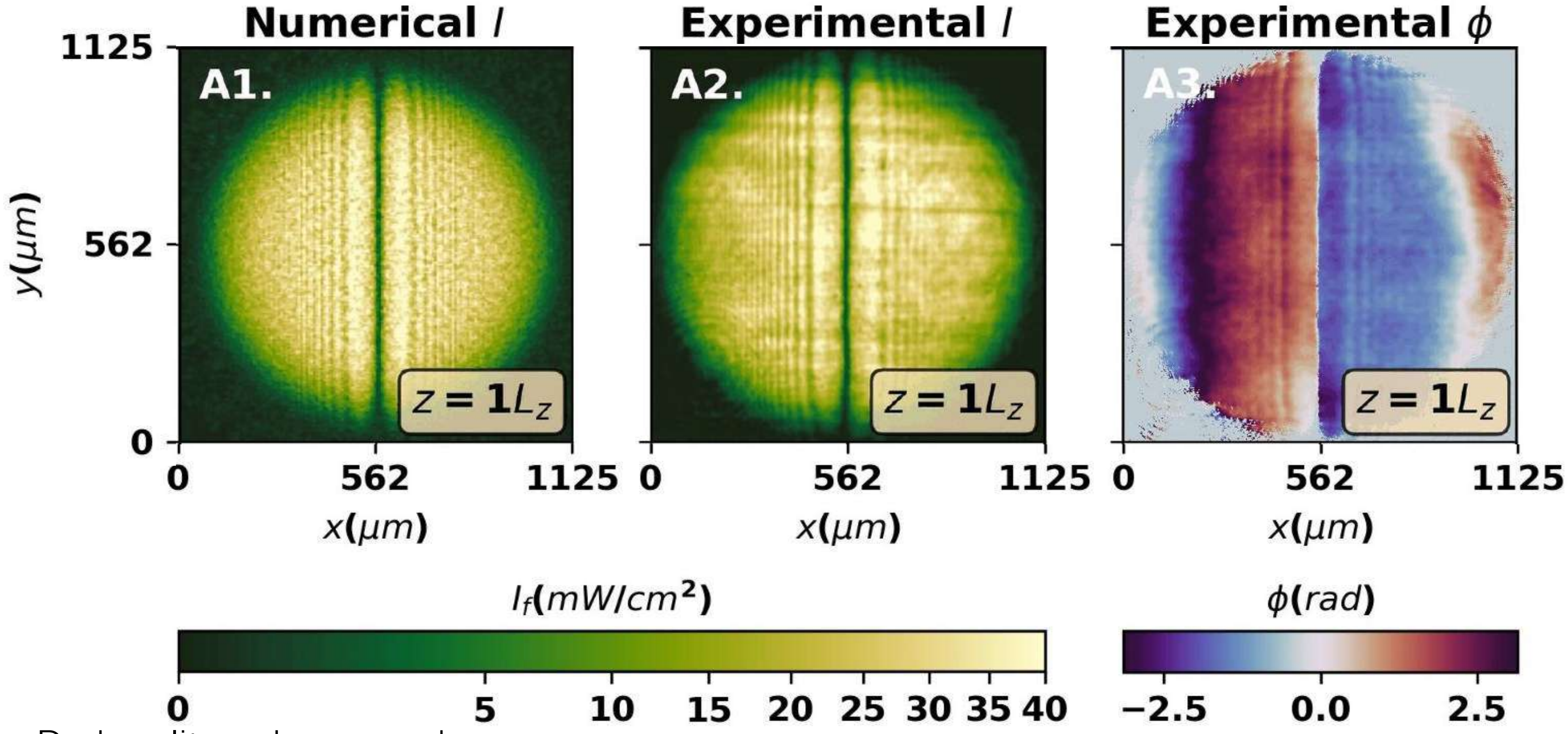


Figure 27 – Dark soliton decay, snake instability, and shock waves expansion.

Tiago D Ferreira et al. arXiv:2312.12336 (2023)

Optical Feedback Loop in Fluids of Light

Experimental results: Dark Soliton decay and shock waves expansion

The **shock waves expansion also follows** the **numerical simulations**.

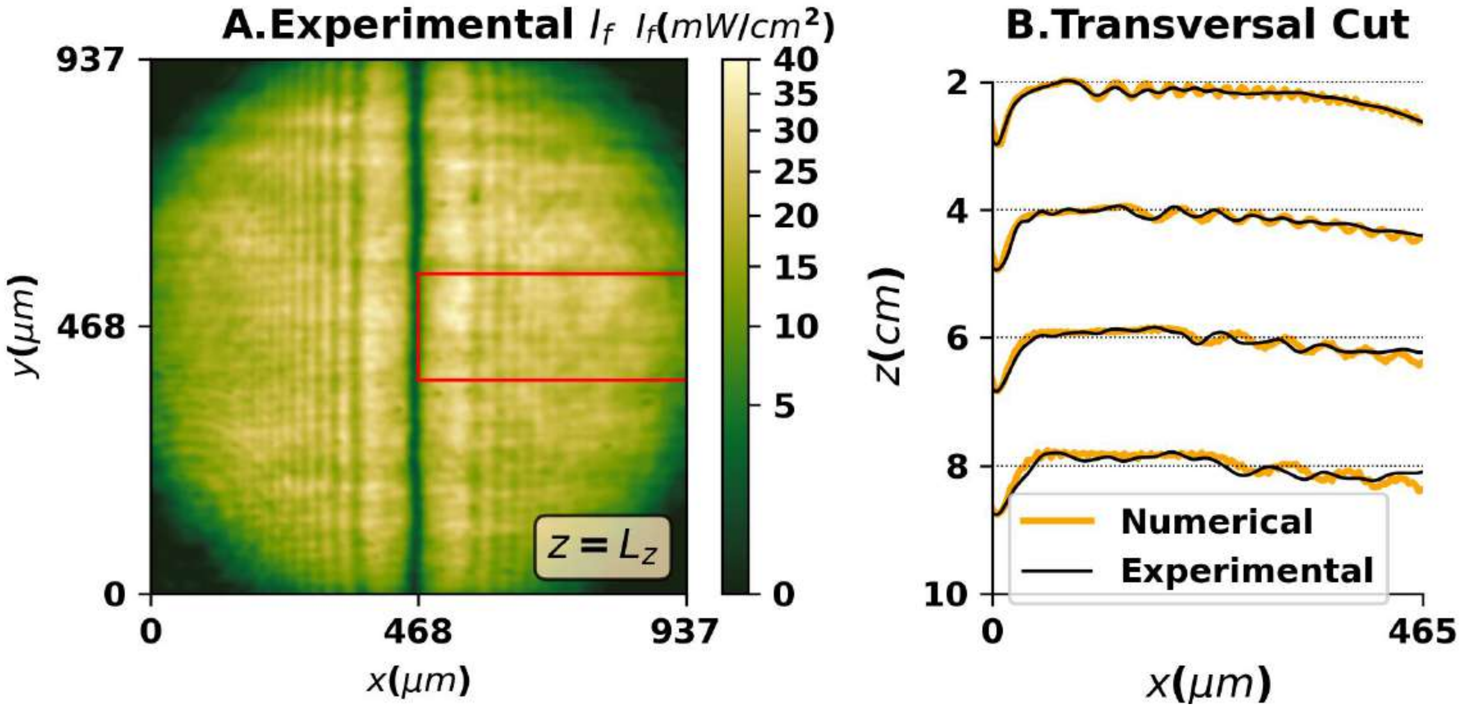


Figure 28 – Comparison between the experimental and numerical expansion of the shock waves.

Tiago D Ferreira et al. arXiv:2312.12336 (2023)

Optical Feedback Loop in Fluids of Light

Experimental results: Collision between three flat-top states

Old method!

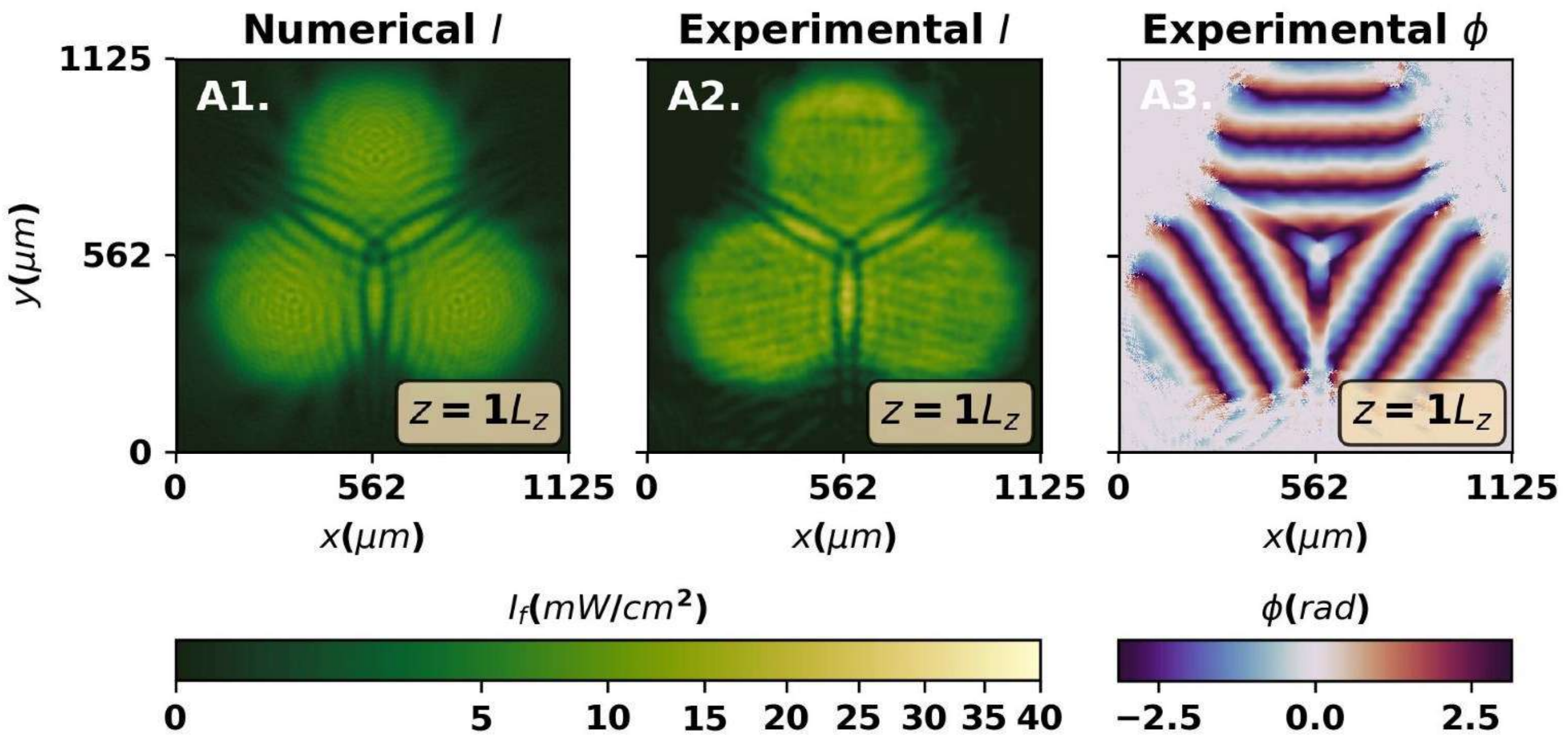


Figure 29 – Collision dynamics between three flat-top states.

Tiago D Ferreira et al. arXiv:2312.12336 (2023)

Optical Feedback Loop in Fluids of Light

Experimental results: Collision between three flat-top states

Feedback Loop for 6 passages!

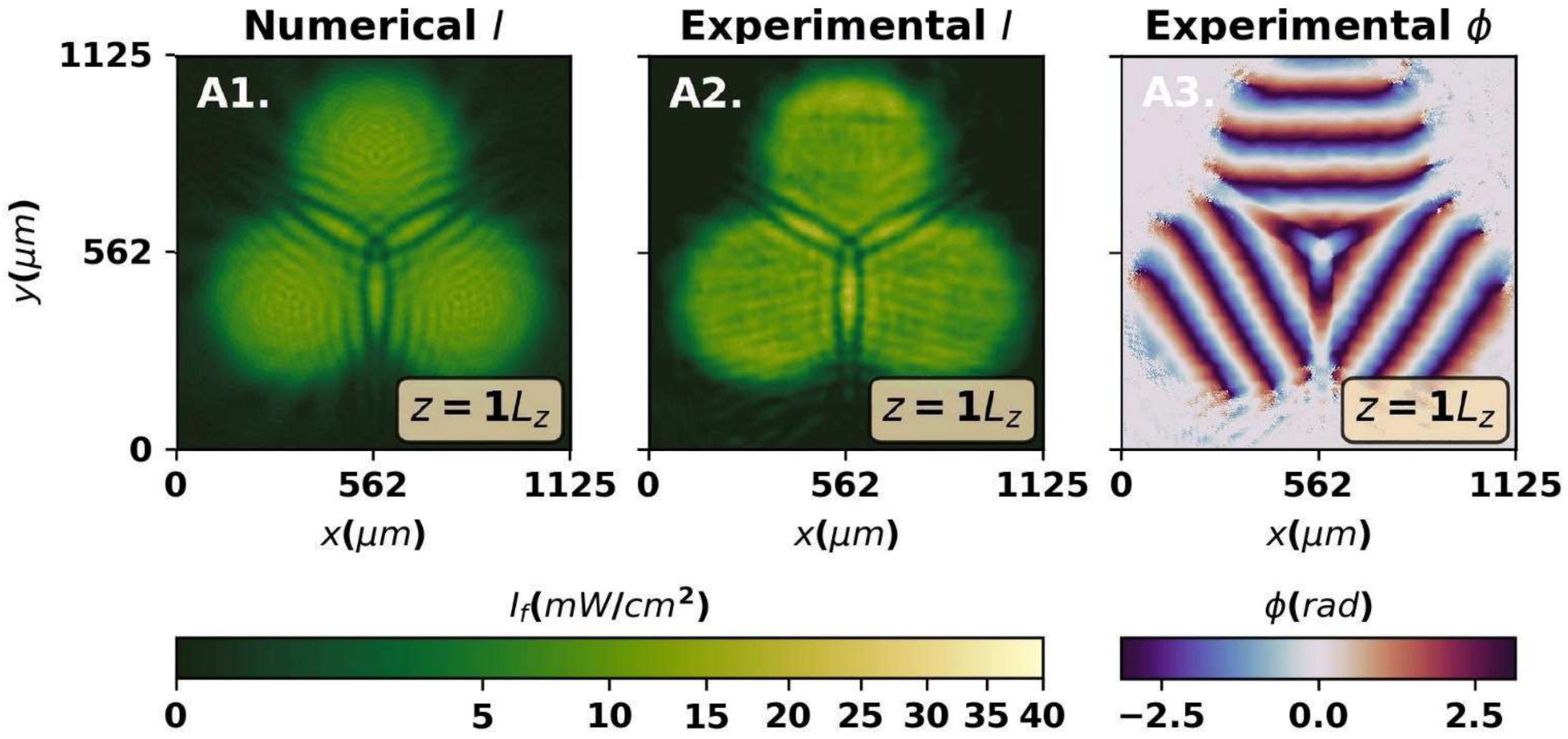


Figure 29 – Collision dynamics between three flat-top states.

Tiago D Ferreira et al. arXiv:2312.12336 (2023)

Optical Feedback Loop in Fluids of Light

Experimental results: Other preliminary results

Exploration of more **complex** and **non-trivial** configurations.

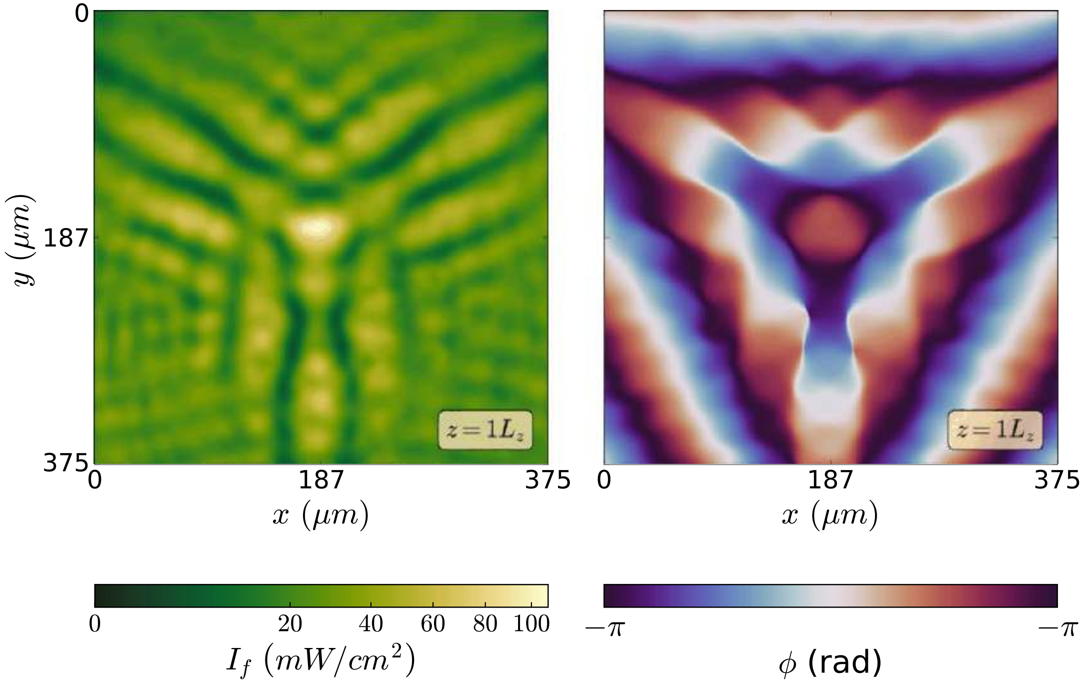


Figure 30 – Dynamics for the vortex formation and vortex collision with sound emission

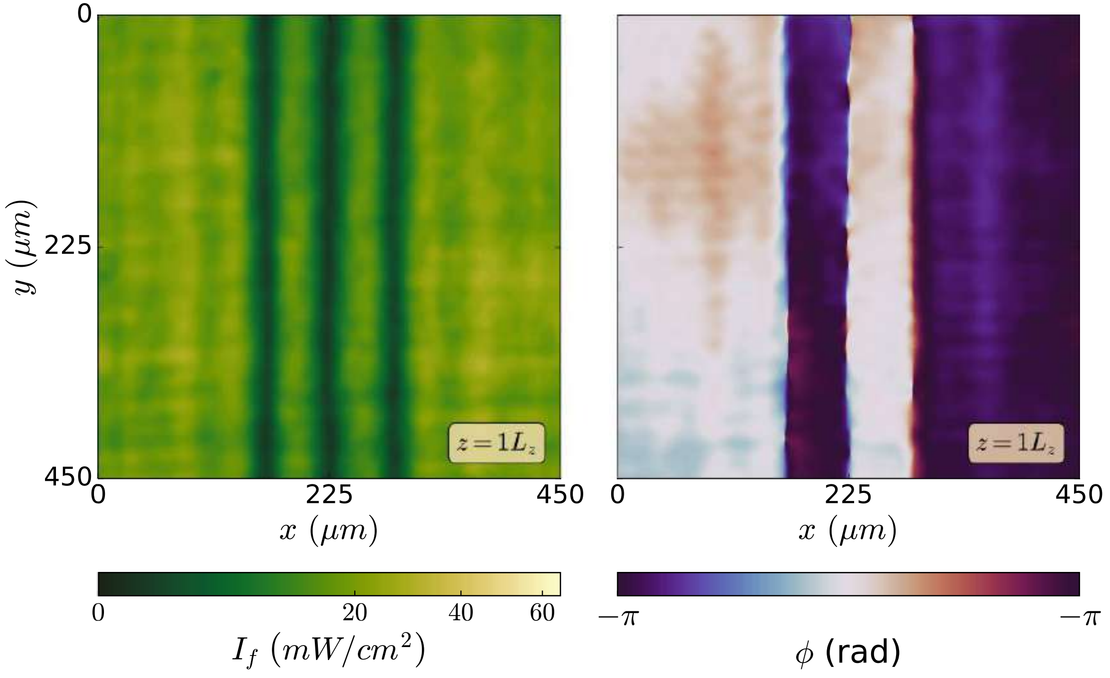


Figure 32 – Dynamics for the decay of three dark solitons.

Optical Feedback Loop in Fluids of Light

Important takeaways

The **current version** of the **Optical feedback loop** is **capable of**:

Create arbitrary states with **arbitrary amplitude** and **phase profiles**.

Perform the **loop** for **up to 6 passages** with **qualitative results** that **agree** with the **numerical simulations**.

Observe dynamics that were **previously impossible** with our **experimental setups**.

We now have a more **versatile physical simulator** of **nonlinear Schrödinger equation.**

Acknowledgments

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Thank you for your attention