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Beam shaping elements for single photon sources based on 3D printed micro-optics

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Abstract. Multiple researchers have explored the use of 3D printed micro-optical components as interfaces to quantum point emitters by considering different designs and configurations. Typically, these designs involve parametric structures optimized in combination with idealized point source models following the principles of imaging optics. In this work, we propose a different approach based on the use of well-known numerical routines developed in the field of illumination optics. We compare the obtained design to reference parametric 3D printed based interfaces, which have been used in the context of 3D printed micro-optical interfaces to single photon sources.

1. Introduction

Multiple quantum technology applications rely on the efficient transfer of single photons across remote nodes. In order to scale these systems to the realm in where their true potential can be exploited, it is required to count with individual single photon emitters' photonic interfaces. From all of the possible approaches, the use of 3D printed based micro-optical components has been proposed as a cost efficient and scalable platform to realize these tasks [1]. Via the use of 3D printed micro-optical interfaces, the increase of extraction and collection efficiency into centimetre scale objectives has been demonstrated. Most of these designs are based on surface profiles, which can be described via a few parameters [2, 3], and as such, these do not fully exploit the capabilities offered by 3D printed micro-optics which allow for the utilization of each voxel as a degree of freedom. In this work, we employ a different design approach based on inverse design methods, commonly used in the field of illumination optics. Via these techniques, it is possible to tailor both the irradiance and field phase profiles in such a way that the coupling of light into a single mode fibre can be increased.

2. Methods

Our design task consist of converting the intensity profile generated by a point emitter into a spatial field distribution suitable for maximizing the overlap with the mode supported by a single mode fibre. To realize this, we employ a technique that has been presented in the context of illumination design tasks for zero-etendue sources. Our numerical approach is based on the algorithms presented in [4], [5] and [6]. To start, we obtain equi-flux distributions for the source intensity and for the desired target irradiance distributions. Instead of directly sampling the source's angular intensity distribution, we sample its stereographic projection, which allow us to restrict the evaluation to a two dimensional plane. These equi-flux distributions are obtained by finding the ray-mapping functions while using a common equi-flux dummy distribution source as in [5]. Approximate solutions to these equi-flux distributions can be found by solving the optimal-transport problem. For this, the algorithm presented in [4] was utilized. However, it is well known that for non-paraxial and near-field situations, the solutions obtained from the algorithm in [4] do not result in an integrable surface normal vector field [5] [6]. Based on this, we follow the same approach presented in [6] in which an integrable surface normal vector field is obtained via the utilization of a symplectic flow-mapping scheme.

Following this approach, we are able to generate a set of three surfaces that realize the intended field transformation. Differently from what has been presented in [6], we use a double surface scheme to split the needed refractive power to perform the energy tailoring process. These two surfaces are generated by following the point-by-point surface construction algorithm presented in [7]. A third surface is finally utilized in order to have control over the output wavefront. This surface is constructed based on the constant OPL condition. Finally, as in [6], the resulting surfaces are obtained by performing the referred steps in an iterative manner until the associated surface normal are sufficiently integrable.

3. Results and comparisons

As a source model, a point source with a uniform intensity profile has been used. In this specific case, we are interested in transforming this intensity profile into a

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Gaussian-like energy distribution. This target profile has been chosen based on the idea that the mode supported by a single mode fibre can be well approximated by a Gaussian-like distribution. In order to perform non-sequential ray-tracing analysis, spline based surface interpolation functions are directly generated from the set of obtained discrete points representing each surface. An overview of a system obtained through the proposed numerical approach is presented in Fig. 1. As reference and for comparison, we have also generated a TIR lens following the same principle used in [1]. For the TIR case, no energy redistribution requirements were taken into account and the only goal was to transform the source rays into a set of collimated rays at the output. A cross sectional view of this TIR system can be observed in Fig. 2.

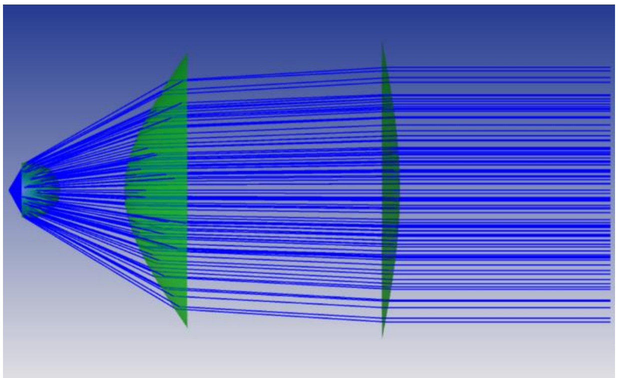

Fig. 1. Optical system obtained from proposed numerical approach. The first two surfaces are used for redistributing the input intensity profile into a Gaussian-like distribution. Finally, the third surface is used to generate a flat wavefront.

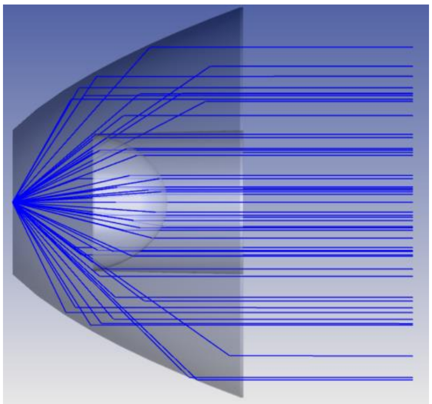

Fig. 2. TIR based optical system. Differently from the system presented in Fig. 1, this TIR has been generated only under the requirement of generating a flat output wavefront.

Following, non-sequential ray-tracing analysis for both systems was performed. The same source characteristics were used in both cases. As a source, a point source with an angular extent of 65 degrees has been used. A refractive index value of 1.5 has been used for the medium to the left of the first freeform surface, in between the second and third surfaces from the system shown in Fig. 1 and for the medium to the left of the TIR structure in Fig. 2. Figures 3 and 4 present the irradiance distributions obtained after both optical systems. As shown in Fig. 3, the irradiance distribution obtained from the field tailoring based approach has a better Gaussian-like resemblance in contrast to the irradiance obtained from the TIR system shown in Fig. 4. It must be emphasized that both systems generate a set of collimated rays from the same initial source intensity. However, there is no guarantee that just generating a flat wavefront results in an adequate spatial energy distribution suitable for maximizing the field overlap to the mode supported by a single mode fibre, if no energy redistribution requirements are imposed.

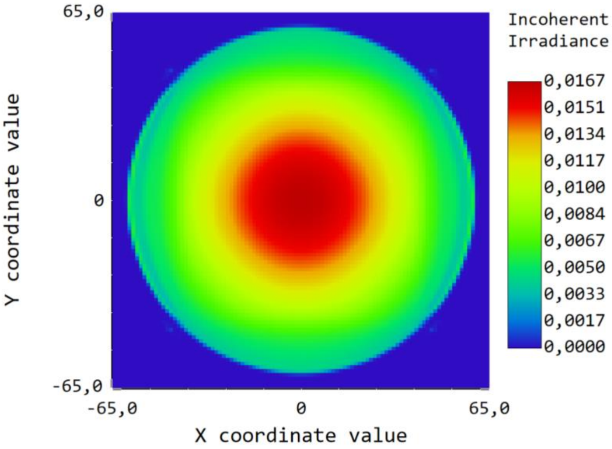

Fig. 3. Irradiance distribution obtained from optical system shown in Fig. 1.

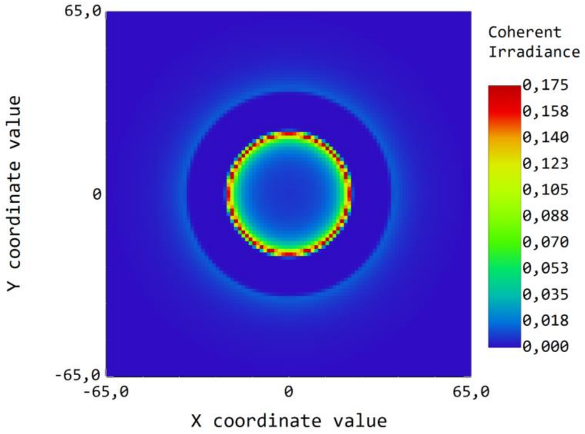

Fig. 3. Irradiance distribution obtained from optical system shown in Fig. 2.

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