Efficient Full-wave Simulation of Wavefront Shaping to Focus Light through Biological Tissue

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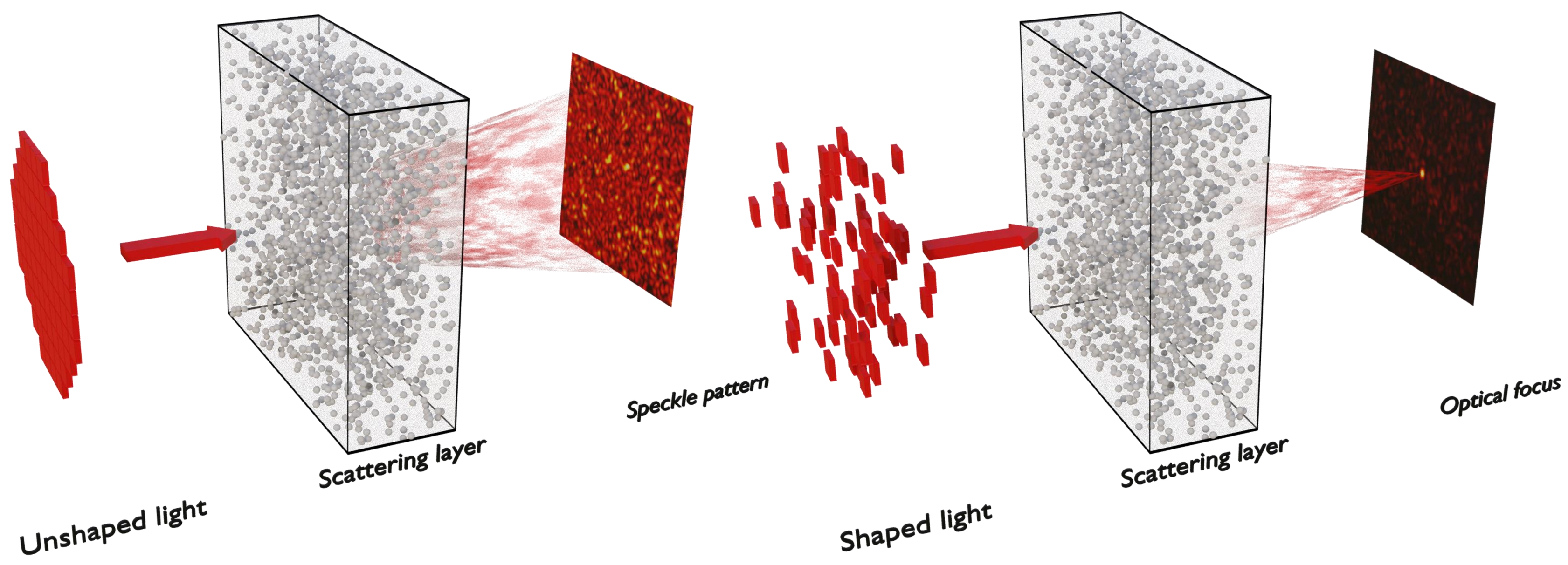
Summary of wavefront shaping

1. **Tissue** strongly **scatterers** visible and near infrared light.
2. This results in a significant **intensity decrease** over **depth.**
3. Many imaging modalities such as **optical coherence tomography** and **light-based microscopy** are **depth limited**[1].
4. One method to extend light's penetration depth is **wavefront shaping:**

If we spatially modulate incident light we can control its propagation through a scatterer, allowing light to constructively interfere to produce an optical focus at arbitrary locations within or beyond said scatterer[2].



Demonstrating the principles of wavefront shaping. Spatially modulated light is able to produce an optical focus through even a highly scattering medium.

We have developed a computational approach to simulating wavefront shaping through biological tissue

Computational investigations of wavefront shaping

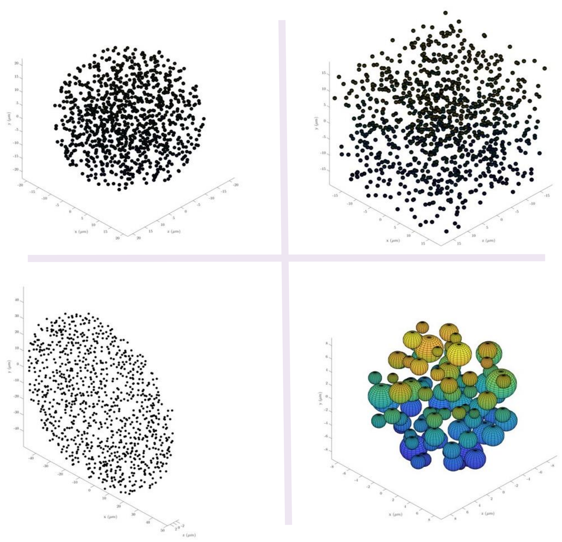
- Computational methods could **complement experimental investigation**, which is often constrained by a lack of control.

Computational methods are able to:
1. Evaluate the field inside a medium.
2. Resolve both amplitude and phase information.
3. Control a medium's optical properties and geometry.

- Current approaches are either **too computationally intensive** to model volumes large enough to significantly benefit from wavefront shaping, or **too incomplete** to model underlying deterministic scattering and interference processes accurately.

Method for simulating wavefront shaping

- We propose coupling the **T-matrix** method with the **discrete particle model** to create an efficient and rigorous simulation of light propagation through **biological tissue** which we use to model **wavefront shaping.**
- The T-matrix method propagates light through a medium of **scattering spheres.**
- By controlling the density, radii, and refractive indices of these spheres we can design **bespoke domains** with desired optical properties (using Mie theory).



Examples of various discrete particle domains.

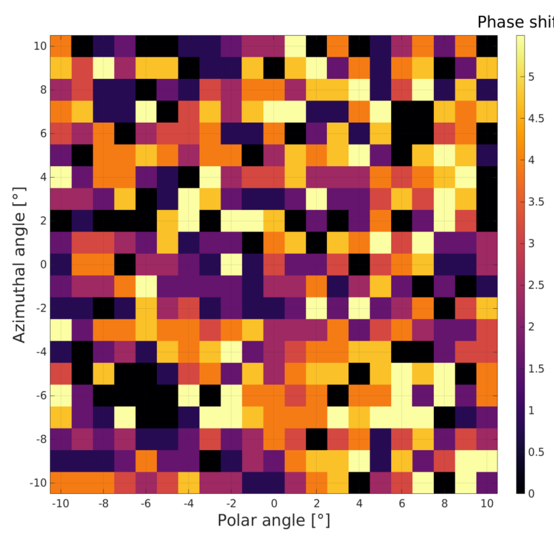
- Using the **discrete particle representation**, we are able to design domain with optical properties matching those of **biological tissue**.
- We use the **angular spectrum method** to simulate complex incident beams which are synthesised as a spectrum of plane waves.

Model demonstration through phantoms and tissue

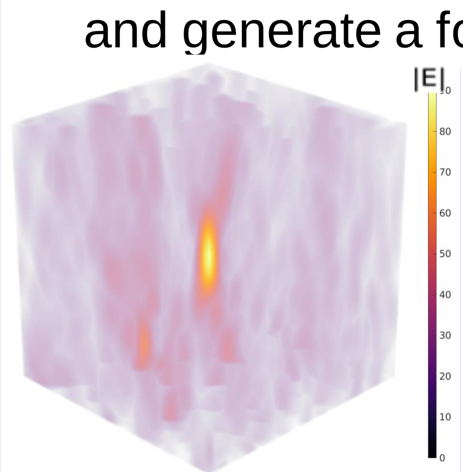
- To demonstrate our model, we simulate wavefront shaping through both a phantom of **titanium dioxide** spheres and a **tissue-like domain:**

Scattering medium	Medium geometry [µm]	Sphere radius [µm]	Refractive index	Density by volume	Transport mean free path [µm]
TiO_2 phantom	10x30x30	1.00µm	2.6	0.2600	5
Tissue media	100x100x100	1.72µm	1.6	0.0077	1000

- 441 different plane waves were propagated through the medium with incident polar and azimuthal angles varying ±10°.
- A **stepwise sequential algorithm** with **full-phase control** optimised the phase maps (seen on the right) to **shape the incident wavefront** and generate a focus at a target region.

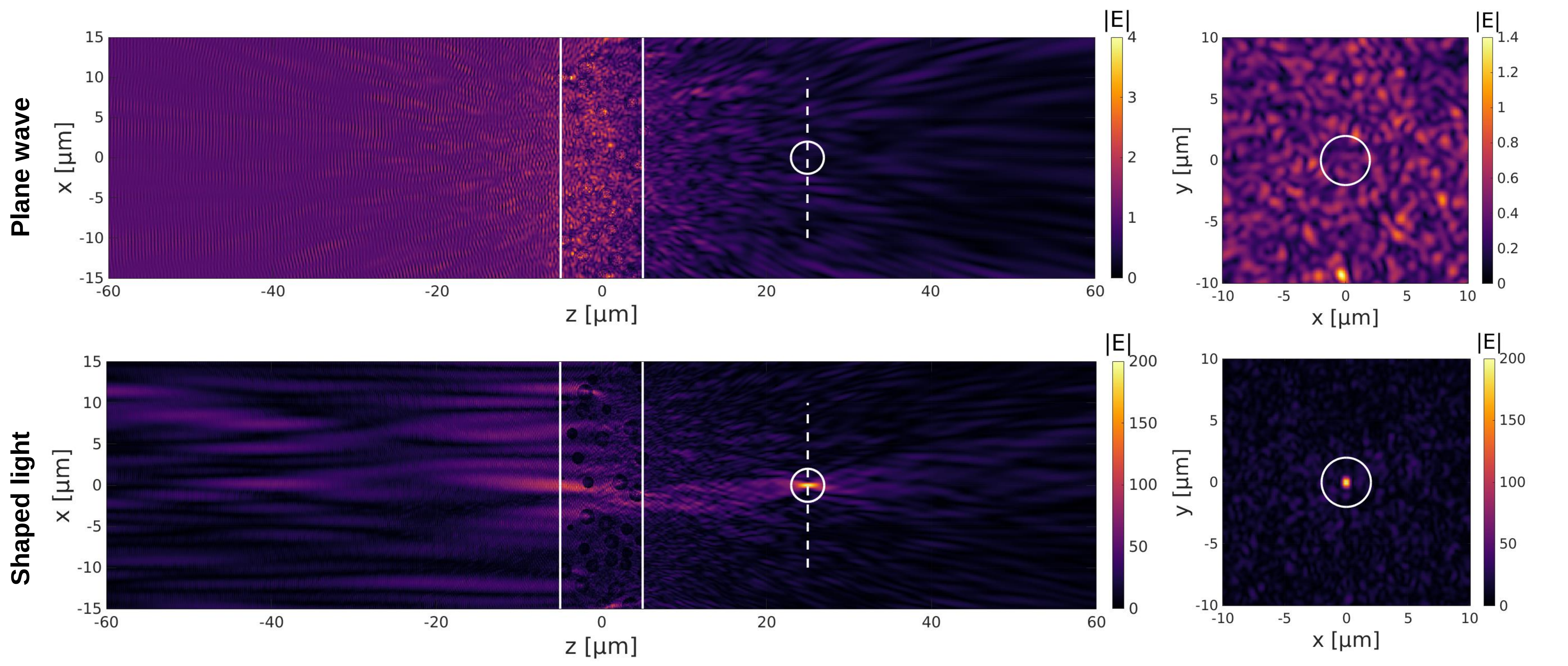


Phase maps made using the stepwise sequential algorithm optimised to focus through TiO_2.



Our approach allows us to produce 3D visualisations of the focus shown here for a tissue-like domain.

- We were able to produce an optical focus through both the TiO_2 phantom and tissue-like domain.
- Our technique allows us to **evaluate the field inside a scattering medium** and produce 3D visualisations of our generated focus.
- Our full-wage approach is **10X faster** to compute than the pseudospectral time-domain method.



The titanium dioxide domain (delineated by the solid white lines) scatters an incident plane wave, but a properly shaped wavefront can generate a focus in the target region (highlighted by the white circle). The generated optical focus can be clearly seen by imaging the xy plane across the target region, depicted by the dashed lines.

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[2] Vellekoop, I.M. and Mosk, A.P., 2007. Focusing coherent light through opaque strongly scattering media. *Optics letters*, *32*(16), pp.2309-2311.

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