Realization of Free-Space Long-Distance Self-Healing Bessel Beams

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A new approach for generating long-distance self-healing Bessel beams, which is based on a ring-shaped (annular) lens and a spherical lens in 4*f*-configuration, is reported. With this, diffraction-free light evolution of a zeroth order Bessel beam over several meters is shown and available scaling opportunities that surpass current technologies by far are discussed. Furthermore, it is demonstrated how this setup can be adapted to create Bessel beam superpositions, realizing the longest ever reported optical conveyor beam and helicon beam, respectively. Last, the self-healing capabilities of the beams are tested against strong opaque and non-opaque scatterers, which again emphasizes the great potential of this new method.

1. Introduction

Bessel beams—electromagnetic wave packets with an amplitude envelope described by a Bessel function—are diffraction-free entities with superior self-healing capabilities.[1] As such, they are in principle ideal tools for optical communication through turbulent atmosphere.[2] However, until this day, Bessel beams can only be achieved with a few centimeters in length even under ideal conditions, which limits their use for most long-range applications.[3]

Bessel beams were first suggested by Durnin in 1987[4] and experimentally realized soon after.[5] At the time, people used the fact that Bessel beams are equivalent to a conical superposition of plane waves and hence are represented by a ring of infinitesimal thickness in the angular frequency domain. Therefore, the simplest way to achieve a finite energy approximation of a Bessel beam is to use an annular aperture that is placed in the back focal plane of a thin spherical lens.[5] However, this method is rather inefficient, as most of the incident power is obstructed by the annulus. A Bessel beam may also be created using an axicon, or conical lens element, which provides the conical superposition of the wave components in real space.[6,7] This offers a higher efficiency, but the Bessel beam still only exists in the focal region of the conical lens, such that for beams exceeding a few centimeters unrealistically small base angles or very large axicon diameters would be required.

Although experimentally generated Bessel beams are still far away from their theoretical counterparts, they already find use in various applications, such as optical particle manipulation,[8,9] atomic dipole traps,[10] nonlinear optics,[11] microscopy,[12] material processing,[3] and quantum communication.[13] Moreover, superpositions of Bessel beams are applied for conveyor beams,[14,15] helicon beams,[16–18] or general radially self-accelerating beams.[19] Due to their excellent self-healing capabilities,[20] they may take a superior role in free-space terrestrial and satellite communication.[2] Recent studies suggest that Bessel beams are well suited for stable long-range communication through turbulent media.[21] However, these theoretical considerations have to assume a technology which surpasses currently achievable propagation lengths by far.

In our work, we report on the generation of Bessel beams in free space that exceed current experimentally reachable propagation lengths by about two orders of magnitude; that is, we present diffraction-free light evolution over several meters at

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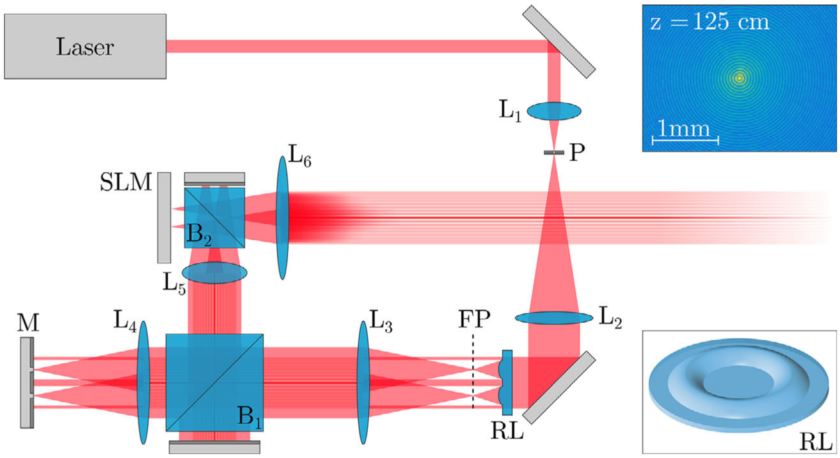

Figure 1. Experimental setup for the generation of high quality Bessel beams. The beam of a helium–neon laser is expanded using a telescope [L_1, P, L_2] and launched into the ring-lens [RL]. In order to remove residual light, the focal plane was imaged onto a mirror [M] that reflects only the sharp light ring, using a 1:1, 4*f*-configuration [L_3, L_4]. After reflection, the beam propagates again through the beam splitter [B_1] and is imaged onto the spatial light modulator (SLM) using lenses [L_4] and [L_5]. If no additional phase was required, the SLM was replaced by a conventional mirror. After passing again through [B_2], the sharp, cleaned-up and scaled ring is Fourier transformed using the lens [L_6].

optical wavelength. To this end, we employ a sophisticated yet simple optical component, which resembles a cylindrical lens that is morphed to a closed ring-like form. Such devices have been used well before the invention of the laser for imaging purposes. Here we use them in reverse, to focus the incoming light into a sharp ring-shaped focal plane.[6,22] After Fourier transforming this extremely narrow ring of light a high-quality Bessel beam of zeroth order is obtained. By adding a helical phase, also higher order Bessel beams are achievable. In a sense, this approach is similar to the annular slit by Durnin et al.; however, without the inherent loss of an annular aperture. Moreover, it overcomes the technical limitations of a diffractive ring-lens as reported by Xin et al.[23]

2. Experimental Section

For our experimental implementation, we fabricated two prototype specimen: one with a single ring-lens for the generation of a single Bessel beam, and one with two concentric ring-lenses for generating a superposition of Bessel beams. Both were realized in-house by means of diamond machining. **Figure 1** shows an illustration of the constructed prototype characterization setup. All technical specifications for the optical components can be found in the supplementary material.

Note that this setting is not optimized for efficiency; coating the ring-lens and using a preceding beam-shaping component would render the filter-mirror [M] and the associated optics [B_1, L_4] unnecessary. Moreover, [B_2] was merely used to ensure normal incidence on the SLM. With this, we achieved a ring of radius $R = 1.48$ mm and full width at half maximum (FWHM) of $w = 4.9$ µm. Importantly, ring-width and shape are strongly influenced by the illumination pattern incident on the ring-lens as well as residual aberrations. Those, in turn, can alter the propagation dynamics of the ensuing Bessel beam, as we discuss in the Supporting Information. From numerical simulations, the above values are expected to provide a Bessel beam of zeroth order, which is 1.73 m in length and has an FWHM of the central lobe of 30.8 µm. For comparison, a Gaussian beam of similar width would reach 6.8 mm in length.

3. Results

3.1. Long-Range Propagation

We experimentally recorded the propagating Bessel beam with a movable CCD camera and measured the width of the beam's central intensity maximum. As shown in **Figure 2**, it increases from 29 to 33 µm over a total range of 2.5 m.

A Gaussian beam of the same initial width would over the same distance broaden by a factor of about 600. Even a Gaussian of ten times that beam waist would still broaden by a factor of six. Note that the recorded experimental Bessel beam is longer than our theoretical prediction. This was accomplished by shifting the Fourier-lens [L_6] with respect to the ring plane. This introduces an additional phase term to the beam, which allows to trade parts of the diffraction-free nature for an increase in propagation range.

3.2. Optical Conveyor Beams

In a second experiment, we demonstrate the realization of an optical conveyor beam, that is, a beam that exhibits a set of evenly spaced focus-like high intensity peaks along the propagation direction. Such beams are potentially useful in particle manipulation,[15] material processing,[24] or laser-assisted plasma generation.[25,26] To this end, we fabricated a device with two concentric ring-lenses in order to prepare a superposition of two Bessel beams of zeroth order. With a setup similar to that described in Figure 1 (see Supporting Information) we achieved ring radii of $R_1 = 1.48$ mm and $R_2 = 2.61$ mm, respectively. We measured the peak intensity of the beam in three distinct

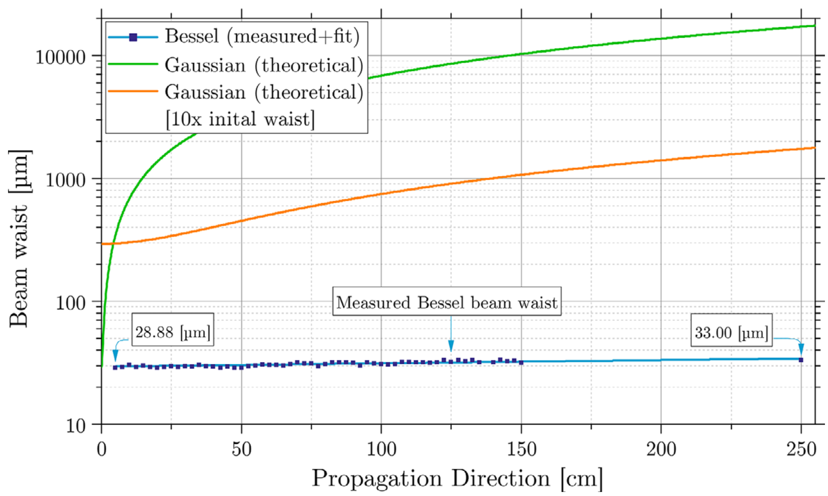

Figure 2. Comparing the diffraction of our Bessel beam with a Gaussian beam. Diffraction behavior for the central lobe of a zero-order Bessel beam (measurements: dark blue squares, fit: light blue line) in comparison to Gaussian beams of identical (green line) and ten times larger beam waist (orange line), respectively.

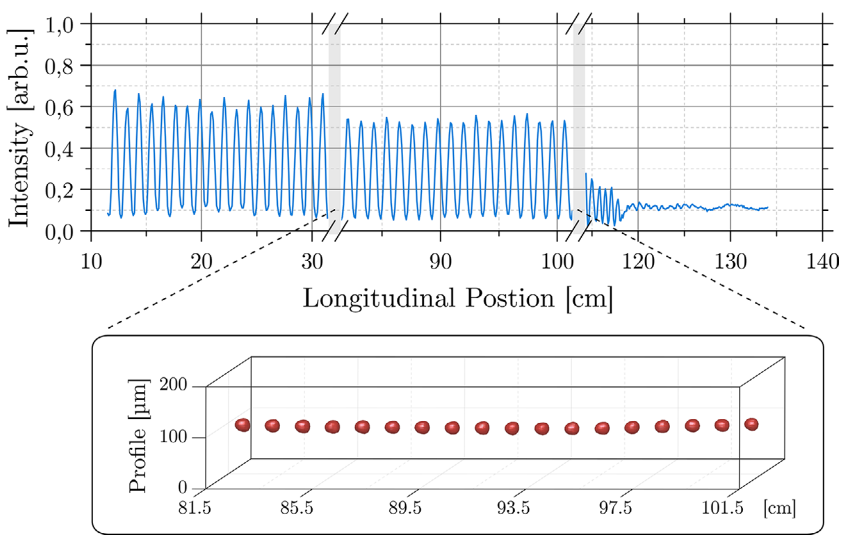

Figure 3. Realization of a long-range optical conveyor beam. In the upper plot a cross section of the peak intensity along the optical axis for two superimposed zeroth order Bessel beams is shown. The bottom inset shows an iso-intensity graph for the central interval with 50% of the peak intensity considered as its iso-surface. The beam contains about 100 high intensity peaks over a propagation distance of 110 cm.

intervals using an electronically controlled linear stage, as shown in **Figure 3**, and achieved 18 high intensity peaks per 20 cm interval. Note that the conveyor beam is shorter than the single Bessel beam presented in Figure 2. This is because the Bessel beam associated with the larger ring inherently exhibits a shorter propagation range and ceases to exist after about 110 cm.

3.3. Helicon Beams

When adding different helical phase orders to the individual Bessel beams from before, a helicon beam is formed.[16] Helicon beams are a special case of radially self-accelerating beams[19] and exhibit continuous spiraling trajectories. To this day, they are mostly generated using holographic techniques, which limits the number of achievable rotations to a mere handful. In our experiment, we prepare the phase orders $n_1 = -1$ and $n_2 = +2$ to obtain a helicon beam with a threefold rotational symmetry. The beam profile is recorded as before. From the collected volume data, an iso-intensity graph was calculated which is shown in **Figure 4**. The beam exhibits 36 full revolutions over a propagation range of 120 cm. This, together with the higher efficiency obtainable with our ring-lens device, makes helicon beams finally accessible to various fields of research and industrial applications.

3.4. Self-Healing

A peculiar feature of Bessel beams are their extreme self-healing properties, allowing them to reestablish the initial field

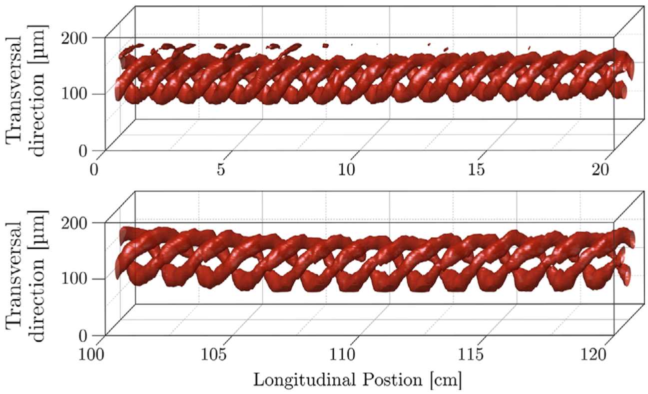

Figure 4. Generation of helicon beams. Shown is the iso-intensity graph for the three main lobes of a helicon beam built from two Bessel beams with orders $n_1 = -1$ and $n_2 = +2$. The iso-surface corresponds to 33% of the peak intensity. The entire beam contains 36 full revolutions over a propagation distance of 120 cm.

distribution even after rather devastating perturbations.[27,28] Importantly, in an experiment, this property will scale with the number of side lobes in the amplitude distribution of the Bessel beam. Our single beam from the beginning for instance supports 267 of those lobes within the FWHM of its apodization function (see supplementary material for more details), whereby excellent self-healing capabilities are anticipated. To assess the self-healing capacities of our beam experimentally, an opaque obstacle in form of a small screwdriver was placed 2 cm behind the Fourier lens, blocking a major part of the beam, as shown in **Figure 5**a. Although the beam experiences heavy distortions right after the obstacle (Figure 5b), after about 1 m of propagation it is essentially restored (Figure 5c). Most impressively, even the peak power remains at 96.9 % of the unperturbed case. In order to further quantify our results, the intensity distribution of each propagation step (with obstacle) was cross-correlated with the undistorted case (without obstacle). The results are shown in Figure 5d and indicate a 98.4 % recovery of the beam after 120 cm propagation.

We envision free-space optical communication through turbulent media as one of the most important applications of our method for generating high-quality long-range Bessel beams. In this vein, it is imperative to demonstrate that our generated beams are not only resilient against solid obstacles but also against non-opaque scatterers such as water-droplets. The latter type of scatterers poses a much greater challenge to the self-healing mechanism, as light is not simply removed but instead interferes with other parts of the beam profile along the propagation direction. To mimic such a rain-like scenario in the laboratory, we prepared a special sprinkler-container and placed it above the beam-line. The container holds 0.5 L of water and has 60 randomly positioned holes of 1 mm diameter along a path of 3 cm width and 12 cm length. It was placed 15 cm after the Fourier lens and 90 cm before the CCD camera, such that

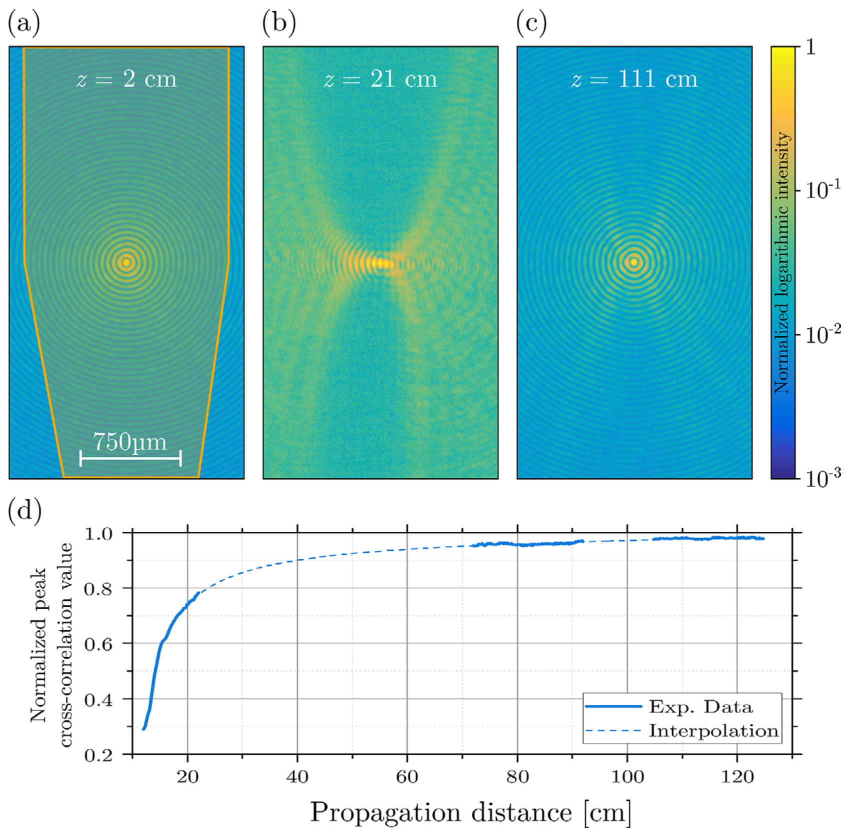

Figure 5. Self-healing capability of the generated single Bessel beam. a) Sketch of the blocked region. b) Intensity distribution closely after the beam block. c) Intensity distribution after the beam self-healed. d) Cross correlation between self-healing blocked Bessel beam and undistorted beam.

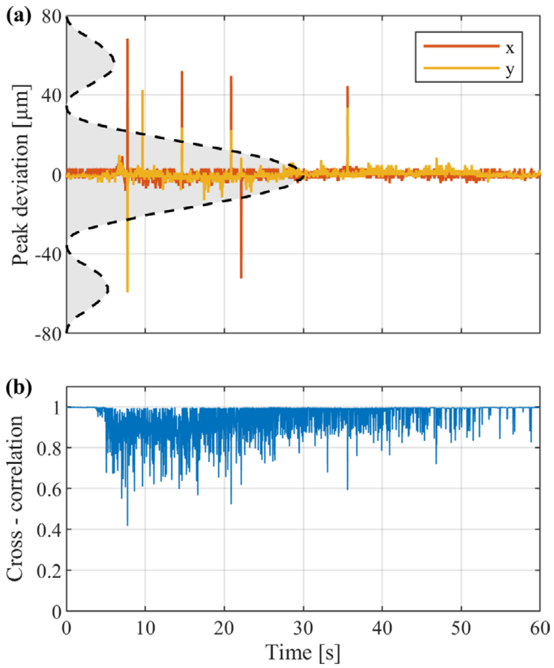

Figure 6. Beam stability under rain-like scattering conditions. a) Position of the high intensity maximum over time, while water is pouring through the beam. The gray area on the left indicates the Bessel profile. b) Cross-correlation between the unperturbed beam and the distorted one over time. See supplementary video material for a more visual impression.

there is sufficient distance for the self-healing to occur. While pouring water through the beam, we recorded the beam-profile and subsequently determined the point stability of the central high intensity lobe as shown in **Figure 6**. Although the outer regions of the beam are subject to heavy distortions, the central lobe is always clearly visible and remarkably stable throughout the entire measurement. The heaviest average fluctuations we have observed are 3.9 µm in horizontal and 3.3 µm in vertical direction, respectively. Both values are around 10 % of the central lobe's FWHM.

4. Conclusion

The quality and range of experimental Bessel beams strongly depends on their lateral extent and, thus, on an appropriately large aperture. Our ring-lens technology excels in this regard. For one because the ring-lens is not the aperture limiting component, but moreover because the setup is easily adaptable to a reflective configuration in which the Fourier lens is replaced by a parabolic mirror. This way, the beam diameter could easily be increased from currently a few centimeters into the range of meters, which would further amplify the already extraordinary propagation and self-healing characteristics of our beams. With this, the utilization of Bessel beams in long-range optical communication through turbulent atmosphere and satellite applications is now in close reach. Nonetheless, we still foresee many exciting questions and prospects for future research: For example, is it possible to omit the Fourier transforming lens in large-scale settings and replace it by simple beam propagation into the far-field? Moreover, is it possible to overcome the inherent diffraction limit of the ring-lens using a metamaterial hyperlens-design,[29,30] such that the ring-width reaches the sub-wavelength regime? Last, what happens when a secure single-photon-based communication channel is implemented and quantum effects start to play a role? The answer to these and other questions are now in reach experimentally.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

beam-shaping, Bessel-beams, laser-technology, self-healing, telecommunication

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