Light Springs with Tunable Orbital Group Velocity

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Introduction

Structured light has emerged as a research field dedicated to controlling the degrees of freedom of light sources. Spatiotemporally coupled beams have emerged as a new class of structured light. By connecting the spatial and temporal properties of light, it is possible to generate helical wave packets, also known as Light Springs (LS) [1].

Recently, the tunability of the longitudinal group velocity in spatiotemporally coupled beams was demonstrated [2]. The longitudinal group velocity can achieve super- and subluminal values, unlocking unprecedented control over the wave packet. LS have an even more peculiar characteristic: an orbiting intensity profile, which motivates the definition of a new tunable velocity in space-time beams: the Orbital Group Velocity (OGV).

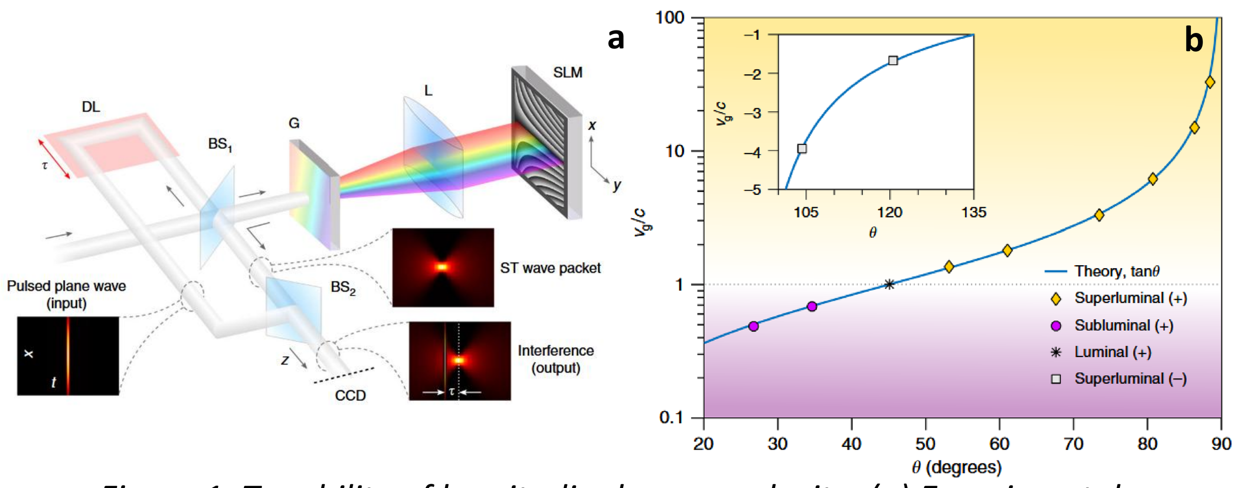

Figure 1: Tunability of longitudinal group velocity: (a) Experimental Setup and (b) Sub- and Superluminal tunability. Adapted from [2].

Experimental Setup: Light Springs

LS is a complex form of structured light that is generated through the combination of a diffractive axicon and a Spatial Light Modulator (SLM) (Figure 2a). The axicon diffracts the frequencies coming from the broadband pulse into rings with different radii. The SLM then assigns to each ring a different topological charge (Figure 3a), a typical hologram used can be seen in Figure 2b. This relation created between each frequency and the different topological charges generates the spatiotemporal property characteristic of a LS.

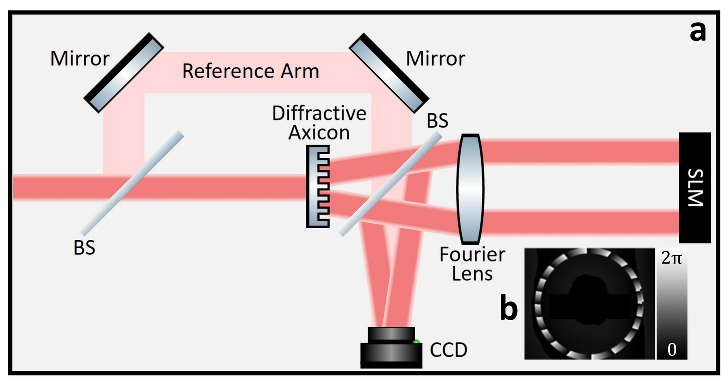

Figure 2: Experimental Setup (a) and typical hologram (b) used to generate LS with a Ti:sapphire LASER (800nm, 40fs@1KHz, 4W). BS is a Beam Splitter, and CCD is a Coupled Charged Device.

Once the LS is created, Off-Axis Digital Holography (OADH) is used to reconstruct it. OADH allows for complete reconstruction of the electromagnetic field via interferometry. By interfering the LS with a plane wave (Reference Arm in Figure 2a), it is possible to access both the amplitude and phase of the LS and recreate the isosurface of the LS (Figure 3b).

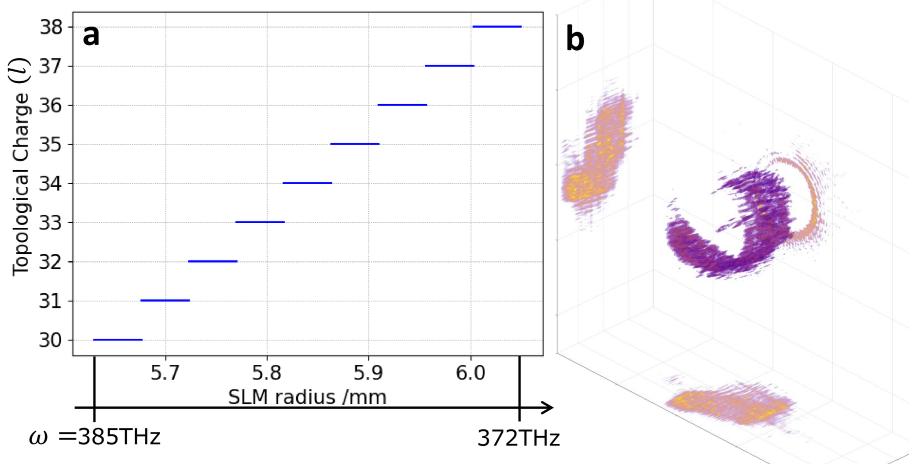

Figure 3: The topological charges are distributed linearly in the SLM screen (a), which creates a light spring reconstructed via OADH (b).

As the LS propagates, the intensity profile rotates along the propagation axis. This orbiting intensity profile rotates at a given velocity. This velocity is a new property that emerges from the LS typical helical wave packet: the OGV. The OGV depends on how the LS is created, and its properties can be tuned by adjusting the LS characteristics.

Orbital Group Velocity

A LS has an orbiting intensity profile when considering the intersection of it through a thin orthogonal plane (Figure 4). This motivates the definition of the OGV, a new tailorable quantity. The OGV depends on the characteristics of the LS, and can be defined as

$$OGV_{theoretical} = \frac{\partial \omega}{\partial l} * r_{LS} \text{, and} \qquad (1)$$

$$OGV_{experimental} = \frac{\partial \alpha(t)}{\partial t} * r_{LS} \text{ .} \qquad (2)$$

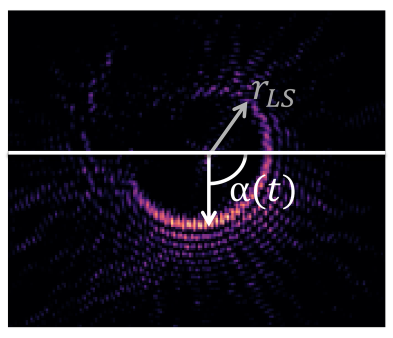

Figure 4: The measurement of the OGV depends on the radius (r_{LS}) and angle ($\alpha(t)$) of the LS.

Where ω is the frequency, l is the topological charge, $\alpha(t)$ is the clockwise angle the LS does with the x-axis (Figure 4), and r_{LS} is the LS radius.

The theoretical OGV takes into account the quantities used to generate the LS. The frequencies (ω) come directly from the laser, particularly for the Ti:sapphire laser used in this work, the frequency range was 385THz to 372THz. The topological charges (l) are assigned by the SLM. In this work, the topological charges varied between 20 and 110 (Figure 5).

The experimental OGV, on the other hand, takes into account how the orbiting profile of the LS evolves in time, considering its intersection with a thin orthogonal plane. This means measuring how $\alpha(t)$ changes as the LS propagates.

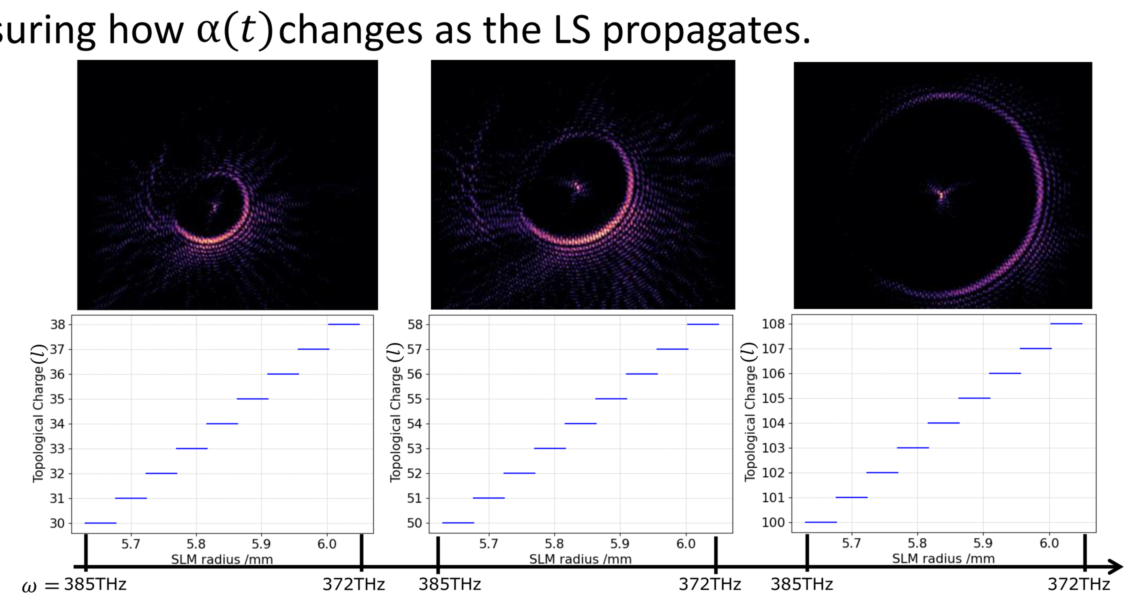

Figure 5: By changing the topological charge, it is possible to change the radius of the LS, which allows control over the OGV.

Orbital Group Velocity Tunability

As can be seen in Equation 1, the OGV can be tuned by either changing the total topological charge applied to create the LS or the radius of the LS. In principle, both of these approaches could result in a wide tunability range for the OGV. However, the tunability via control of the radius is not only simpler to implement experimentally, but also offers a greater tunability of the OGV. Particularly, by tuning the radius of the LS, it is possible to achieve super- and subluminal values of the OGV (Figure 6).

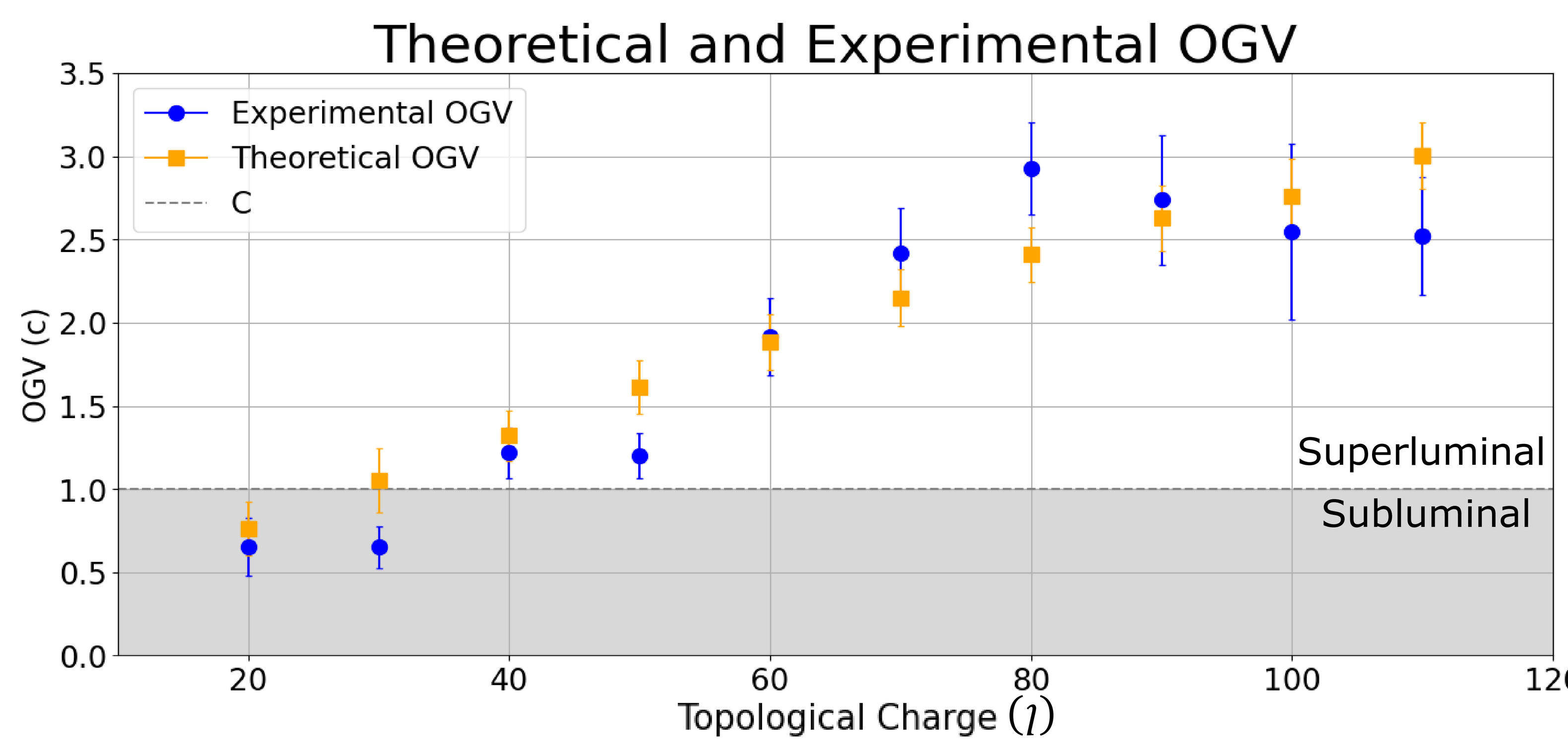

Figure 6: Tunability of the OGV. By changing the radius of the LS, it is possible to access super- and subluminal values.

The velocity range accessed with the OGV also unlocks new experimental possibilities. One key property that the OGV tunability unlocks is the control of how the wave packet energy can be exchanged when interacting with matter. For subluminal values of the OGV, the peak of the intensity profile could interact directly with matter, creating hotspots. On the other hand, for superluminal values of the OGV, the peak of intensity rotates so fast that it could suppress effects arising from hotspots, since the energy is more evenly delivered.

The tunability of the OGV, therefore, can potentially unlock a new degree of control in light-matter interaction systems. Since the OGV can act as a knob, controlling how the energy from the beam is delivered to matter. Additionally, the OGV can also control which phenomena arise from the light-matter interaction. With subluminal values of the OGV, accessing multiphoton absorption or activating more strongly certain nonlinearities that could be resonant with the LS hotspot, for example. Since the subluminal values would favour localized field enhancements. Alternatively, superluminal values of OGV can potentially lower peak damage, nonlinearities, or thermal effects. Since the energy is more evenly distributed due to the rapidly rotating intensity profile of the LS.

Conclusions and Perspectives

The control over the degrees of freedom of light sources has proved to be an incredibly fruitful research field, allowing not only access to complex phenomena but also the enhancement of effects once difficult to study. Spatiotemporally coupled beams are a particularly interesting class of structured beams, since they have peculiar properties. LS, in particular, is a unique form of space-time coupled beam. Its characteristic orbiting profile allows an additional tunable degree of control: the OGV.

The OGV can be used as a potential knob to tune light-matter interactions. Particularly, the OGV can serve as an interesting way of studying synthetic motion [3]. Since the superluminal regime accessed with the OGV could provide a new platform for synthetic motion, potentially enabling the possibility to explore fundamental physical phenomena that are commonly inaccessible in a typical experimental system.

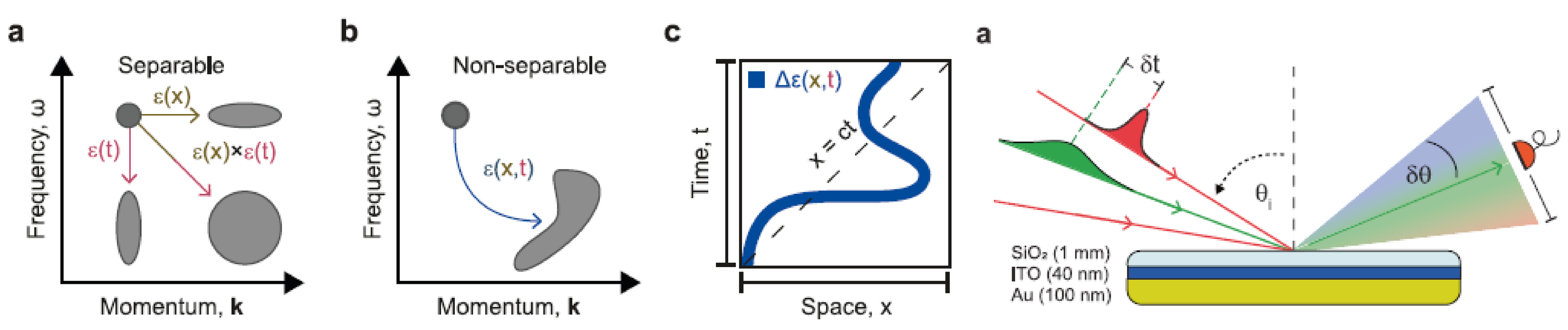

Figure 7: Synthetic motion studies relativistic phenomena not constrained by the speed of light. Adapted from [3].

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