A design method to generate thin micro-optical freeform (MOF) beam shapers by clipping or wrapping an original and much thicker freeform surface is provided. MOF elements are situated at the border between refractive and diffractive optical elements. The influence of parameters such as the clipping factor \( q \), the peak-to-valley amplitude of the original surface, the design wavelength, and the spectrum of the light source (single wavelength and multiple wavelength lines) into the quality of the output intensity distributions has been studied. Integer \( q \) values are mandatory for good quality at monochromatic illumination. On the contrary, the quality obtained by broadband illumination oscillates with \( q \) and peaks maximally at around \( q = 3 \).

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1. INTRODUCTION

Advances in optics have been closely related to progress in manufacturing methods. As an example, the arrival of powerful and fast computers as well as the development made in computer numerical control (CNC) tools were extremely important factors in the design and fabrication of complex optical elements, such as aspherical and freeform surfaces [1,2]. In a similar way, laser sources paved the way for diffractive optical elements (DOEs), which have experienced a strong interest from the optics research community in the last 25 years [3].

Transmissive optical elements can be mainly classified into two divisions or domains: refractive and diffractive. Aspherical and freeform surfaces belong to the former domain, whereas DOEs fit in the latter division. In the following paragraphs, a comparison of the two domains is made in order to emphasize the differences between them.

Ray-tracing techniques are sufficient to explain light propagation through and beyond refractive elements. On the other hand, since interferences are the basis of the diffractive domain, the wave behavior of light must be contemplated when designing diffractive elements.

Differences are also significant when comparing the topography of elements from each domain. The refractive domain is characterized by surfaces with macroscopic continuous features that are mostly insensitive to the wavelength of light: only material dispersion plays a role in transmissive refractive elements. Conversely, the DOEs’ wavelength dependence is prominent, since they are thin elements with microscopic features that modulate incident light by means of diffraction. These devices require highly coherent light sources for proper operation and are very sensitive to variations in the illumination wavelength and to fabrication errors. Furthermore, the quality of the intensity distributions they produce is substantially reduced by the effect of speckle noise [4].

Caustic generators are examples of refractive beam-shaping freeform surfaces [5,6]. Their surface shapes are obtained after inputting the target intensity distribution into an algorithm that solves the inverse problem by geometric propagation of light rays. On the other hand, the iterative Fourier transform algorithm (IFTA) is one of the most widely used methods in the design and optimization of DOEs [7–9].

Numerous studies on hybrid optical elements (i.e., elements combining both refractive and diffractive properties) have been made in the last decades [10–13]. The need for mastering beam-shaping techniques is continuously increasing in industries such as consumer electronics, illumination, biomedical engineering, defense, and security [14–18]. In this context, elements combining the advantages of both domains in terms of image quality, light source independence, wavelength
The fabrication of refractive beam-shaping freeform elements is well-mastered. Techniques like multi-axis ultraprecision diamond turning or micromilling allow the fabrication of such nonrotationally symmetric structures with outstanding accuracy and resolution [2]. Despite the fact that surface finish can be excellent for these “macro”-structures, the machining process can be significantly time-consuming and inefficient, especially in the case of raster milling.

A miniaturization and/or flattening of freeform beam-shaping structures is sought, since it will ensure compactness, and hence, better system integration. Nonetheless, attention must be paid to this miniaturization process, since it could not be infinitely performed. The étendue (i.e., the product of source area by the solid angle of a certain light beam) has to be conserved. A significant element thickness reduction, while keeping the projection distance constant and without impairing the optical performance, requires, therefore, a different design strategy.

Tooling-related issues (tool path, tool orientation, and tool geometry) make CNC milling inappropriate for micro-optical freeform (MOF) structures. Laser writing lithography has been used to machine freeform structures with low peak-to-valley amplitudes. Higher peak-to-valley surfaces (up to 60 μm) can be achieved at the expense of surface quality and process repeatability, owing to the lack of control of photoresist dynamics [19]. High intensity light beam ablation, using an excimer laser, can address ablation depths as low as 100 nm on large and shallow areas, hence allowing the fabrication of MOF elements while keeping an acceptable surface quality [20,21].

This work presents a top-down approach to design miniaturized beam-shaping structures lying at the border between diffractive and refractive domains, so-called MOF elements [22], and, moreover, studies the limits between the two domains. The limitations of the fabrication method are also considered in this design strategy. Finally, an experimental result is presented.

2. DESIGN METHOD

MOF element design starts by the generation of a freeform beam-shaping surface, obtained, for instance, by the method described in [6]. Depending on its dimensions, proper lateral and vertical scaling might be necessary to downsize the original surface and/or its projection distance. A further reduction in thickness of the element can be achieved by wrapping or clipping its surface profile while keeping the image size and projection distance constant. This procedure is described by the following equations:

\[ h_x(x, y) = h(x, y) \mod H_c, \]

\[ H_c = q \lambda_D / \Delta n(\lambda_D), \]

where \( q \in \mathbb{R}_{>0} \) is the clipping factor, \( \lambda_D \) is the design wavelength, and \( \Delta n(\lambda) \) is the refractive index difference between the element material and the surrounding medium. For the special case of \( q = 1 \), the wrapping or clipping height \( H_c \) corresponds to a \( 2\pi \)-phase shift of the output light field. The schematic in Fig. 1 shows the typical arrangement for a MOF beam shaper.

Three freeform beam shapers have been studied in this work. They generate as output the portrait images of: Alan Turing (AT), Rafael Nadal (RN), and Roger Federer (RF). Table 1 shows the dimensions and other parameters of these elements: in-plane area \( A \), peak-to-valley amplitude \( PV \), projection distance \( z \), sampling size \( \Delta x \) and number of samples \( M \) and \( N \). The sampling size has been kept constant for both \( x \) and \( y \) axes as well as for both element and image planes. The intensity distribution generated by each element \( I_{out} \) has also been included there. Note the disparity in contrast among the different \( I_{out} \), which is directly related to the algorithm used in the generation of the freeform surface, to the different element dimensions (\( A \) and \( PV \) values), and also to the gradients of the surfaces. For instance, the RF beam shaper, being flatter and slightly smaller than its counterparts, generates a lower contrast \( I_{out} \). The design wavelengths used in the simulations, as well as the refractive index of the element material (polycarbonate surrounded by air), can be checked in Table 2.

It will be proved in the following sections that the clipping/wrapping method can significantly reduce the thickness of the MOF beam shaper, at the expense of introducing multiple folds or wrinkles in the otherwise highly continuous surface. Therefore, a tradeoff exists between output image quality and vertical compactness of the beam shaper. For instance, for \( q = 10 \) at \( \lambda_D = 641 \) nm, the final \( PV \) amplitude is just 11.06 μm.

### Table 1. Relevant Parameters for the Three Freeform Beam Shapers Used in This Work

<table>
<thead>
<tr>
<th>( \lambda_D ) [nm]</th>
<th>AT</th>
<th>RN</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>( PV ) [μm]</td>
<td>215.20</td>
<td>447.90</td>
<td>102.94</td>
</tr>
<tr>
<td>( z ) [mm]</td>
<td>6.40</td>
<td>17.00</td>
<td>17.00</td>
</tr>
<tr>
<td>( \Delta x ) [μm]</td>
<td>0.32</td>
<td>0.32</td>
<td>0.31</td>
</tr>
<tr>
<td>( M, N ) [μm]</td>
<td>20000</td>
<td>20000</td>
<td>20000</td>
</tr>
</tbody>
</table>
the Gaussian filter SPD for Fig. 2. Ratio of height profile SPD lying inside the FWHM circle of
Signal-to-noise ratio (SNR) as described in [24] has been used
A. Single Wavelength Illumination
In order to both respect sampling constraints and consider
free-form elements. The structures have been
be produced than standard and smooth freeform ones.

3. Simulation Results
Free-space light propagation beyond the MOF elements has
been simulated by means of the angular spectrum of planar
waves method [23] in MATLAB. The structures have been
approximated as thin-phase elements.
In order to both respect sampling constraints and consider
fabrication inaccuracies of sharp edges into the simulations, the
clipped height profile has been convoluted with a Gaussian filter.
Figure 2 plots the ratio of energy from the spectral power
density (SPD) of the different clipped or wrapped height profiles lying inside the FWHM circle of the Gaussian filter SPD on the total energy. A FWHM value in the space domain of 3 μm has been chosen for this purpose, based on the lateral resolution of an excimer laser ablation fabrication process. Owing to a limitation in computational memory, simulations have been restricted to q ≤ 5. The influence of filtering becomes noticeable when small clipping factors (e.g., q ≤ 1) are applied. Furthermore, a flatter original element (i.e., having lower PV amplitude for a similar lateral size and hence a fewer number of folds) is less sensitive to the influence of the filter (see the RF curve standing above the rest in Fig. 2).

A. Single Wavelength Illumination
Signal-to-noise ratio (SNR) as described in [24] has been used
as merit function to evaluate the quality of the output intensity
distributions. Light fields at the illumination wavelength λ,
propagated through the original unclipped freeform structures, have been used as reference functions (see I_out at Table 1). The quality evaluation shown in Fig. 3 reveals that, for single wavelength illumination, only at integer clipping factor values the image signal is much above the noise level. Only at these values light does not interfere destructively to impair the desired intensity distribution. The SNR also increases with increasing q, as the number of discontinuities or folds in the surface is reduced; thus more energy lies inside the filter SPD circle of FWHM diameter. At low design wavelengths, since the clipping height H_c is directly proportional to λ^3, a higher number of folds is introduced in the MOF element surface. This explains why the quality at integer q values for 532 nm is lower than that for 641 nm. Furthermore, a mismatch in the illumination and design wavelengths produces a shift in the quality peaks, which are no more positioned at integer q values. The new position of the local maxima in q can be determined in a different wavelength λ by multiplying q by the following factor:

\[ \alpha = \frac{\lambda}{\Delta n(\lambda)} \cdot \frac{\Delta n(\lambda_D)}{\lambda_D}. \]  

Unfortunately, the sampling rate of q used in Fig. 3 is not high enough to show all of the shifted peaks of the unmatched blue curve. Figures 4(a) and 4(b) show the surface maps for the AT beam shaper and Figs. 4(c)–4(f) some of the output intensity distributions at significant q values.

Figure 5 reveals that the MOF element generating the best quality images, with respect to its reference, corresponds to the flattest original freeform element, or the one with fewer folds or wrinkles for the same clipping factor. Furthermore, in agreement with the curves in Fig. 2, it is also the least affected structure by the filtering process. In other words, low-contrast MOF elements generate intensity distributions which are truer to its reference one.

B. Multiple Wavelength Illumination
Simulation of broad spectrum illumination has been performed by sampling the spectral power distribution of a standard white LED at five equidistant spectral lines (see Fig. 6), and then propagating each light field independently.
In this approach, it is assumed that partially coherent light is a superposition of the irradiance from uncorrelated coherent waves. Thereby, the resulting fields are later combined into an RGB image by using the Colorlab Toolbox [25] for MATLAB. Finally, the RGB image has been converted to a gray-scale image and its SNR has been computed, as shown in Fig. 7. The position of the local maxima in q can be determined in a different design wavelength by dividing q by α. A design whose λD were sitting in the central sample of the illumination spectrum would generate quality local maxima at clipping factors closer to integer values.

So as to avoid incurring sampling errors for every λ and λD combination up to, at least, q = 5, the number of samples has been increased to M = N = 25000, which corresponds to Δx = 256 nm and σ = 4.97 (for the same FWHM filter as in Section 3.A). Contrary to the results of Fig. 3, the SNR curves upon multiple wavelength illumination do not drop to 1. This can be explained by the fact that the summation of gray-scale intensity distributions coming from color images has been used in the computation of the SNR instead of single complex fields. It is also worth mentioning that the coherence length of the colorful source is much shorter than that of the monochromatic planar-wave source. Actually, in order to avoid light interferences that could create unwanted artifacts in the output intensity distribution, it would be enough that the coherence length of the source is shorter than the clipping height.
$H_c$ of the MOF element. A rough estimation of the source coherence length gives 2.74 μm, by using the expression $(\lambda^2/\Delta \lambda$).

The reader may also have noted that the SNR gives very similar results at very low $q$ values (e.g., $q = 0.125$, and at $q \approx 1$) which could be counterintuitive. At very low $q$ values, the huge number of folds around the whole MOF surface, in addition to their small height and the filtering process, makes the zeroth order prominent in the multiple wavelength configuration output. If the zeroth order is suppressed for each spectral line, the SNR curve drops to much lower values at very low $q$ values, while it remains comparable at $q \approx 1$ (refer to Fig. 8). Moreover, the SNR curves do not increase linearly as they did in the case of monochromatic illumination (at integer clipping factors). Indeed, the oscillation amplitude in Fig. 7 decreases with $q$ after a certain value, and the expected trend is that the SNR reaches a certain saturation value.

A true color merit function, namely the independent feature similarity (IFS) index [26], has also been evaluated in Fig. 7. The IFS curve behavior fits appropriately that of the SNR curve for $q \geq 1.5$ at $\lambda_D = 641$ nm and for $q \geq 2.25$ at $\lambda_D = 532$ nm. At lower $q$ values than the ones aforementioned, the SNR curve fits better the subjective quality evaluation than the IFS curve: compare Figs. 9(a) and 9(b) with their corresponding SNR and IFS values at Fig. 7.

The IFS index quality evaluation for different MOF elements also differs significantly from the SNR curves for low $q$ values, as shown in Fig. 10. The element providing the lowest SNR values, namely RN, is also the one with the highest IFS values of the three elements. Being the element with the highest surface gradients, its folds are the closest to each other. At certain clipping conditions, diffraction effects from folds overlap and give a quite homogeneous output color in relevant regions of the output intensity distribution. These regions are almost free of dark fringes [see RN $I_{out}$ at Fig. 11(c) and compare it with its reference at Fig. 11(a)]. The IFS index is a better indicator of the quality perceived by the human vision system than SNR. As the folds separate from one another with increasing $q$, darker fringes appear in the output, and both SNR and IFS are impaired [compare RF intensity outputs at Figs. 11(d) and 11(f) and their corresponding quality values at Fig. 10]. For a $\lambda_D$ centered in the illumination spectrum, the best IFS results are expected to be obtained at $q \approx 3$. For the $q$ values where the mismatch between IFS and SNR curve shapes is considerable (e.g., $q \lesssim 2$ for AT and RN, and $q \lesssim 1$ for RF) diffraction artifacts are present. Indeed, these effects happen in the region where the height of the structure is smaller than the source coherence length, as $q \lesssim 2.5$.

**Fig. 8.** SNR as function of low clipping factor for different design wavelengths and multiple wavelength illumination of the AT MOF element. Solid symbols and lines represent the normal output and empty symbols and dashed lines show the output with zero-order suppression. The two insets illustrate the output of the standard and the zeroth-orderless curves for $q = 0.5$ and $\lambda_D = 641$ nm.

**Fig. 9.** Numerical simulation of $I_{out}$ of the AT MOF beam shaper for multiple wavelength illumination at different clipping factors for $\lambda_D = 641$ nm: (a) $q = 0.625$, (b) $q = 1$, (c) $q = 2.25$, and (d) $q = 3.5$.

**Fig. 10.** SNR (solid symbols and lines) and modulus of the IFS index ([IFS], empty symbols and dashed lines) as function of clipping factor for different MOF beam shapers at $\lambda_D = 532$ nm and multiple wavelength illumination.

4. Fabrication

Excimer laser ablation has been used to fabricate the AT MOF element on a polycarbonate substrate foil [27]. Polymer
processing allows cost-effective structuring, since the required ablation threshold fluence is not high, as compared to other materials. In the fabrication process used in this work, high energy UV light pulses at 248 nm wavelength are propagated through a half-tone chromium mask, and then projected by a 0.13 NA objective onto the substrate. Despite the high amount of image artifacts in the intensity distribution at the focus position [see Fig. 12(c)], this preliminary result is very encouraging for a structure with $PV$ of 11.06 μm. Further work needs to be conducted in order to reduce the surface roughness [refer to Fig. 12(b)] and improve the outcome, as well as the fabrication of structures with different $q$ values.

5. CONCLUSIONS

A design method of compact MOF beam shapers has been proposed by wrapping or clipping the original freeform surface profile. An additional low-pass filtering has been applied in order to avoid aliasing effects in light propagation. Monochromatic and multiple wavelength planar-wave illumination have been propagated through the structures, and the fidelity of the results with respect to the reference distributions has been evaluated. The number of folds of the MOF beam shaper is directly linked to the $PV$ amplitude of the original freeform element and therefore to the contrast of its output image. In both illumination cases, quality increases as the number of folds is reduced.

Single wavelength illumination reveals that at noninteger clipping factors the quality of the resulting intensity distribution is extremely poor, due to the large coherence length of the light source. In case of a mismatch in the design and illumination wavelengths, the clipping factors providing relatively good image quality are shifted.

In the conditions of broadband illumination, a shorter coherence length of the source than the clipping height $H_c$ allows better quality along a wider range of clipping factors, not only at specific values. Quality increases with $q$ in an oscillatory way, but the amplitude of these oscillations tends to decrease. A true color merit function, namely the IFS index, shows different behavior than the SNR for $q \lesssim 1.5$, but is more accurate in representing subjective quality evaluation for the rest of $q$ values. A clipping threshold value for obtaining good quality color intensity distributions is difficult to set, yet diffraction artifacts become less important when $q \gtrsim 2$. For a design wavelength centered in the illumination spectrum, the best expected quality results correspond to $q \approx 3$. The images obtained from the fabricated sample are promising results for the validation of the simulation work.
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