Hologram-based architecture for fan-in coupling in four-core fibers

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Abstract—This study presents a fan-in coupler architecture for a four-core fiber, implemented using a single diffractive optical element (DOE). The DOE selectively excites two opposite cores while the remaining ones serve as receiving channels. The DOE was designed using an iterative algorithm, resulting in a computer-generated hologram and fabricated using two-photon polymerization (TPP). Numerical simulations and experimental measurements confirmed correct operation of the concept. The proposed coupler shows strong potential for applications in fiber-optic sensing and optical communications.

The development of modern fiber-optic technologies requires functional and application-tailored couplers, especially those dedicated to multicore fibers (MCFs) [1]. One of the promising approaches involves fan-in/fan-out couplers implemented using a single diffractive optical element (DOE) [2, 3]. In such implementation, a DOE is placed on the MCF facet and is responsible for appropriately bending of the incident wavefront so as to excite the selected fiber cores.

Diffractive optics enable arbitrary wavefront shaping. Appropriately designed structures can generate, for instance, Airy beams [4], optical vortices [5], or tailored intensity profiles featuring multiple focal spots [6]. More advanced DOE functionalities are typically designed using iterative algorithms [7, 8] or methods employing neural-network-based optimization [9]. When a continuous phase-only encoding is used in the design stage, DOEs can theoretically achieve diffraction efficiencies approaching 100%, meaning that the entire incident optical power is redistributed into the desired intensity distribution behind the element [10]. In practice, however, the efficiency is limited by Fresnel reflections at elements interfaces, material absorption, shadow effects [11], and other technological or geometrical factors.

State-of-the-art 3D micro- and nano-printing technologies, in particular two-photon polymerization (TPP), enable the fabrication of DOEs on fiber facets with a resolution approaching 100 nm [12]. This allows precise fabrication of structures operating in both the near-infrared radiation range and visible spectral range [13]. Two fabrication strategies are commonly used: direct printing of DOEs on the fiber facet [14], or printing a DOE on a dedicated alignment scaffold [15] that provides the required axial distance and rotational alignment relative to the MCF core layout.

This study presents a hologram-based DOE architecture that can be used as fan-in coupling in MCFs, suitable for fabrication on the fiber facet. The hologram is designed to excite two opposite fiber cores simultaneously, while the remaining two cores act as receiving channels. Such a configuration is particularly attractive for fiber-optic sensing and optical communications. The fan-in coupler proposed in this study was designed based on the Fibercore SM-4C1500 (8.0/125)/001 multicore fiber featuring a square core arrangement with a core-to-core spacing of 50 µm. This study was motivated by DOEs originally developed for THz radiation (de)multiplexing [7, 16]. The structures presented in previous THz-range studies served different purposes and operated on different principles; in this study, only a similar design methodology was adopted and applied to a new structure operating in the visible radiation range.

To implement the proposed concept, the DOE was generated using a modified algorithm derived from the Gerchberg–Saxton method, resulting in a computer-generated hologram [8, 9]. The obtained phase distribution was encoded as a grayscale map, where pixel values in the range 0–255 correspond to the phase delay introduced by the element in the range from 0 to 2π. The designed structure has a focal length of 400 µm and a diameter of 150 µm, and wavelength of 655 nm. The structure was designed for illumination with a Gaussian beam emitted from a single-mode fiber. The phase map of the DOE is shown in Fig. 1.

Subsequently, numerical simulations were performed using the LS 6.0 software based on a modified convolution method [17]. The structure was illuminated with a Gaussian beam, and the resulting intensity distribution was analyzed at a propagation distance of 400 µm. The obtained intensity distribution is presented in Fig. 2, where the positions of the fiber cores and cladding are marked in white.

The numerical simulation results confirm that the structure operates as intended and fulfils the designed functionality. The DOE redirects the incident radiation into two focal spots whose positions coincide precisely with the two opposite cores of the four-core fiber. It is important to emphasize that no residual signal was observed either in

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the cladding region or in the remaining two cores, indicating high efficiency of the DOE and, consequently, high coupling effectiveness.

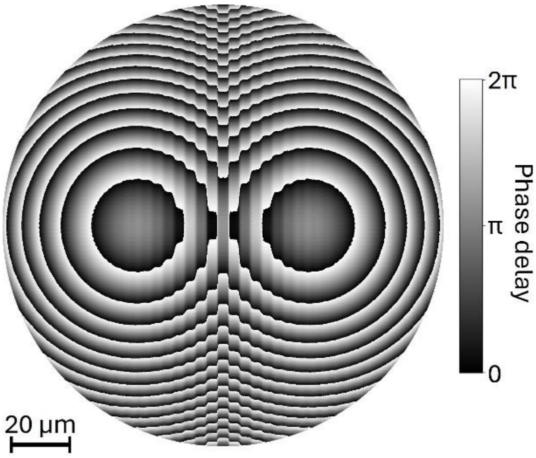

Fig. 1. Phase map of the structure implementing the fan-in coupler designed to excite two opposite cores of the four-core fiber.

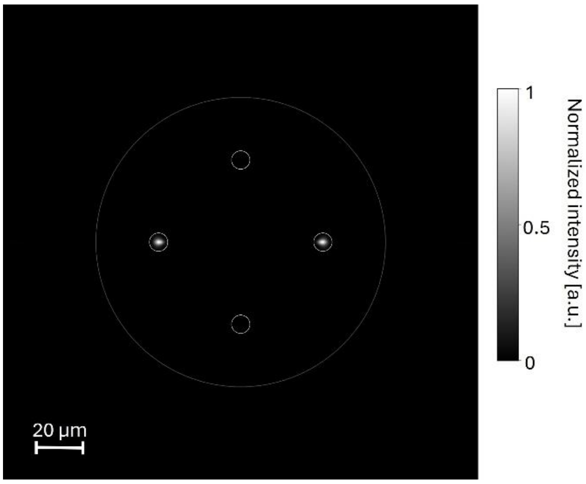

Fig. 2. Numerical simulation results showing the intensity distribution at the facet of the four-core fiber. The positions of the cores and the cladding are marked in white.

Based on the obtained phase map (shown in Fig. 1), a 3D model of the structure was generated. Each pixel, represented by a specific grayscale value, was extruded to the corresponding height according to Eq. (1). In this way, the fabricated structure introduces the desired phase delay and, consequently, redirects the incident radiation in the designed manner:

$$h(x,y) = \frac{\phi(x,y)}{2\pi} \cdot \frac{\lambda}{n - n_0}, \tag{1}$$

where $h(x,y)$ denotes the local height of the structure responsible for the phase delay $\phi(x,y)$, λ is the operating wavelength, n is the refractive index of the DOE material, and n_0 is the refractive index of the surrounding medium (typically $n_0 = 1$ for air).

The DOE was fabricated using TPP with the Photonic Professional GT2 system (Nanoscribe GmbH) employing the IP-Dip2 photoresist (n = 1.55 at 655 nm wavelength). The structure was printed with a vertical and lateral resolution of 200 nm. The spatial model was discretized into 6 phase levels, providing high diffraction efficiency above 91%. Additionally, a 400 nm thick substrate layer and a 5 µm width frame were incorporated into the design to ensure printing stability. A microscope image of the fabricated structure on a flat silica substrate is shown in Fig. 3.

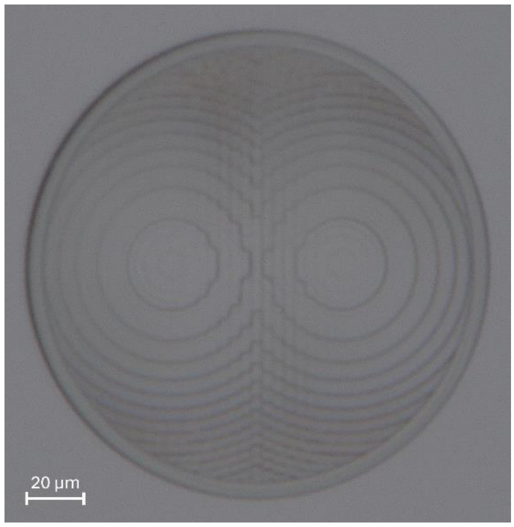

Fig. 3. Microscopic image of the structure fabricated using two-photon polymerization (TPP) on a flat silica substrate.

The proposed solution was subsequently verified experimentally. The measurements were performed illuminating structure with 655 nm wavelength radiation emitted from a single-mode fiber. The obtained results, presented as the transverse intensity distribution recorded at an approximate distance of 67 mm behind the structure, are shown in Fig. 4. As the observation distance increases beyond the focal plane, the image of the focal spots appear enlarged; therefore, the intensity distribution in Fig. 4 is presented using angular coordinates. The positions of the four fiber cores are marked in white. The inset in Fig. 4 shows the phase map of the fabricated structure.

The experimental results presented in Fig. 4 clearly confirm the correct operation of the proposed concept. They are fully consistent with the numerical simulation results shown in Fig. 2. The structure successfully redirected the incident radiation into two focal spots whose positions correspond precisely to the cores of the four-core fiber. No significant residual signal was observed in the analyzed intensity distribution, indicating the absence of undesired power leakage and confirming proper beam redirection. It should be noted, however, that approximately 9% of the optical power was redirected into higher diffraction orders, which was not recorded during the measurements presented in Fig. 5. This effect results from the limited resolution achievable with the TPP fabrication method used in this study. For structures designed for optical communication applications at a wavelength of 1550 nm, the phase profile could be quantized into 15 levels, ensuring a diffraction efficiency of approximately 99%.

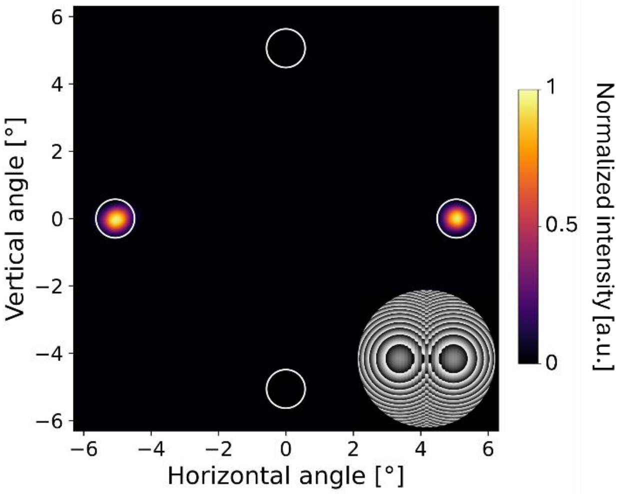

Fig. 4. Intensity distribution recorded at an approximate distance of 67 mm behind the structure, with the positions of the fiber cores marked in white. The inset shows the phase map of the verified structure.

In conclusion, this study demonstrates a fan-in coupler that can be used in a four-core optical fiber (once redesigning to the target wavelength), implemented through a single hologram-based DOE designed using an iterative algorithm. The element enables selective excitation of two opposite fiber cores, while the remaining cores may function as receiving channels. Numerical simulations, supported by experimental validation, confirm the proper operation and robustness of the proposed concept. The structure presented in this study can be fabricated directly on the facet of a multicore fiber. This approach enables the realization of a fully functional, fiber-integrated fan-in coupler. Moreover, the proposed approach can be extended to wavelengths other than 655 nm considered in this study. In addition, DOEs designed in this manner can be used to excite any desired combination of MCF cores.

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