Real-time holographic backlighting positioning sensor for enhanced power coupling efficiency into selective launches in multimode fiber

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This paper presents a qualitative, real-time backlighting positioning sensor for the alignment of an optical beam to a minutely deviated diffraction order axis to increase the power coupling efficiency into a multimode fiber in selective launches. Results show that the technique facilitates the alignment of the lenses to the first diffraction order axis and improves the power coupling efficiency into a multimode fiber.

Keywords: selective launches; multimode fiber; power coupling; optical fiber sensor; measurement; feedback; spatial light modulator

1. Introduction

In many modern optical assemblies, precision in the alignment of the position and direction of an optical beam through each component is critical for optimizing power coupling efficiency. Typical optical alignment technologies include gratings [1], interferometric sensors [2], aberration sensors [3], piezoelectric micrometers stages [4], photolithographically etched grooves [5] and ceramic or metallic ferrules [6].

In multimode fibers, power coupling efficiency is confounded by microbends, vibrations, manufacturing defects in the refractive index profile and fiber geometry, which give rise to time-varying power modal coupling and modal dispersion fluctuations [7,8]. In view of the random nature of the channel, it is difficult to constrain a static filter at the transmitter capable of compensating the random modal fluctuations. To address this, adaptive holographic techniques using spatial light modulators (SLMs) have been proposed [9–16]. For efficient optical alignment, the SLM in these systems may be used to create several reference wave fronts to specific positions or angles for aligning different degrees of freedom and for the projection of focused reference points to facilitate optical alignment [17,18]. Here, this idea is extended further by the novel incorporation of backlighting for real-time qualitative observation of the responses in the change of the position and tilt of optics so that appropriate remedial measures may be identified. The backlighting may be used as an alternative to a single-photon avalanche diode (SPAD) photodetector array, as used in [18] in conjunction with an SLM for providing feedback mechanism in the alignment process. For successful fabrication of small-scale commercial optical applications, affordable high-accuracy alignment solutions are necessary. The dual functionality of the SLM in the proposed technique provides a cost-effective optical alignment solution for holographic selective launches into a multimode fiber.

The paper proceeds as follows. Section 2 discusses the pre-alignment steps in the backlighting technique for aligning lenses to the zeroth diffraction order axis. Section 3 then elucidates the step-by-step alignment of lenses to the first diffraction order path in the backlighting technique and presents snapshots of the alignment process. Finally, Section 4 discusses the power coupling efficiency measurement from the new backlighting technique.

2. Construction of holographic backlighting positioning sensor

A cage system was constructed to provide a compact and precise mounting assembly for the backlighting positioning sensor, as shown in Figures 1 and 2. Three lenses and pinhole were positioned concentrically in individual z-translation stages within the cage system, mounted on a translation stage, goniometer and rotation stage. The goniometer and rotation stage respectively provide pitch and yaw movements for the cage system, as illustrated in Figure 2. The point of
Figure 1. Experimental setup containing cage system which consists of pinhole, second lens and fiber collimator mounted on goniometer, rotation stage and translation stage. Directions of rotations provided by goniometer and rotation stage are indicated. (The color version of this figure is included in the online version of the journal.)

Figure 2. Construction of cage system for backlighting. (The color version of this figure is included in the online version of the journal.)
rotation for both tilt and pitch movement was carefully
set to the center of the pinhole.

The pitch and yaw of all lenses were first precisely
aligned to the zeroth diffraction order. A 128 × 128
pixel transmissive binary amplitude SLM was posi-
tioned at the center of the collimated beam from the
beam expander. L1 was positioned at a distance equal
to its front focal length from the SLM. To align L1, a
mirror, placed in the kinematic mount for L1, was
used. The pitch and yaw of the mirror was adjusted
until the back reflection from the mirror coincided with
the transmitted pattern from the SLM. The mirror was
then removed and L1 was reinserted into its kinematic
mount, without altering the pitch and yaw. L1 was
then moved gradually in the x-y positions, while
maintaining the pitch and yaw, until the collimated
beam converged to the same optical axis as the SLM,
in the back focal plane of L1. A mirror was used as an
aid to align the tilt and the position of the entire cage
system to L1. The pinhole, in the first z-translation
stage, was replaced by a mirror which is used as an
alignment aid.

In order to match the tilt of the cage system to the
tilt of L1, the following steps were taken. The SLM was
switched off so that any part of the collimated
expanded beam which passed through the active area
was transmitted. The back reflection from the mirror in
the pinhole mount was observed, while gradually
altering the pitch and yaw of the cage, until it coincided
with the main beam immediately after L1. In this
manner, the pitch and yaw of the cage system were
matched to the pitch and yaw of L1.

To position the pinhole exactly at the back focal
length of L1, the SLM was returned to its position and
the binarized Fourier transform hologram of the LP_{01}
mode was placed on the SLM. The mirror in the first
z-translation stage in the cage system, was moved in
the z direction until the size of its back reflected beam
was the same as the main beam after L1. The
mirror was then removed, and replaced by the pinhole.
Hence, in this manner, the pinhole would be located
exactly at the back focal point of L1.

Then, without altering its pitch and yaw, the entire
cage system was moved in the x and y position so that
pinhole was exactly at the first diffraction order

3. Experiment for aligning optical beam to
diffracted axis

The experimental setup for aligning an optical beam
passing through a pinhole, L2 and L3 to the first
diffraction order axis is shown in Figure 3. A 1 km
graded-index multimode fiber was placed in the back
focal plane of L3. A bright white light source was
propagated from the output endface to the input
endface of the multimode fiber. The position of the
white light source and its direction of propagation are
shown in Figure 3. The fiber core was assumed to be
completely filled by the white light. Also, it is known
that the cladding of the multimode fiber more absorb-
ing than its core. To ensure that L2 was positioned at a
distance exactly equal to its front focal length away from
the pinhole, L2 was moved in the z position until
the focus point of the backpropagated white light was
exactly at the pinhole.

Having positioned the pinhole, L2 and L3 along the
same axis within the cage system, as described in
Section 2, the entire cage system was further tilted so
that it was aligned to the axis of the first diffraction
order of L1. The steps for aligning the cage system to

![Figure 3. Experimental setup for backlighting to align the cage system to the axis of the first diffraction order from Fourier plane of L1. (The color version of this figure is included in the online version of the journal.)](image)
the axis of the first diffraction order are as follows. The complex field of the Fourier transform of the transverse modal field of a MMF is given by [19]:

\[ \Psi = \mathcal{F} \left( R L_{m-1}^i(V R^2) \exp \left( -\frac{V R^2}{2} \cos(\phi) \right) \right), \]

(1)

where \( \mathcal{F} \) is the Fourier transform operator, \( L_{m-1}^i \) is the generalized Laguerre polynomial, \( R \) is the radius of the fiber core, \( V \) is the normalized frequency, \( l \) is the azimuthal mode number, \( m \) is the radial mode number and \( \phi \) is the azimuthal angle of the fiber core. The complex field is then binarized according to the mapping given by [20]:

\[ u^2 + \left( v + \frac{1}{2} \right)^2 \leq \frac{1}{4}, \quad u \leq 0, \]

(2)

where \( u \) is the real part of the complex field and \( v \) is the imaginary part of the complex field.

The binarized field was displayed on the SLM and used as a projection point for the alignment process. Using the center of the pinhole as the point of rotation, the entire cage system was then tilted in both pitch and yaw movements while preserving the \( x \) and \( y \) positions, such that the backpropagated white light coincided with the red first diffraction order pattern. A beamsplitter was used to direct the light reflected from the fiber input endface to a color video camera, as shown in Figure 3. The beamsplitter was placed in back focal plane of \( L2 \) as this was the closest position to the front endface of the multimode fiber possible during the launching of the generated modal field into the multimode fiber. \( L3 \) and the input endface of the multimode fiber were securely enclosed in a fiber collimator so that they were concentric and the distance between them is precisely the focal length of \( L3 \) [21].

The superposition of the reflected red laser beam from the fiber endface and the backpropagated white light was observed on the color video camera. Media 1 (see online supplementary material) is an example of real-time output from a video camera during the alignment of lenses in a cage system to the first diffraction order axis in a selective launch into a multimode fiber. Single-frame excerpts from video recordings from Media 1 are shown in Figure 4. In Media 1 and Figures 4–6, the white circle is the backpropagated white light and the red pattern inside the white circle is the reflected generated modal field from the input endface of the multimode fiber. The modal field at the input endface of the fiber was generated by taking the Fourier transform of the binarized first harmonic of the Fourier transform of the theoretical modal field a weakly-guiding infinite parabolic multimode fiber, isolating the first diffraction order and then taking the second Fourier transform using \( L2 \) [22]. The intensity of the red light on the CCD increased with the power reflected from the front endface of the multimode fiber. The size and shape fluctuations of the red modal field pattern in the movie were caused by the fine movements of the goniometer and rotation stages through the adaptive alignment process. The movement of the white circle in Media 1 was caused by the movement and tilt of the cage system in response to the feedback from the intensity and direction of the red pattern within the white circle in the output from the video camera. The effect of each corrective measure was then observed via the superposition of the red and white light from the output of the video camera in real-time. The cycle was repeated until the generated modal field was accurately aligned to first diffraction order axis.

In Figure 4 and Media 1, the red modal field pattern impinged the white circle on the left (Figure 4(a)–(c)). This indicated that the generated modal field impinged to the left of the multimode fiber core and remedial measures to move the generated modal field towards the right were taken (Figure 4(d)–(f)). The remedial measures were made by adaptively adjusting the \( x \), \( y \) and \( z \) translation stage of the cage system to direct the generated modal field back to the center of the core. The opposite direction was taken when the red modal field pattern within the white circle moved towards the right, as observed in Figure 5.

In addition, when the red modal field pattern expanded, as in Figure 6, or contracted, this indicated that the generated modal field impinged the multimode fiber core at an oblique angle and remedial measures were required to tilt the generated modal field so that it was incident at the input endface of the multimode fiber core at a normal angle. This was achieved by adaptively adjusting the goniometer of the cage system to adjust the incident angle of the generated modal field with respect to the input endface of the multimode fiber.

Through the adaptive corrective measures, on average, the intensity of the red modal field decreased. The fluctuations were due to remedial action taken in response to the immediate feedback received from the superposition of red modal field pattern and white circle observed from the output of the video camera. Based on the real-time observation of the superposition of the red modal field pattern and white circle, the \( x \), \( y \) and \( z \) position of the cage system was adaptively adjusted using the translation stages whilst the tilt and yaw of the cage system were adaptively adjusted using the goniometer so that the red modal pattern gradually faded. Towards the end of each experiment, the red modal pattern gradually faded and disappeared, as observed in Figure 4(f), Figure 5(f) and Figure 6(f). For each experiment at this position and orientation, the reflected red light from the input endface of the
multimode fiber was minimized. This indicated that the maximum input electric field had been coupled into the multimode fiber. Thus, at this position and angle, the entire cage system was accurately aligned to the axis of the first diffraction order axis of $f$. The resolution of the sensor is 0.05 μm for linear displacements and 0.05° for angular deviations.

4. Power coupling efficiency improvement using backlighting alignment technique

To evaluate each corrective measure taken based on the superposition of the red modal field pattern and white circle in the backlighting technique, the amplitude and phase of the generated modal field at each pixel was measured and electric field of the generated mode, $E_{in}$, was calculated. The power coupling efficiency was evaluated using:

$$
\eta_{in} = \frac{\int_{A_{core}} E_{in}(x,y) E_{in}^*(x,y) \, dx \, dy}{\int_{A_{core}} |E_{in}(x,y)|^2 \, dx \, dy} \frac{\int_{A_{core}} |e_{im}(x,y)|^2 \, dx \, dy}{\int_{A_{core}} |e_{in}(x,y)|^2 \, dx \, dy},
$$

where $E_{in}$ is the polarized generated modal field and $e_{im}$ is the polarized transverse electric field for $LP_{im}$ of a
weakly guiding multimode fiber having an infinite parabolic refractive index. $LP_{lm}$ modes within range of azimuthal mode numbers $l = 0, 1, \ldots, 4$ and radial mode number $m = 1, 2, 3, 4$ were excited. The values of the power coupling efficiency into the desired mode before and after the backlighting alignment techniques are given in Table 1. For each experiment, the initial setting for the size of the binarized modal field on the SLM was different, resulting in different pre-backlighting power coupling efficiency values for each experiment. The change in the size of the binarized modal field on the SLM influences the size of the generated modal field. Different sizes of binarized modal fields were used in the experiments as it is known that without backlighting, the size of the generated modal field affects the power coupling efficiency. Thus, various sizes of the binarized modal field are used in order to determine the effect of the size of the binarized field on the improvement in the power coupling efficiency with backlighting. It is observed that the power coupling efficiency improvement due to backlighting generally increases as the binarized modal field is reduced from 9.5 mm to 8.5 mm. The percentage increase in the power coupling efficiency into the

Figure 5. Single-frame excerpts from real-time video recording of superposition of reflected red helium–neon laser beam from the fiber endface and backpropagated white light when generated first diffraction order impinged on the right of multimode fiber core during alignment of lenses in a cage system to first diffraction order axis in a selective launch into a multimode fiber. (The color version of this figure is included in the online version of the journal.)
Figure 6. Single-frame excerpts from real-time video recording of superposition of reflected red laser beam from the fiber endface and backpropagated white light when generated first diffraction order impinged the multimode fiber core at an oblique angle during alignment of lenses in a cage system to first diffraction order axis in a selective launch into a multimode fiber. (The color version of this figure is included in the online version of the journal.)

desired mode is 5% to 20%. This demonstrates that the backlighting positioning sensor facilitates the alignment of an optical beam to a diffracted axis and improves power coupling for selective launches in a multimode fiber.

A photodetector array was used for comparison of the power coupling efficiency against the backlighting positioning sensor. It was found that the percentage increase in the power coupling efficiency before and after the use of the photodetector array was between 5% and 12% within the same range of binarized modal field sizes. This is due to the difficulty in determining the source of misalignment in the \( x, y, z \) positions and the angles (tilt, yaw, pitch). With the backlighting positioning sensor, the size and shape of the red modal field pattern indicate the current position and angle, while the movement of the white circle provides the response of the motion undertaken previously. Thus, it is easy to predict the most appropriate subsequent step to improve the power coupling efficiency.
5. Conclusions

A simple qualitative real-time backlighting positioning sensor for the alignment of an optical beam to a diffraction order axis was demonstrated. The backlighting positioning sensor was applied to a holographic selective launch into a multimode fiber. Results obtained demonstrate that the new backlighting positioning sensor is capable of improving the power coupling efficiency for selective launches in multimode fiber. The low fabrication cost and simplicity in the design makes the holographic backlighting positioning sensor practical for tracking rapidly moving objects in real-field applications.

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References