Potentials and Limitations of Multipath Lenses for Optical Wireless Transceivers

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Introduction

The superior modulation bandwidth of laser diodes (LDs) makes them an ideal candidate for transmitters in optical wireless communication (OWC). One of the most important limitations in human-accessible environments is laser safety [1] which limits the transmission power and thereby coverage and range. The average LD power can be increased by means of optical components to reduce the power density or to increase the maximum permissible exposure (MPE). The power density is reduced by increasing the beam diameter and the emission angle θ_e to reduce the impinging optical power onto the human eye. The MPE is the limit value for the laser class defined by IEC 60825-1 [1]. Within certain limits, the MPE is influenced by the wavelength λ and the size of the apparent source. A large apparent source avoids sharp focus points on the retina.

Traditionally, the apparent source and thereby the MPE is increased by using conventional lenses, different kinds of diffusers [2], or LD arrays [3] or multiple distributed fibers. Recently, a new approach with multipath lenses (MPLs) was demonstrated in a Gbit/s OWC Link [3, 4]. Fig. 1 depicts the working principle of an MPL. The lens splits the LD beam into multiple sub beams. The spots overlap in the geometrical far field and form the transmitter FOV. Due to the different positions of each sub beam relative to the human eye, their focus points are spread over the retina and the power density is reduced. The arrangement is eye-safe, if each of the focus points, each group of focus points, and the totality of the focus points meet laser safety. Diffusors and laser arrays have a similar effect. In the case of LD arrays, each LD is the origin of its own sub beam. In the case of the diffusor, the individual sub beams are not distinguishable.

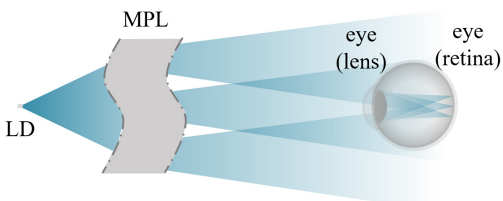

Fig. 1. General working principle of an MPL.

The MPL achieves the separation of the LD beam into sub beams with a faceted surface. Each of the facets has a freeform geometry, which is tailored to the LD and the application. This is in contrast to conventional lens arrays, where each lens is equal. One promising algorithm for the calculation of the freeform surfaces is ray mapping. It allows versatile FOV shapes with high efficiency and control over the power distribution within the FOV. As a result, the key advantage of MPLs is their ability to form precise transmitter spots with efficiencies of more than >90% [4]. Thereby, the MPLs are suited for line-of-sight communication with a defined FOV shape. The lenses are fabricated in an injection-molding process. The tooling requires ultra-precision turning and milling.

The simplest realization of a MPL is shown in Fig. 2 (a) [4]. It uses only one surface for refraction. One drawback of this design is the distance between LD and MPL z_{MPL}. It is determined by the LD emission angle θ_{LD}. Since θ_{LD} is often <20°, a large-sized MPL requires a large spacing z_{MPL}. An additional optical element can solve this issue at the expense of component count. Fig. 2 (b) shows an alternative: a flat MPL with steps at the bottom side that use total internal reflection to deflect the rays [5].

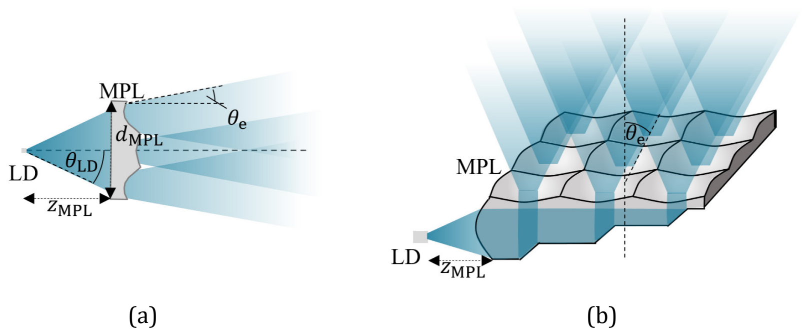

Fig. 2. (a) Refracting MPL [4] (©IEEE, 2022). (b) Flat MPL using total internal reflection [5].

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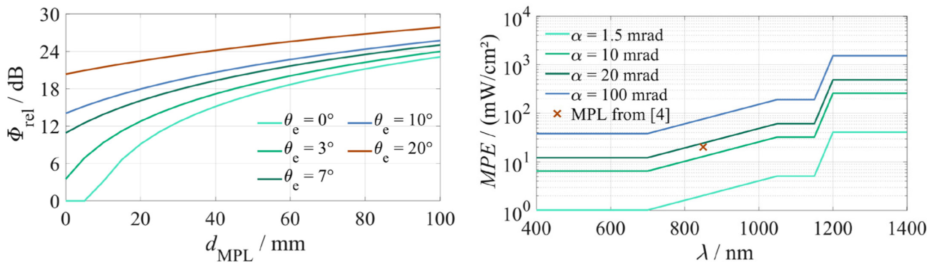
Fig. 3 gives an estimation of the possible eye-safety improvement of an MPL. To evaluate the influence of the beam power density on the allowed transmission power without a change of the MPE, we assume a homogenously illuminated lens with a diameter d_{MPL}. The lens forms an ideal circular transmitter spot with homogenous irradiance and steep edges. The lens achieves the MPE for a point source over the entire spot. Thereby, the relative improvement Φ_{rel} can be expressed as the ratio of the area of transmitter spot $A_{TX\,FOV}$ and the area of the entrance pupil A_{pupil} as shown in equation (1). $A_{TX\,FOV}$ is derived from trigonometry. z_{MHP} is the most hazardous position, which is the minimum distance in most cases (z_{MHP} = 100 mm).

$$\Phi_{rel}(d_{MPL}, \theta_e) = \frac{A_{TX\,FOV}}{A_{pupil}} = \frac{\left(z_{MHP}\tan(\theta_e) + \frac{d_{MPL}}{2}\right)^2 \pi}{\left(\frac{7\text{ mm}}{2}\right)^2 \pi} \qquad (1)$$

According to Fig. 3 (a), the improvement scales with transmitter angle θ_e and d_{MPL}. The influence of θ_e is strong for small lenses and becomes weaker with increasing d_{MPL}. An exemplary lens with d_{MPL} = 20 mm and a FOV angle of θ_e = 7° would allow for a 16 dB higher transmission power compared to an LD without the lens and parallel output. The advantage of the MPL over such a conventional lens is the additional increase of the MPE.



(a) (b)

Fig. 3. (a) Relative transmission power improvement compared to a point source with parallel beam (laser class 1/1M) vs. lens diameter d_{MPL}. (b) MPE vs. optical spectrum for thermal retinal damage (laser class 1/1M [1], exposure time: t_{ex}=100s).

Fig. 3 (b) illustrates the MPE over the optical spectrum for some angles α of the apparent source according to IEC 60825-1 [1]. $\alpha = \alpha_{min}$ = 1.5 mrad classifies the source as a "point source". $\alpha = \alpha_{max}$=100 mrad is the maximum extent. By increasing α, an improvement of up to 15.7 dB is possible. Our previous MPL prototype [3] features α = 16.2 mrad and increased the MPE from 2.04 mW/cm² by 10 dB to 20.27 mW/cm² and allowed for an output of up to 354 mW at λ = 850 nm [3]. A conventional lens with a similar diameter and a similar θ_e would only allow 36 mW because it does not increase the MPE.

The MPL size is typically limited by available space or manufacturing costs. The fabrication costs are composed of tooling costs and sample costs. The initial tooling costs are critical for low-volume production and rise with MPL size. One way of reducing tool costs is to reduce accuracy. By choosing a larger milling or turning tip, the rounding radius of the facet edges becomes larger, which is problematic for small facets. Another way to reduce tooling costs is the reduction of polished surface area by minimizing the facets while maintaining their spacing. The surface in between the facets is optically not active and needs no polishing. Their spatial extent plays only a marginal role in eye safety because they are treated as a point source anyways. However, this approach requires an additional surface to deflect rays onto the facets.

The estimations from Fig. 3 assume homogenously illuminated facets. However, since most laser sources feature a Gaussian-shaped emission profile, the central facets feature more power than the edge facets. As a result, the angular extent α of the image on the retina is smaller and the MPE lower. An additional optical interface can solve this issue by distributing the power over the facets. Our future work will focus on this topic. For instance, the MPE of the MPL prototype from [3] could be increased theoretically by 4.5 dB. Considering some nonidealities an improvement of up to 3 dB seems realistic.

References

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