Design and alignment strategies of 4*f* systems used in the vectorial optical field generator

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In this paper, the design and alignment strategies of 4*f* systems used in the vectorial optical field generator are described in detail. Reflection-type 4*f* systems were adopted due to limited spacing. Alignment patterns are designed and introduced as alignment tools so that the optical property (degree of freedom) controlled by each specific spatial light modulator section can be visualized and alignment of the 4*f* systems can be performed using the CCD image sharpness as the metric. In particular, blurring due to diffraction effects is minimized when the 4*f* system is fully aligned.

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1. Introduction

The 4*f* system is a commonly used optical relay that usually consists of two positive lenses with the input plane located one focal length (f_1) in front of Lens 1 and the output plane located one focal length (f_2) after Lens 2. The magnification is found to be equal to $-f_2/f_1$. In particular, a one-to-one relay (−1 magnification) can be achieved if the two lenses have the same focal length ($f_1 = f_2$). Mathematically, the 4*f* system can be understood as a cascade of two Fourier transforms using two identical Fourier lenses:

$$\mathcal{F}\{\mathcal{F}\{g(x,y)\}\} = g(-x,-y).$$

In a well aligned, one-to-one 4*f* relay system, as shown in Fig. 1, the output field is an inverted replica of the input, as shown in the previous equation, thus eliminating any extra phase terms and minimizing diffraction effects. High-fidelity optical field reconstruction can be achieved between the object and image planes. 4*f* systems are widely used in various imaging systems for accurate reconstruction of the optical field [1–4] and Fourier plane filtering [5,6].

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2. Implementation of 4*f* Systems in a Vectorial Optical Field Generator

In one of our previous works [7], a vectorial optical field generator (VOF-Gen) capable of creating arbitrarily complex beam cross section was designed, built, and tested. Based on two reflective phase-only liquid crystal spatial light modulators (SLMs), this generator is capable of controlling the spatial distributions of all the parameters of an optical field, including the phase, amplitude, and polarization (ellipticity and orientation), on a pixel-by-pixel basis. In order to fully control these degrees of freedom in generating any vectorial optical field, four SLM sections that can be independently operated are required. As shown in Fig. 2, two phase-only SLMs (HOLOEYE 1080P) are used in the VOF-Gen system, and each of them is divided into two sections to take advantage of the SLM's large format and high resolution (HDTV, 1920 × 1080, pixel size 8 μm), where each of the SLM sections is responsible for the spatial

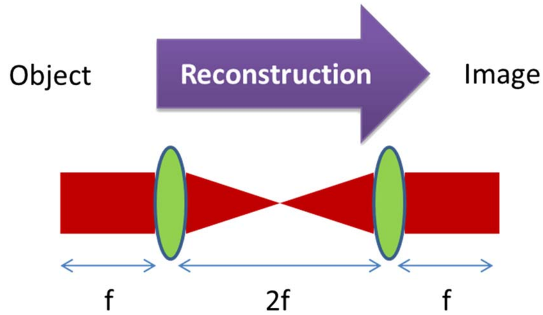

Fig. 1. One-to-one 4*f* optical relay system.

modulation of the optical field in phase, amplitude, polarization rotation, and retardation, respectively.

In order to minimize the diffraction effects and preserve the high-frequency components in the generated optical field, 4*f* systems are introduced to relay the optical field from one SLM section to the next. To ensure the sharpness of the optical field, longitudinal alignment needs to be performed to satisfy the 4*f* condition. Meanwhile, different SLM sections need to be laterally registered for pixel-by-pixel generation of the optical field. As a result, transverse alignment of the 4*f* system is also required.

Two different types of 4*f* system are adopted in the VOF-Gen design. Conventional 4*f* systems with two positive lenses (L) are used to relay the field from Section 2 to Section 3 and from Section 4 to the CCD camera, consisting of L2/L3 and L5/L6, respectively. To relay the optical field from Section 1 to Section 2 and from Section 3 to Section 4, a reflection-type lens/mirror 4*f* relay system was adopted, due to the proximity of the two SLM sections within one SLM panel (15.36 mm × 8.64 mm). Two 50/50 polarization beam splitters are used to direct the beam propagation, shown by the blue arrows in Fig. 2. An opaque blocker is placed between the two beam splitters to avoid cross talk due to direct propagation. A 2 in. (50 mm) diameter lens with 200 mm focal length is used to focus the beam, and a mirror is used to reflect the focused beam so that it will be recollimated by the same lens. In Fig. 2, the reflection-type lens/mirror 4*f* relay systems are shown as L1/M1 and L4/M2 for Section 1 to 2 and Section 3 to 4 relay, respectively. To relay the field to the adjacent SLM section in the same SLM, a small displacement is intentionally introduced between the beam and optic axis of the lens so that a spatial separation is present between the forward and backward propagating beams. The displacement needs to be aligned to center the reflected beam on the corresponding SLM section. A large-aperture lens with a longer focal length ensures that the aberration due to the decenter is kept minimal. Spatial filters SF1 and SF2 are placed at the Fourier plane and can be used for filtering out the high-spatial-frequency term.

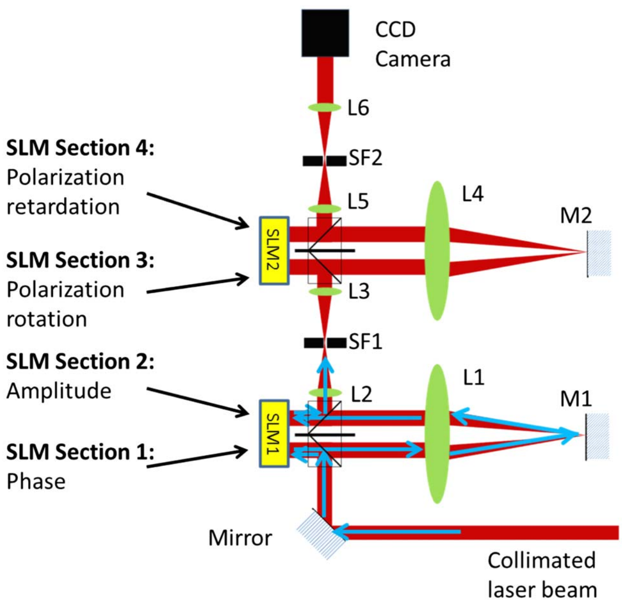

Fig. 2. 4*f* systems used in the VOF-Gen system.

3. Alignment Procedures of 4*f* Systems

A. Longitudinal Alignment

The longitudinal alignment of the 4*f* system involves longitudinal translation along the optical axis for the lens pairs in the conventional 4*f* system and the lens and mirror in the reflection-type 4*f* system. The longitudinal alignment is realized in the following two steps.

Due to the fact that the input beam is collimated in our system, a shearing interferometer was used as a collimation checker to align the 2*f* distance between the two lenses, as illustrated in Fig. 1. In our VOF-Gen system, this alignment step will determine the spacing between L2 and L3, L5 and L6 for the conventional 4*f* systems and the spacing between L1 and M1, L4 and M2 for the reflection-type 4*f* systems. Once the largest interference fringes off the shearing interferometer can be observed, the output beam is well collimated and the 2*f* distance can be precisely determined.

In order to align the rest of the 4*f* imaging systems, namely the *f* distance before the first lens and *f* distance after the second, a pattern with fine features was designed based on the concept of high-fidelity optical field reconstruction. The CCD camera was used to observe the pattern as a figure of merit for the alignment. Different optical fields were generated according to the functionality realized by the specific SLM section.

In our experiment, an alignment pattern of three pairs of horizontal and vertical crossing lines is generated with binary amplitude or orthogonal polarizations. The width of each line and spacing is designed to be 100 μm, shown in Fig. 3. This pattern is used in creating different optical fields with different degrees of freedom for the longitudinal alignment of the 4*f* system. Specifically, for the amplitude alignment step (SLM Section 2), the alignment pattern is designed with 100% transmission in the blue area and 0% in

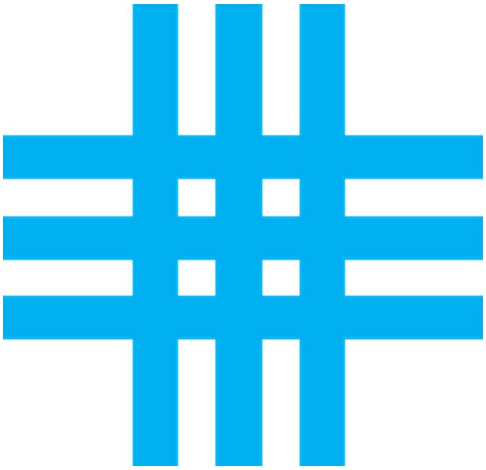

Fig. 3. Alignment pattern with fine features for $4f$ system alignment. Each line is 100 μm wide.

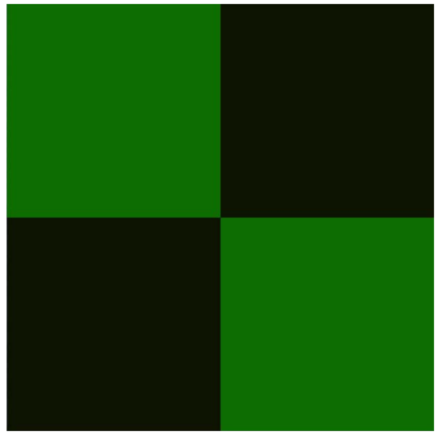

Fig. 5. Four-quadrant pattern for the transverse alignment.

the white area. Similarly, to align the polarization rotation (SLM Section 3) and retardation (SLM Section 4), alignment patterns are designed so that the blue/white areas are 45°/135° linearly polarized and right-hand circularly polarized (RCP)/left-hand circularly polarized (LCP), respectively.

The longitudinal alignment is performed in a sequential manner, as shown by the flow chart in Fig. 4. The first $4f$ system to be aligned is the one between the CCD and SLM Section 4, consisting of L5 and L6, where the retardation modulation is achieved. The RCP/LCP alignment pattern illustrated in Fig. 3 is loaded onto the VOF-Gen system. A circular polarizer is placed in front of the CCD camera, and only the blue pattern with RCP can be detected. The longitudinal distances in the $4f$ system are aligned by adjusting the micrometer on the translational stages so that the sharpness of the CCD image is maximized. At this point the first $4f$ relay system is fully aligned in the longitudinal direction. Then the alignment needs to be performed for each of the following $4f$ relay systems in a similar way. The blue area in the 45°/135° linear polarization alignment pattern is revealed using a linear polarizer along 45° to align the L4/M2 reflection-type $4f$ system. Lastly, the $4f$ relay system (L2/L3) from Section 2 to Section 3 with a binary amplitude alignment pattern can be directly recorded using the CCD camera, and the longitudinal distances can be determined by maximizing the sharpness of the CCD image. To align the $4f$ system between SLM Section 1 and Section 2, a phase alignment pattern is required. Even though phase cannot be directly recorded, a

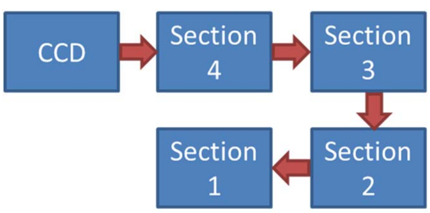

Fig. 4. Flow chart of the alignment procedure.

pattern with a π phase difference in the blue area can be used. Due to the undefined phase at the pattern boundary, it will appear as a dark line in the camera. This can be used as the longitudinal feedback for the $4f$ system between Sections 1 and 2.

B. Transverse Alignment

To align the $4f$ systems in the transverse (x, y) direction, four-quadrant alignment patterns (Fig. 5) with binary amplitude or orthogonal polarizations were introduced. Similar to the longitudinal alignment strategy, the x and y translations of the lenses in the $4f$ systems are adjusted so that the centers of the four-quadrant CCD images overlay the center of the input Gaussian beam for realizing different functionalities. Further transverse alignment of the $4f$ systems involves overlaying the patterns in different SLM sections. This is achieved by displaying this four-quadrant pattern for all SLM sections simultaneously. Due to the abrupt phase change in the SLM phase pattern, the boundary can be observed in the CCD camera. Fine alignment of the $4f$ systems can be performed so that the "cross" patterns are overlaid.

4. Results and Discussion

As an example, the results of the $4f$ system longitudinal alignment in Sections 2, 3, and 4 are shown in Figs. 6(a), 6(b), and 6(c), respectively.

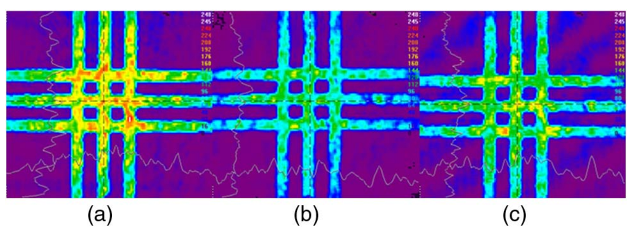

Fig. 6. Alignment results for (a) amplitude modulation: the intensity is directly captured by the CCD camera; (b) polarization rotation: the intensity is captured after a linear polarizer; (c) retardation: the intensity is captured after a circular analyzer. In all cases, the rectangular dark areas of 100 μm × 100 μm are visible, with fairly sharp edges. This shows that the $4f$ relay systems are well aligned and the blurring due to the diffraction effect is minimized through the VOF-Gen from the input plane to the CCD camera.

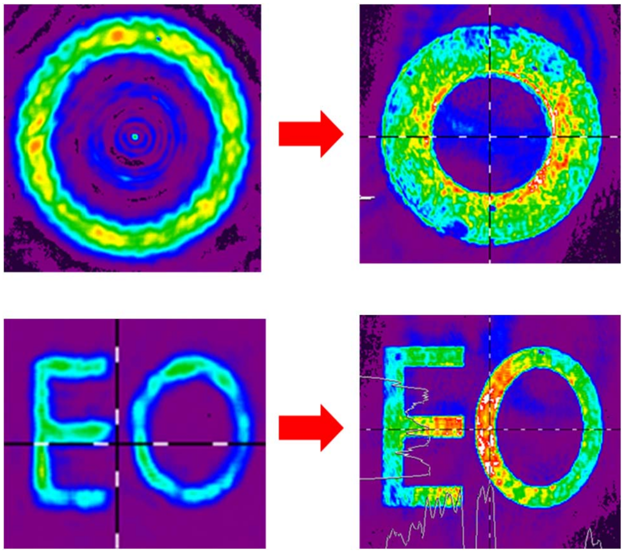

Fig. 7. Comparison of the same patterns generated by the VOF-Gen system without (left) and with (right) well-aligned $4f$ systems.

Ring and "EO" logo patterns are generated by the VOF-Gen system without and with well-aligned $4f$ systems, as shown in the left and right parts of Fig. 7, respectively. As we can see, without the well-aligned $4f$ system, the field captured by the CCD camera is blurred and smeared out, and the high frequencies are not preserved. This is an indication of diffraction blurring. With well-aligned $4f$ systems, the diffraction effects have been minimized and sharp edges are observed due to the perfect optical field reconstruction from the $4f$ systems.

5. Conclusions

The design and alignment strategies of the $4f$ systems used in the VOF-Gen were described. A reflection-type $4f$ relay system was adopted due to limited space. The alignment procedure was presented in detail. Alignment patterns were designed as alignment tools for $4f$ systems so that the degree of freedom to be realized in the specific SLM section could be visualized by the user using a CCD camera. In particular, the $4f$ imaging system's longitudinal alignment could be determined by adjusting the distances to obtain optimal sharpness, where the diffraction blurring effect was minimized.

Further improvement can be made so that rather than observing the sharpness of the CCD images, a computer algorithm can be developed to numerically evaluate the sharpness through standard deviation or differential calculation. Implementing this calculation in a computer script will ensure quantitative feedback that is more consistent and objective.

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