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Intensity distribution angular shaping – Practical approach for 3D optical beamforming

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ABSTRACT

We present approach of optical design which enables to obtain aspheric lens shape optimized for providing the specific light power density distribution in space. Proposed method is based on the evaluation of corresponding angular intensity distribution which can be obtained by the decomposition of the desired spatial distribution into virtual light cones set and collapsing it to the equivalent angular fingerprint. Rigorous formulas have been derived to relate refractive aspheric shape and the corresponding intensity distribution which is used for lens optimization. Algorithms of modeling and optimization were implemented in Matlab© and the calculated designs were successfully tested in Zemax environment.

1. Introduction

Capability to shape light power density distribution in three-dimensional spatial domain is a valuable asset in a number of scientific and practical applications. In this context one can mention about car headlight technology, optoelectronics security barriers, optical communication systems, military identification *friend-or-foe* modules (IFF), laser shooting simulators and many others [1–3]. Regarding the above mentioned applications and the scope of their possible configurations, the range from several meters up to kilometers should be taken into account. Typical (laser) beam shaping methods concentrate on two-dimensional (x, y) coherent optimization of spot size and uniformity at single distance z [4–8] which in most cases is associated with fiber-coupling or material processing. Large scale three-dimensional shaping is frequently limited to divergence control [9–12]. Hardly any scientific reports can be found regarding the problem discussed. Nevertheless, in some specific practical applications, one may require power density distribution totally different from what is provided by constant-divergence or focused laser beam. Spatial light distribution or equivalently – a beam shape, may be regarded as the distribution of optical power surface density ρ [W m^{-2}] in space. The examples of such representations are given in Fig. 1, where except from traditional (constant-divergence) Gaussian beam model (Fig. 1, left panel), two other cases have been included: required light emitted from car headlights (Fig. 1, middle panel) and beam model for a laser rangefinder with additional IFF capability (Fig. 1, right panel). The distributions were calculated in mathematical software environment and are provided as representative examples. The asymmetry of car headlights correct illumination results from safety reasons. The drivers coming from the opposite direction should not be dazzled, so the "piece" of beam responsible for illumination of road axis cannot stare towards long distance. On the other side a road shoulder can be more illuminated, so more optical power can be directed in this region. Concerning laser rangefinder, designers typically tend to minimize beam divergence due to resultant better target selectivity and improved signal to noise ratio in the detection module. IFF feature on the other side requires significantly larger beam divergence to reduce aiming requirements. Consequently, a laser rangefinder with IFF capability might provide double-divergence beam.

Considering the level of optical power surface density distribution in three-dimensional space $\rho(x,y,z)$, light beamforming can be oriented for shaping the surface S_{thr} determined by given threshold value ρ_{thr}, namely $S_{thr}(x,y,z)$: $\rho(x,y,z)=\rho_{thr}$ (Fig. 1, middle panel). Depending on the application, the desired beam shape may be rotationally symmetric or not. Being devoted for radial aspheric lens design, the method described in the paper deals with the latter case. A generalization to non-symmetric approach is feasible, however, it would acquire significantly larger mathematical complexity and is needed for the design of asymmetric free-form optics components.

2. Angular intensity distribution and conical approximation

Each light source can be represented by its intensity distribution $I(\varphi,\lambda)$ [W sr^{-1} nm^{-1}] in angular and spectral domain which

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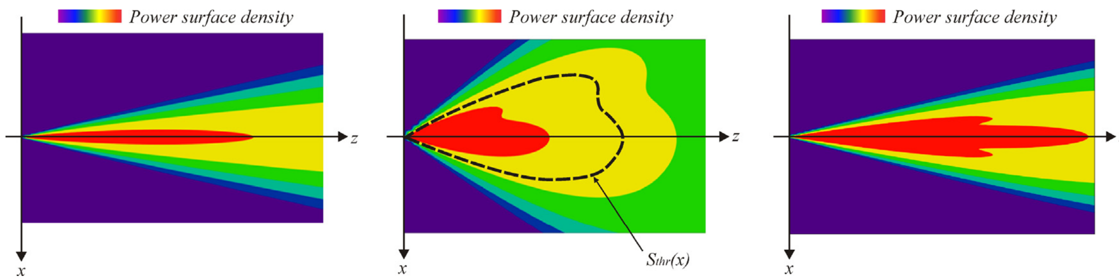

Fig. 1. Representations of light distributions in space of classical constant-divergence beam (left) and shaped beams (middle – car headlights, right – range-finder with IFF capability). Optical power surface density $\rho(x,y,z)$ cross-section in x–z plane is considered.

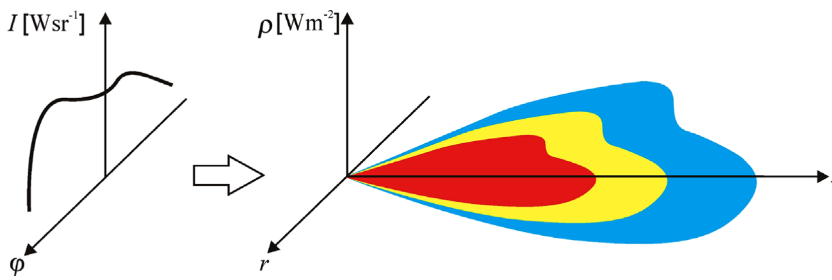

Fig. 2. Angular intensity distribution as a determinant of light distribution in 3D space.

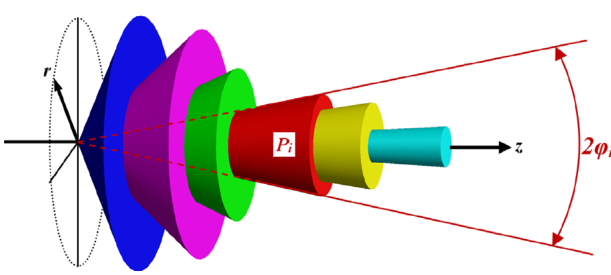

Fig. 3. Idea of conical approximation. Desired 3D light distribution is approximated by finite sum of virtual light cones.

can be used to determine how optical power density $\rho(x,y,z,\lambda)$ [W m^{-2} nm^{-1}] is spread in space and across the spectrum [13]. Laser applications in most cases tend to limit the analysis to the spatial domain due to quasi-monochromatic regime [14] and also in this paper authors considers solely spatial coordinates, namely $I(\varphi,\lambda)\rightarrow I(\varphi)$ [W sr^{-1}] and $\rho(x,y,z,\lambda)\rightarrow\rho(x,y,z)$ [W m^{-2}]. For refractive beam shaping element, quasi-monochromatic regime should not be a problem, but effect of dispersion needs to be taken into account. Additionally, considering the rotational symmetry of the problem, (x,y) coordinates can be reduced to (r,z) coordinates (Fig. 2).

In a number of practical applications, the problem is addressed in the opposite way. Considering the desired and thus known light distribution in space, one have to design optical system which will provide this distribution. It can be done by the evaluation of the corresponding angular intensity distribution first. The proposed method deals with this challenge by incorporating so called conical approximation. This method is based on the approximation of the desired optical distribution with a sum of finite number of virtual conical top-hat (uniform cross section) beams (Fig. 3). Each individual cone i is represented by half-divergence angle φ_i and optical power P_i. This approach evidently limits possible configurations to rotational-symmetry cases, as mentioned previously, however one can easily provide additional degree of freedom i.e. cone inclination angle to extend to asymmetrical regime.

It should be stated, that the proposed conical approximation is nothing more than a tool to obtain required intensity angular distribution which corresponds to the desired optical power threshold surface shape in 3-D space. Any other methods to deal with this issue are also accepted in the proposed approach. Simply, to design the relevant aspheric lens one have to determine the intensity angular distribution correctly.

Intensity I_i resulting from i-th light cone can be expressed by the following formula:

$$I_i(\varphi) = \frac{P_i}{\pi\varphi_i^2} 1(\varphi_i - |\varphi|) \tag{1}$$

where $1(\cdot)$ denotes the Heaviside function. Effectively, the net effect from all cones is represented by the sum of all contributing intensities:

$$I(\varphi) = \sum_{i=1}^{N} \frac{P_i}{\pi\varphi_i^2} 1(\varphi_i - |\varphi|) \tag{2}$$

where N is the total number of cones used to approximate the required shape. Concerning optical power density distribution in 3-D space, one can easily obtain the corresponding formula:

$$\rho(z,r) = \sum_{i=1}^{N} \frac{I_i(r/z)}{z^2} = \sum_{i=1}^{N} \frac{P_i 1(\varphi_i - (r/z))}{\pi(\varphi_i z)^2} \tag{3}$$

Iso-surface S_{thr} associated with a given threshold ρ_{thr} defines the following condition:

$$(z,r) : \rho_{thr} = \sum_{i=1}^{N} \frac{P_i 1(\varphi_i - (r/z))}{\pi(\varphi_i z)^2} \tag{4}$$

which enables to obtain the numerical values of P_i, φ_i and N. Including these parameters in Eq. (2) provides the desired angular distribution $I(\varphi)$.

3. Optical design methodology

Once, the desired intensity signature is calculated, measured or deduced, the optical design can begin. In the presented methodology one assumes to have a light source which is collimated to certain full-divergence angle θ_0 and then there is aspheric correction to achieve the target angular intensity distribution (Fig. 4). Having both elements successfully designed, they can but do not