A novel concept for coherent beam combining is presented based on a simple setup with micro-lens arrays. These standard components are used in a proof-of-principle experiment for both coherent beam splitting and combination of $5 \times 5$ beams. Here a combination efficiency above 90% is achieved. We call this novel concept mixed aperture.

Fig. 1. Geometries for CBC. (a) Tiled aperture. (b) Filled aperture. (c) Described geometry in this paper: Mixed aperture.
With cylindrical MLAs a line profile results and for square MLAs with a pitch of 500 µm which define the effective focal length of a MLA. The second MLA in combination with the Fourier-lens FL acts as a beam splitter. With the correct choice of fundamental design parameters an, in particular, equal power distribution can be achieved in the focal plane of the first MLA. This diffraction pattern in the far field, another diffraction pattern is shown in Fig. 3 (red lines) for the same MLA as used in Fig. 2 (c). Due to the lenses, the incident beam is divided into several partial beams (blue lines). According to geometrical optics, the focus result in the center of the micro-lenses. Here the focus represents the main maximum. Moreover, diffraction effects also cause side maxima between the main maxima, which is also visible in Fig. 4. Obviously, the diffraction pattern in the focal plane of the MLA is dependent on the characteristics of the MLA which includes the effective focal length \( f_{MLA} \) and the numerical aperture \( NA \). Hence for the angle \( \Theta_{MLA} \) applies

\[
\Theta_{MLA} = 2NA = \frac{a}{f_{MLA}}.
\]  

(2)

Thus, if \( \Theta_{max} \) is inserted in Eq. (1) for \( \Theta \) and is rearranged to \( m \) it follows

\[
m = \frac{a^2}{\lambda f_{MLA}} (m = 0, 1, ...).
\]  

(3)

Here, \( m \) is the total number of created orders in the far field of the MLA, which is shown in Fig 3. It follows that by choosing the focal length \( f_{MLA} \) and the pitch \( a \), the number of orders \( m \) can be set. Therefore, in Eq. (3) \( m \) represents the number of beams \( N \) and the number of channels, respectively, and agrees well with the findings in [19, 20, 22]. This theoretical consideration, Eq. (2) and Eq. (3), enable to design an MLA setup acting as beam splitter. With the correct choice of fundamental design parameters an, in particular, equal power distribution can be

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**Fig. 2.** Types of MLAs: (a) cylindrical (b) square MLAs. (c) Setup with MLAs as beam homogenizer, splitter and combiner element.

**Fig. 3.** Simulated normalized intensity as function of the diffraction angle for beam splitting based on Fig 2 (c).

**Fig. 4.** Schematic beam propagation (geometrical optics) for the beam propagation through one MLA until the focal plane.

**Table 1.** Beam splitting and combining parameters.

| \( \lambda \) | N | \( f_{MLA} \) | \( f_{FL} \) | FF | \( \Delta x \) |
|---|---|---|---|---|---|
| 1.03 µm | 5 \times 5 | 46.5 mm | 500 µm | 0.5 m | 34 % | 1 mm |
achieved. Accordingly, the design parameters of MLAs are selected such that an odd or even number of beams $N$ is obtained. A setup where a well defined beam splitting process is possible should be reversible. For the combining process this means that if $N$ channels should be combined the parameters for the MLAs have to fulfill Eq. (3) to reach a high combining efficiency.

For beam splitting, the generated beams result in the far field of the first MLA as shown in Fig. 2. Accordingly, for beam combining it is necessary to arrange the beams in the near field next to each other. This step is identical to the tiled aperture geometry. In contrast to the tiled aperture approach, in the far field a central combining element is placed, which is equal to the filled aperture geometry. Thus, in the plane of the combination element an interference pattern results. The interference condition results from the pitch of the MLAs. Therefore, Eq. (3) must be fulfilled to create a single spot. For this reason, the FF does not limit the combining efficiency as the tilted aperture approach does. This is an advantage compared with the FF does not limit the combining efficiency as the tilted aperture approach, because high combining efficiencies -above 90%—are possible, independent of the selected FF.

After the combining element, the combined beam results in the far field. Hence, the MLA combining setup is neither labeled as a tilted aperture nor as filled aperture. For this reason, the term mixed aperture approach is introduced for this new combination method and the advantages of both combination geometries are combined. It is possible to reach high combining efficiencies above 90% but only one central combining element is used. The mixed aperture is shown in Fig. 1(c).

The next step for beam combination is to determine the relative phase for each channel to achieve constructive interference. This creates a suitable phase front for the beam combination and ensures a high combination efficiency. Therefore, the angle spectrum of the beam homogenizer illuminated by the wave function $\psi$ is considered

$$\Psi(\Theta) = \exp \left(\frac{2\pi i}{\lambda} f_{\text{MLA}} \Theta^2\right) \sum_m \exp \left(\frac{2\pi i}{\lambda} f_{\text{MLA}} \frac{\lambda}{a} m \Theta\right)$$

(4)

with $\hat{\psi}(\Theta) \sim \exp \left(-\frac{\Theta^2}{\Theta_\text{R}^2}\right)$ the divergence $\Theta_\text{R}$ of the incident beams. For details see Ref. [7]. In Eq. (4) the phase factor accounts for the difference in optical path between the apertures. The variable $m$ represents the position of the individual beam which should be combined. The split and combined beams are defined as diffraction orders, where the central spot represents the zero order. By this declaration, variable $m = \pm(N - 1)/2$ is defined accordingly. Furthermore, the characteristics (position and size) of the individual beams which should be combined play an important role. Therefore, with the use of a FL with the focal length $f_{\text{FL}}$ (note $f_{\text{FL}} = f_{\text{FLin}} = f_{\text{FLout}}$) a spacing between the spots in the focal plane follows with $\Delta x = f_{\text{FL}} \cdot \lambda/a$.

Accordingly, the FF can be defined as $FF = 2w_{\text{in}}/\Delta x$ with $w_{\text{in}}$ the beam waist of the individual beams. For the combined beam the beam waist $w_{\text{out}}$ depends on the FL which is used to image the far field with the focal length $f_{\text{FLout}}$ and it follows $w_{\text{out}} = w_{\text{in}} \cdot f_{\text{FLout}}/f_{\text{FL}}$. The beam waist directly at the position of the first MLA $w_{\text{MLA}}$ is given by $w_{\text{MLA}} = 2a/(FF \cdot \pi)$.

For beam splitting $w_{\text{MLA}}$ represents the input beam and for beam combination it corresponds to the beam radius at the 2 MLA. To determine the splitting $\eta_{\text{split}}$ and combining efficiency $\eta_{\text{comb}}$—not to be confused with the system efficiency—[10], the intensity distribution of the far field is considered. All undesired orders are considered as efficiency loss, which is referred to boundary fields. This boundary field is cut off and set in relation to the 0. Order. This results in the splitting efficiency $\eta_{\text{split}}$ with

$$\eta_{\text{split}} = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x,y)dx\,dy}{\frac{D_{\text{FF}}^2}{2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x,y)dx\,dy}.$$  

(5)

Here, $I(x,y)$ is the intensity distribution in the far field. The combination efficiency $\eta_{\text{comb}}$ results in

$$\eta_{\text{comb}} = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x,y)dx\,dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x,y)dx\,dy}.$$  

(6)

In a proof of principle experiment the beam splitting and combination is done with MLAs (for specifications, see Tab. 1). The experimental setup and simulations are depicted in Fig. 5. Here, a mode-locked ultra-short pulse laser source at 1030 nm with a bandwidth of 10 nm is used. Due to the low NA of our setup, a homogeneous intensity distribution results despite the high bandwidth. Then a telescope follows that collimates the beam (red line) and a $\lambda/2$-wave plate is used to choose the correct polarization for the SLM. After this the incident Gaussian beam, with a beam waist $w_{\text{MLA}}$ of 0.94 mm at MLA1 (approx. 4 micro-lenses are illuminated) is split into small high intensity beamlets, as shown in Fig. 4. In the far field these beamlets interfere and yield a homogeneous distribution of equidistantly 5 $\times$ 5 spaced spots (blue line). The phase match, is done with a liquid-crystal-on-silicon based SLM that is positioned in the focal plane of the FL. The SLM represents only one option to control the absolute phase, other phase shifters are also possible. Therefore, with the phase factor in Eq. (4) the phase $\delta \varphi$ results in

$$\delta \varphi(m_x, m_y) = -\frac{2\pi i}{\lambda} f_{\text{MLA}} \left(\Theta_x^2 m_x^2 + \Theta_y^2 m_y^2\right),$$

valid for Fig. 5. It should be noted that to calculate the phase a factor of two has to be considered. This is necessary because the phase difference results for the beam splitting and combination process.

The next step is the beam combination (green line). Here the combination path is the backwards version of the beam splitting part. Consequently, beam profiles at the individual planes, MLA2 and MLA1, agree with the beam profiles in the beam splitting path. At the end, the combination efficiency is proven in the far field. Therefore, a 2f-setup is added (purple line). In the plane of the camera we present two cases: once the phases in the far field these beamlets interfere and yield a homogeneous distribution of equidistantly 5 $\times$ 5 spaced spots (blue line). The phase match, is done with a liquid-crystal-on-silicon based SLM that is positioned in the focal plane of the FL. The SLM represents only one option to control the absolute phase, other phase shifters are also possible. Therefore, with the phase factor in Eq. (4) the phase $\delta \varphi$ results in

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through the imperfect focal length of the MLA (see Eq. (3)). The beam combination of the generated 25 beams is depicted in Fig. 7 and a combination efficiency of 90 % is achieved. Thus, the efficiency of the experiment is close to the theoretical limit (based on the simulation in Fig. 6) at 93 %, which has been determined by simulation, based on Eq. (6). At this point, it should be noted that no active stabilization is necessary for this low power experiment, because all beams are split from the same source. The situation will be different with independent amplifiers, where an active stabilization is essential to achieve a high combination efficiency.

In conclusion, a novel, compact and simple setup based on MLAs for CBC of $N \times N$ beams is presented. To the best of our knowledge this was the first time that CBC with MLAs was presented. This method is a mixture of the combining geometry tiled and filled aperture. Therefore, the term mixed aperture is introduced. The single channels are placed side by side in the near field and in the far field a central combining element is placed. For the combining element a pair of well defined MLAs is used. In the present setup an input beam was split into $5 \times 5$ beams. Subsequently, these 25 beams were combined to a single beam with a combination efficiency of 90 %. Finally, it should be noted, that the presented method offers a simple scaling in terms of the number of combined channels, and, thus for energy and power scaling of a potential high power CBC platform.

Disclosures. The authors declare no conflicts of interest.

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