Flat-top laser beams over an extended range

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Abstract. Designs based on single diffractive-optical-elements for obtaining flat-top laser intensity distributions that remain constant over a long range during free-space propagation are presented. Flat-top beams with different orders $n$ exhibit a different range of propagation. For various working distances $z$, the resulting flat-top beam yields a different depth of focus. By controlling spectral properties of laser distributions, it is possible to maintain invariant flat-top intensity distributions for relatively long propagation distances.

1. Introduction

Flat-top laser distributions have been incorporated into several applications, such as annealing of photovoltaics, micromachining, laser scanning, laser radar antenna arrays, and lithography [1-3]. The formation of flat-top beams (uniform intensity profile) involves intensity and phase modulations with either transmissive or refractive or diffractive optical elements [4-5]. Such elements redistribute the intensity distribution of a propagating beam.

Perfect flat-top beams have sharp edges, resulting in strong diffraction and distortions during propagation. Such strong diffraction and distortions can be alleviated by reducing the flatness requirement of the propagating beams. For applications where long working distances are required, it is essential to extend the depth of focus. For achieving the long depth of focus, consider the flat-top beam with round edges, which have a continuous conversion from uniform intensity to zero intensity [5-6]. Usually, $n$ stands for the order of super-Gaussian flat-top beam, and the order $n > 2$ yields nearly flat-top laser distribution. For instance, the flat-top laser distribution with $n = 6$, whose intensity profile remains constant over a long propagation distance whereas the flat-top distribution with $n = 12$ distorts rapidly during free-space propagation.

In this study, we convert Gaussian distributions into flat-top distributions that maintain relatively uniform phase distribution. The much needed phase-only diffractive optical elements (DOEs) are designed through a modified Grechberg-Saxton (GS) algorithm, to form nearly ideal flat-top laser distributions that have relatively uniform phase distributions. The range of propagation of flat-top beams depends on different parameters such as the order $n$, working distance $z$, beam waist $W_{out}$, and operating wavelength $\lambda$ [5-6]. All these parameters considered into account while calculating intensity distributions of propagated flat-top beams.
2. Basic procedure
In the modified GS algorithm that we used, we begin with a well-known Gaussian field distribution having random phases and then propagate it over a working distance \( z \). After propagation, a new amplitude and phase distributions are obtained, onto which we superimpose non-Gaussian flat-top distribution. The combined new distribution is relayed back to the initial position after spatial filtering, and the procedure continues iteratively until finding the needed phase profile for the DOE. Some representative results are shown in Figure 1. Figures 1(a) shows the intensity distribution of a typical Gaussian input beam \((n = 2)\) with beam waist \( W_{in} = 1.5 \) mm and \( \lambda = 808 \) nm, Fig.1(b) shows the phase profile of a DOE, and Fig. 1 (c) the corresponding nearly flat-top beam, which is a super-Gaussian beam \((n = 6)\). The Gaussian input beam, incident on DOE at \( z = 0 \), is transformed into a super-Gaussian flat-top output beam after propagating a working distance \( z = 30 \) cm.

![Figure 1](image1)

**Figure 1(a,b,c).** Transforming a Gaussian input beam to a flat-top output beam over a working distance of \( z = 30 \) cm. (a) Gaussian input intensity distribution; (b) DOE phase profile at \( z = 0 \); (c) Flat-top output intensity distribution at \( z = 30 \) cm.

3. Results and Discussion

![Figure 2](image2)

**Figure 2.** Calculated intensity cross-section of flat-top beams with different orders \( n \) (= 6, 12, 24 & 48) as a function of propagation distance. The size of the beam waist is \( W_{out} = 2 \) mm, wavelength \( \lambda = 1350 \) nm and the working distance \( z = 30 \) cm.
Figure 2 shows the propagation of flat-top beams with different super-Gaussian powers $n$. It has shown that flat-top beams with large $n$ value distorted very fast upon propagation as compared to flat-top beams with small $n$ value. Accordingly, flat-top beam with $n = 6$ has a longer depth of focus than that of flat-top beams with larger $n (> 6)$ value. However, the flatness of a flat-top beam increases with increasing the order $n$.

![Figure 2](image)

**Figure 3.** Calculated intensity cross-section of flat-top beams with $n = 8$ as a function of propagation distance for various working distances $z$. The size of the beam waist is $W_{out} = 2$ mm, wavelength $\lambda = 1350$ nm.

![Figure 3](image)

**Figure 4(a,b).** Cross-section intensity distributions of flat-top beams of different wavelengths ($\lambda$) as a function of propagation distance. The order $n = 6$ and the working distance $z = 30$ cm.

![Figure 4](image)

The range of propagation and the quality of flat-top laser distributions generated by diffractive phase elements depend on the working distance $z$, as seen in Fig. 3. Figure 3 shows the propagation of a flat-top beam with $n = 8$ for various working distances $z$. The calculated intensity cross-section in figure 3 shows that a flat-top beam propagates a short distance for small working distances $z$. As the working distance $z$ increases, the propagation distance of a flat-top beam also increases. For longer working distances $z$, the resulting small phase range DOE forms a flat-top beam with improved uniform phase distribution, giving rise to propagation distance. Figure 4 shows the intensity cross-section of flat-top beams of two different near-infrared wavelengths as a function of propagation distance. The results of figures 4(a) and 4(b) indicate that the propagation distance over which the laser intensity distributions that remain constant and robustly depends on wavelength $\lambda$, and increases as wavelength decreases. Specifically, flat-top beams of short wavelength $\lambda$ maintain invariant cross-section shape for relatively
longer propagation distance than that of flat-top beams with longer wavelength $\lambda$, as shown in Fig. 4(b).

4. Conclusions
The present study concluded that single-DOE designs and results for generating super-Gaussian flat-top laser beams that can propagate without distortions over a long distance. The designs take into account the order $n$, working distance $z$, operating wavelengths, and beam waist. Note that, the propagation distance of invariant flat-top beams varies with the wavelength $\lambda$. As evident, a flat-top beam with a shorter wavelength $\lambda$ yields a longer depth-of-focus. By increasing the working distance $z$, the propagation distance of a flat-top beam increased significantly. It concludes that as the order $n$ increases the flatness of a flat-top beam also increases, but, it decreases the depth-of-focus of a propagating flat-top beam.

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