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Optical design of transmitter lens for asymmetric distributed free space optical networks

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ABSTRACT

We present a method of transmitter lens design dedicated for light distribution shaping on a curved and asymmetric target. In this context, target is understood as a surface determined by hypothetical optical detectors locations. In the proposed method, ribbon-like surfaces of arbitrary shape are considered. The designed lens has the task to transform collimated and generally non-uniform input beam into desired irradiance distribution on such irregular targets. Desired irradiance is associated with space-dependant efficiency of power flow between the source and receivers distributed on the target surface. This unconventional nonimaging task is different from most illumination or beam shaping objectives, where constant or prescribed irradiance has to be produced on a flat target screen. The discussed optical challenge comes from the applications where single transmitter cooperates with multitude of receivers located in various positions in space and oriented in various directions. The proposed approach is not limited to optical networks, but can be applied in a variety of other applications where nonconventional irradiance distribution has to be engineered. The described method of lens design is based on geometrical optics, radiometry and ray mapping philosophy. Rays are processed as a vector field, each of them carrying a certain amount of power. Having the target surface shape and orientation of receivers distribution, the *rays-surface* crossings map is calculated. It corresponds to the output rays vector field, which is referred to the calculated input rays spatial distribution on the designed optical surface. The application of Snell's law in a vector form allows one to obtain surface local normal vector and calculate lens profile. In the paper, we also present the case study dealing with exemplary optical network. The designed freeform lens is implemented in commercially available optical design software and irradiance three-dimensional spatial distribution is examined, showing perfect agreement with expectations.

1. Introduction

Due to increasing manufacturability of optical surfaces of arbitrary shape, unconventional lenses and mirrors became not only abstract mathematical curiosities, but available alternative for imaging [1] and non-imaging [2,3] applications. Due to the high degree of freedom, aspherical and freeform shapes can be tailored very precisely for the task. Nevertheless, before unconventional lens can be manufactured, the design stage has to be completed, which is not a trivial task. Evaluating optical component geometry, which will redirect the light from arbitrary source to a given target in such a way, that the desired output distribution will be created is challenging inverse mathematical problem. Many approaches have been reported so far. Rigorous problem processing usually requires the application of laborious Monge–Ampère second-order nonlinear partial different equation [4,5]. There are also methods dealing with wavefront modifications [6], compound surfaces [7,8], faceted surfaces [9], edge-ray principle [10,11] and others [12–15]. Overall calculation methodology strongly depends on the particular challenge, especially in terms of two questions: "is the problem rotationally or translationally symmetrical?" and "is the source point or extended?". The latter can be also stated as: "does the incoming flux have zero or non-zero étendue?". In case of rotationally symmetrical configurations and point source assumption, the problem can be reduced to two dimensions, where mathematical formulation is significantly simplified and evaluation methods known for decades [16]. On the other hand, the most challenging situation occurs if 3D geometry is non-symmetrical (cannot be reduced to 2D) and source is extended [17–19].

In this paper, we discuss lens design method for the applications associated with irradiance distribution engineering, especially valuable in the context of free space optical networks where single transmitter cooperates with multitude of receivers.

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Most challenges in the general field of non-imaging optics, particularly those associated with illumination or beam shaping deal with the problem of far-field collimation or prescribed light distribution on a two-dimensional surface, which is typically flat [20–23]. In this work, we also consider prescribed light distribution, however on a curved surface (denoted as Γ). Our goal is to provide the constant effective irradiance at all points of this surface. Term "effective" irradiance corresponds to power captured by hypothetical local detector, which is explained later in the paper. The direct purpose of the presented research was to create effective design method of a lens with entrance surface flat and exit surface of arbitrary shape, being able to transform a collimated, not necessarily uniform input beam, according to the desired geometry imposed by Γ surface. Due to the partial asymmetry of the problem, such effect can be obtained by the application of freeform optics (FFO) technology.

In the case discussed, Γ surface is immersed in three-dimensional space, which in Cartesian nomenclature can be written $\Gamma(x,y,z)$. In our methodology, this surface can be arbitrary and non-symmetrical in terms of its *x-z* plane cross section (curve, denoted as $\partial\Gamma$). In *y*-direction, Γ surface is flat, however its size is proportional to the distance from point (0,0,0). As such, the discussion is limited to *ribbon-like* surfaces. Our interest in this class of surfaces results from the applications of high power semiconductor lasers, which will be discussed in more detail. Narrowing the type of the considered surfaces locates the presented problem in space which could be symbolically named as 2½-dimensional. It enables to develop algorithm significantly less complicated comparing to the methods devoted for totally arbitrary 3D cases. Apart from typical free space optical communication systems, such unconventional light shaping problem corresponds to challenges associated with engineering of variety of optoelectronics techniques, such as complex optical security systems, illumination systems, military laser solutions for identification, optical barriers and others.

As a conceptual example, let us consider a hypothetical general distributed network of optical transmitter and receivers (Fig. 1). All the components are located approximately (given finite tolerance) at the same height (*y*-coordinate). Despite that, the spatial distribution can be of any type and generally lacks symmetry. Additionally, receivers may be oriented in different directions (not necessarily towards transmitter).

Although receivers are located at the same *y*-coordinate, emitted beam cannot have zero divergence in *y*-direction. For this reason it is not possible to apply 2D methodology directly and it has to be modified. Now, if light is emitted by the transmitter towards receivers, it would be desirable to form its distribution in such a way that more power is directed towards further locations, less power in the directions where receivers are installed closer – the problem equivalent to radio antennas emission shaping. Additionally, if a receiver is tilted with respect to *transmitter-receiver* axis, it also requires more power density, since effective capturing aperture is reduced. The power of optical radiation, reaching each receiver has to exceed a certain minimum level P_{min}, below which, due to small signal to noise ratio (SNR), the transmission cannot be established. In order to optimize the energy budget in the system, light should be formed in such a way that threshold power distribution in space is suited to the locations and orientations of receivers. One can imagine purely abstract surface, on which receivers are localized. This surface is exactly what we mean by Γ surface. It is worth to underline the unique type of the challenge discussed. It corresponds to forming the desired shape (imposed by Γ), not with respect to classic irradiance, but with respect to the intercepted power, thus the problem leads to P_{min} iso-surface shaping.

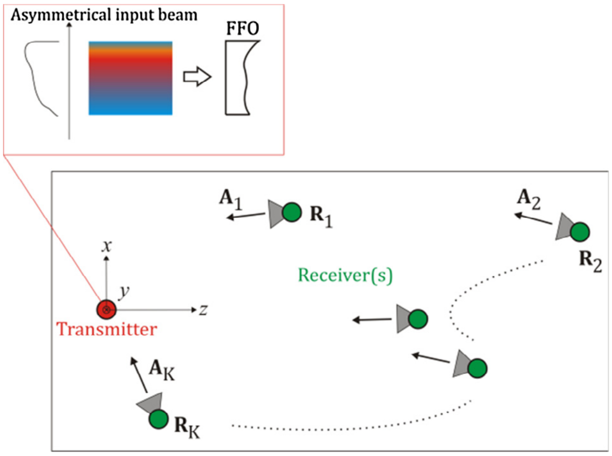

Fig. 1. General optical network composed of a transmitter and collection of receivers. The optimized lens (FFO) is a part of transmitter where it transforms collimated input beam.

2. Mathematical formulation

In our approach, principles of geometrical optics and radiometry are used. The link between power density and local spatial frequency of rays distribution on the target surface is used in order to establish the optimum angular distribution of rays outgoing the transmitter. In other words, having the target surface shape Γ, we calculate such a map of ray intersections with this surface that it guarantees the same power P_{min} captured by a hypothetical detector located at every point on this surface and oriented in arbitrary direction. Refractive surface is then generated by the application of Snell's law in a vector form. Incoming beam is collimated and does not have to be symmetrical in terms of power density cross section profile. The only assumption is weak dependence of the power density distribution in *y*-axis direction, comparing to *x*-axis direction dependence. Such requirement is easily fulfilled by laser diodes output and this is the reason, our approach is primarily targeted at their applications. According to our best knowledge the presented approach to deal with this kind of problem was not presented before.

To systematize the strategy – our goal is to calculate a surface shape of refractive *plano-freeform* optical component. The input data for the problem is constituted by:

- locations of receivers $\mathbf{R}_k$ ($k = 1\ldots K$),
- orientations of receivers $\mathbf{A}_k$ ($k = 1\ldots K$),
- the value of P_{min},
- the input beam horizontal (along *x-axis*) profile M_j ($j = 1\ldots J$) and its vertical (along *y-axis*) angular divergence θ_y,
- refractive index n_{lens} of optical glass.

The proposed computation approach is composed of three steps. In the first stage, having the locations of all receivers, the representation of isosurface $\Gamma(x,y,z)$ is established and also its cross section in *x-z* plane – curve $\partial\Gamma(x,z)$. Then, assuming certain power carried by each ray – dP_{ray}, we determine the distribution of points-vectors $\mathbf{S}_i$ in *x-z* plane, where curve $\partial\Gamma$ should be intersected by rays in order to fulfil the condition that in all points of Γ surface hypothetical detector captures exactly the power P_{min}. The number of these points, N, allows computing the required total power of the transmitter, P_0. In the second stage, the ray representation of the incoming beam is considered. It is also done in *x-z* plane due to the assumed nearly constant profile of the input beam