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Optimization of symmetrical layers of optical caustic beams generated using cylindrical lenses

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Abstract

Generating symmetrical layers of optical caustic beams using a specific configuration of cylindrical lenses is an innovative technique with potential application in precision alignment and other fields. The technique allows to shape the wavefront to generate a beam, which is layered in a plane creating a specific pattern consisting of different number of lines in a transversal plane, depending on the distance from the generator. Prior methods have produced similar beams using spatial light modulators. However, our approach with cylindrical lenses offers a marked reduction in setup complexity and cost, opening the possibility for new applications. The paper shows the possibilities of adjusting the generator for different applications by changing its parameters. Customization enables tailoring the beam characteristics to meet the unique requirements of different tasks, particularly in alignment.

Non-diffracting Beams, Accelerator Alignment, Caustic Beams

1. Introduction

Optical caustics is a well-known phenomenon present in everyday life every time light is reflected or refracted by curved surfaces [1, 2]. Similarly, Optical Caustic Beams (OCB) are characterized by wavefronts by which the rays of light are strongly focused, creating characteristic patterns and beam trajectories, due to the interference.

The discovery of Airy Beams (AiB), characterized by cubic phase, hence with odd symmetry, started the growing research field of caustic beams. This led to the discovery of Symmetric Airy Beams (SAB) [3] and Symmetric Pearcey Gaussian Beams (SPGB) [4]. All symmetric beams, characterized by the absolute valued cubic phase in the case of the SAB and quadratic phase in the case of the SPGB, are generated by phase profiles with even symmetry. OCB has application potential in particle manipulation [5], acceleration [6], or material processing [7].

The state-of-the-art for generating the mentioned beams uses a spatial light modulator (SLM) with the encoded Fourier spectrum of the desired beam and a lens that performs a spatial Fourier transformation [3, 4]. Numerous other generation principles employ specialized off-shelf components [8, 9]. The possibility of a simple generation principle of non-symmetrical AiB using on-shelf cylindrical lenses was reported in multiple works [10, 11].

At CERN, non-diffractive beams are subject to intensive research regarding their useableness for the alignment of accelerator parts [12] and particle acceleration [13]. The OCBs have potential to be used as a reference for alignment thanks to their unique properties, mainly thanks their low divergence.

Due to the vast size of the CERN accelerator complex a simple, scalable, and inexpensive solution for generating such beams is desired. In this work, we present the possibility of generating layers of OCB with even symmetry of the phase using plano-convex cylindrical lenses, which would comply with the set requirements. We will be referring to these beams as Layer Beams (LB). The possibility of tailoring the beam properties for specific applications by varying the parameters and position of cylindrical lenses is also shown. To our best knowledge, this way of generation has never been considered.

2. Methodology

The LB is generated by using a set of cylindrical lenses (Fig 1). The first lens (phase lens - PhL) is illuminated by a Gaussian beam. This lens functions as a phase modulator similar to SLM. Hence, the phase of the light is modulated in such a way that it has even symmetry. This phase modulation occurs in a specific interval of distances behind the PhL, which is different for each lens. This interval is characterized by the fact that local phase profiles have even symmetry and are convex after unwrapping. These phase profiles are not the same in each plane. An example of the wrapped and unwrapped phase modulation can be seen in Fig. 2. Note that the focal length of the PhL needs to be relatively short to achieve the desired phase modulation.

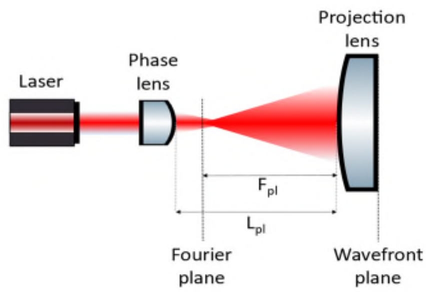

Figure 1. Layer Beam generator

One can also analyse the wavefront in a plane directly behind the PL. This wavefront is convex and has even symmetry, similar to the phase behind the PhL. The local slope of the wavefront defines the caustic properties, meaning how the rays are focused.

The projection lens (PL) is used as a spatial Fourier transforming element. The phase in the focal distance (F_{pl}) from the PL is Fourier transformed, and the LB is consequently generated. This means that changing the distance between the lenses (L_{pl}) affects the plane position from which the phase profile will be transformed. The focal length of the PL affects the Fourier transformation's spatial scaling, hence the beam's properties.

Altering the L_{pl} distance affects the position of the beam's focus and beam curvature. Changing the PL's focal length affects the beam's spatial parameters. Using the long focal length generates a smaller focus, meaning thinner lines in the transversal profile (Fig. 4).

3. Results

The simulation of the LB generated using on-shelf PhL Thorlabs LJ1918L1 with a focal length of 5.79 mm together with PL Thorlabs LJ1703RM with a focal length of 75 mm was done in VirtualLab Fusion©. The L_{pl} distance was 82 mm. Fig. 2 shows the wrapped and unwrapped phase behind the PhL.

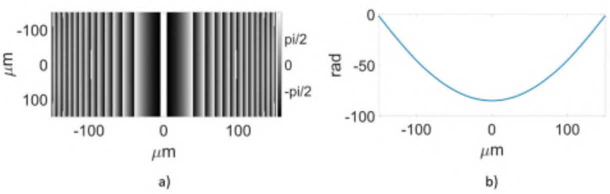

Figure 2. a) Wrapped phase behind the PhL, b) Line-profile of an unwrapped phase behind the PhL

The longitudinal profile can be seen in Fig. 3. Shortening the L_{pl} will decrease the beam curvature. Hence, the beam focus will be shifted at a longer distance from the generator. Shortening the focal length of the PL causes the beam waist to be smaller and the beam focus to be thicker. These effects are due to the changes in the wavefront slope behind the PL.

Notice that LB has a finite distance. Once the L_{pl} becomes too short, the phase profile changes. The wavefront's line-profile behind the PL will have local minima and maxima shaped like a "Sombrero." Once this happens, LB will travel for unlimited distance having similar properties to a so-called Structured Laser Beam (SLB). Note that SLB has a rotational symmetry [13].

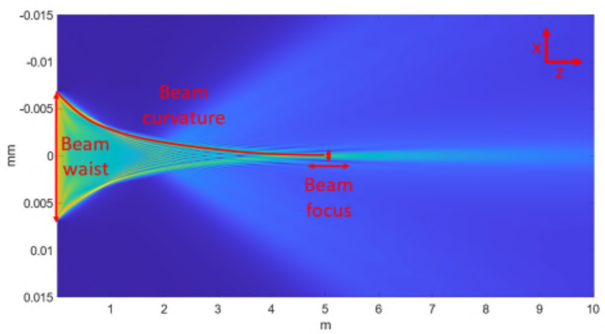

Figure 3. Longitudinal profile of the LB

The transversal profiles in 1, 3, and 5 meters can be seen in Fig. 4. They consist of different number of parallel lines. As mentioned previously, their thickness can be altered by changing the focal length of the PL.

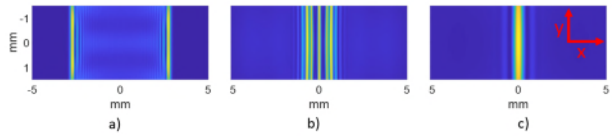

Figure 4. Transversal profile of the LB a) 1 m, b) 3m, c) 5m

4. Conclusion

The method for generating Optical Caustic Beams, namely Layer Beams, using a set of cylindrical lenses, has been presented with examples of how the generator can be tuned to reach the desired properties of the beam.

LB has potential to be used in the context of accelerator alignment, where they can serve as a reference line. One can use the center of symmetry of the pattern as a reference plane. Changing the focal length of the PL to 500 mm can lead to creating a line with a thickness under 10 mm in the LB's focus after propagating over 140 meters. This would mean that the generated line can fit on a regular CMOS chip, and later, the misalignment of the CMOS with respect to the line can be detected.

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