INTEGRATED FIBER-BASED TRANSVERSE MODE CONVERTER

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Abstract

A transverse mode converter based on a binary microrelief implemented directly on the end-face of a few-mode fiber was numerically investigated. The results of numerical simulation demonstrated the converter to form LP-11 and LP-21 modes with high efficiency, providing a more-than 92 % mode purity. Transformations of modes excited by a fiber microbending were also numerically investigated. The excited beams were shown to save their mode purity even in a strong bending as the arising parasitical modes were mostly unguided by the fiber. The resulting beam power and mode content were also demonstrated to depend on the beam and bending mutual orientation for beams with strong rotational symmetry.

Keywords: transverse mode, binary microrelief, few-mode fiber, diffractive optical element.

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Introduction

The highly efficient fiber transverse mode conversion is an actual task for many practical applications [1 – 6]. In [2, 3] it was suggested to use diffractive optical elements (DOEs) for mode conversion and excitation in graded-index fiber. The use of DOEs for optical waveguide radiation control is considered also in [7, 8].

Later the same approach was used for excitation of selected mode in a few-mode step-index fiber [4, 9]. However, use of a separated DOE (phase or amplitude one) with transmission function calculated via amplitude-phase coding methods [2, 3] for selected fiber mode forming leads to energy losses due to appearing of parasitical diffractive orders. Use of a separated phase binary DOE [4, 9] does not allow forming selected modal distribution with required purity due to neglecting mode amplitude distribution.

Another disadvantage of fiber mode excitation by DOEs lies in necessity of DOE adjustments regarding fiber optical axis [2 – 4]. In [10] it was suggested to control the angle of incidence of launching beam for selective excitation of coupled modes in a homogeneous coupled multi-core fiber. The approach [10] also requires complicated adjustment procedure.

The realization of micro relief directly on the end face of fiber is considered, for example, in [11]. The present paper is devoted to investigation of integrated fiber-based mode converter based on binary diffractive microrelief implemented directly on an end-face of few-mode step-index fiber. The few-mode fiber acts as a "filter" of unguided modes and therefore there is no need to use amplitude-phase coding [2, 3] to increase purity of the mode.

1. Investigation of mode excitation using binary on-fiber microrelief

The height function $h(x, y)$ for binary microrelief can be obtained from the diffractive element phase function $\phi(x, y)$ using the following formula [3]:

$$h(x,y)=\frac{\phi(x,y)\lambda}{2\pi(n_{core}-1)}, \qquad (1)$$

where λ is the wavelength, n_{core} is the refractive index of fiber core. The formula is applicable if refractive index of the cladding does not differ significantly from the one of the core.

To check these assumptions and to explore beam propagation in fiber a numerical simulations using beam propagation method [12, 13] was made. Parameters of Corning Glass SMF-28 fiber were used ($n_{core} = 1.4619$, $n_{cladding} = 1.457$, core diameter $d = 8.3$ μm). For the wavelength $\lambda = 0.63$ μm this fiber acts as a few-mode one. To cover fiber core the calculation window was a square with 16.6μm side, discretization step was 0.2λ.

The selective excitation of modes LP-11 and LP-21 was investigated. Their excitation requires phase functions, which are represented in Fig. 1*a*, *b* (white stands for 0 and black stands for π). Using Eq. (1) one can obtain corresponding microreliefs, which are schematically shown in Fig. 1*c*, *d*.

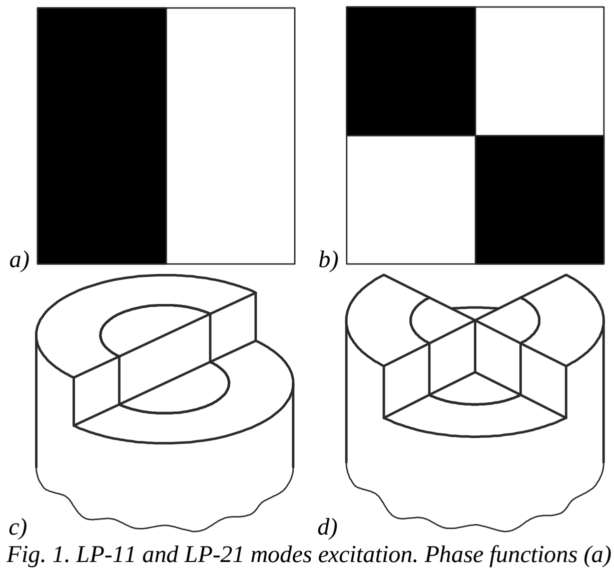

Fig. 1. LP-11 and LP-21 modes excitation. Phase functions (a) and (b) were implemented as microreliefs (c) and (d)

In the first simulation fiber end was illuminated by Gaussian beam (with its waist conformed to the LP-01 mode of the fiber). Propagation was simulated for the distance of 5 mm. Resulting beam amplitude distributions and beam phase distributions are shown in Fig. 2.

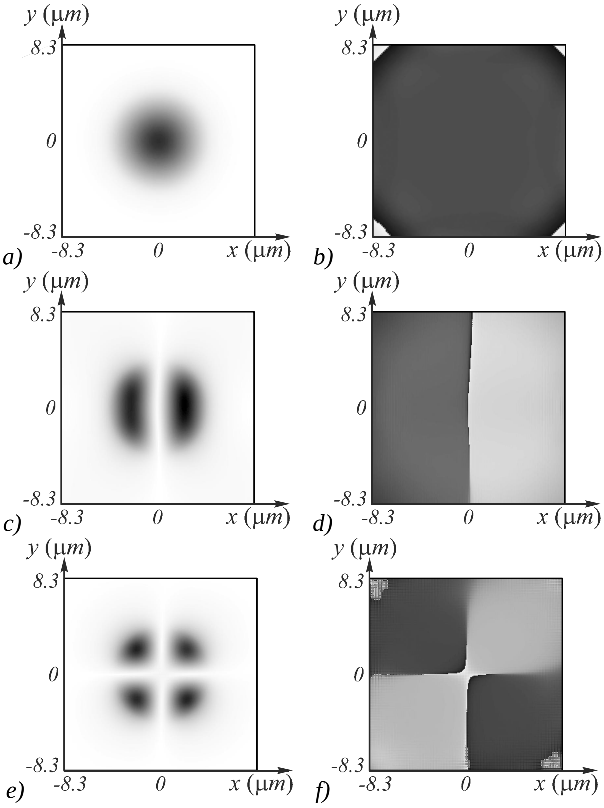

Fig. 2. LP-01, LP-11 and LP-21 modes excitation with Gaussian beam. Cross-section amplitude distributions (a), (c) and (e) and phase distributions (b), (d) and (f) are formed using no microrelief, and microreliefs shown in Fig. 1 (c) and (d), respectively

The amplitude and phase distributions looked promising, but it is essential to know how fast beam becomes stable and how much energy is carried by the beam and the excited mode. Fig. 3 shows dependencies of beam power in the fiber core on propagation distance from fiber's end for modes LP-11 and LP-21 (obviously, there is no reason to investigate such a dependence for the LP-01 mode in case of excitation using conformed Gaussian beam).

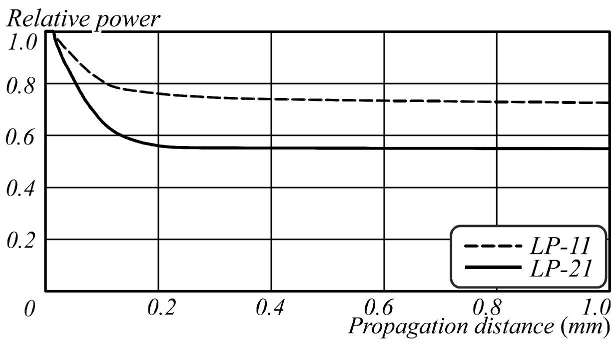

Fig. 3. Beam power in the fiber core depending on propagation distance for LP-11 (upper line) and LP-21 (lower line)

Stabilization distances were found to be approximately 0.45 mm for LP-11 and 0.25 mm for LP-21. Beam powers were approximately 73 % and 55 % of initial powers, and about 92.5 % and 93.5 % of power were carried by the desired modes, respectively.

So, excitation effectiveness was sufficient and most of the beam power was carried by desired modes. Moreover, incoming beam was transformed into the mode on a very short distance (less than 1 mm). It can be explained by the following. Right after diffractive microrelief a beam is a combination of guided fiber modes (with some powers) and some unguided modes, which leave the fiber. Consequently, fiber fragment located behind a microrelief acts as an effective cut-off filter.

The second simulation was made to investigate modes excitation using different source of light. Semiconductor diodes are one of popular sources of coherent beams. They produce beams with complicated enough wavefronts, but using collimators one can obtain a beam with a wavefront close enough to a planar wave. Also, as core diameter of the fiber in study is small, one can assume that that in fiber core region a beam distribution is very close to a constant one. So, the following results represent illumination of fiber end by a planar wave (with other simulation parameters being the same as in the previous simulation). Resulting beam amplitude distributions and beam phase distributions are shown in Fig. 4.

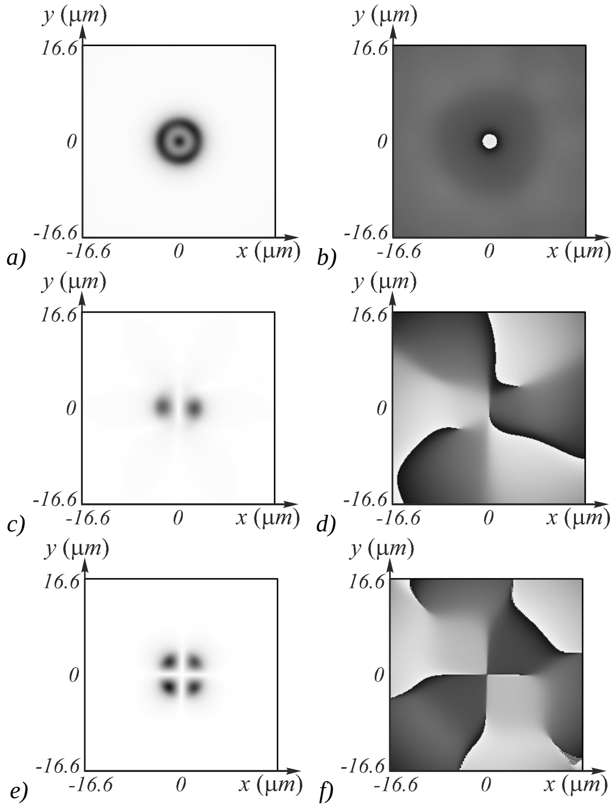

Fig. 4. LP-01, LP-11 and LP-21 modes excitation with Gaussian beam. Cross-section amplitude distributions (a), (c) and (e) and phase distributions (b), (d) and (f) are formed using no microrelief, and microreliefs shown in Fig. 1 (c) and (d), respectively

Obviously, results differ from previous ones (especially it can be seen for the LP-01 mode). In the same way it is essential to know how fast modes stabilize and what percent of power is carried by desired modes. Fig. 5

shows dependencies of beam power in the fiber core on propagation distance from fiber's end for three modes.

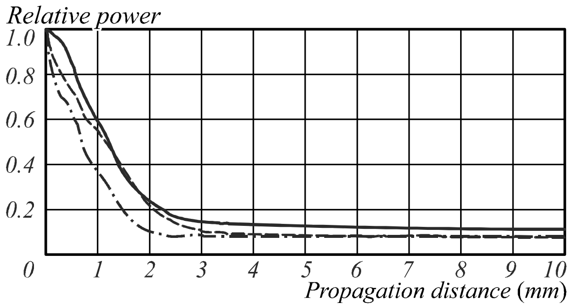

Fig. 5. Beam power in the fiber core depending on propagation distance forLP-01 (upper line), LP-11 (middle line) and LP-21 (lower line)

The first significant difference is that power outcome is much lower in comparison to the case of illumination by Gaussian beam. Beam powers were approximately 12 %, 8 % and 8 % of initial powers. But it is explained easily by initial distribution, which carries most of the power in the cladding area, so this part of the beam just leaves the fiber.

The second important result is that the distance, required for beam stabilization, is much longer (about 4 mm against 0.5 mm in the previous simulation). The reason for this is that planar wave creates more parasitical unguided modes and also transfers some power to cladding, so longer distance is required to filter all this unguided powers out.

The third essential point is that mode content is obviously different even for stabilized beams (see, e.g. Fig. 4*a*). About 49.3 %, 71.8 % and 93.8 % of power were carried by the LP-01, LP-11 and LP-21 modes, respectively.

So, planar waves also can be used to excite higher modes, but stabilization distance is longer and the higher is the mode the better it can be excited using a planar wave. Fiber fragment located behind a microrelief still acts as an effective cut-off filter, but there is more to cut-off.

2. Investigation of modes transformation in fiber bending

It is known that making distortions to a fiber affects the guided beam power and its mode content (for multimode fibers) [2, 3]. From this point it is interesting to know how higher modes survive and preserve their purity in such distortions. Here one simple but revealing distortion, namely fiber bending, was studied.

For demonstration the case was simulated, where fiber lies on two supports with 1 mm between them and the bending occurs due to a force applied to the fiber straight between the supports (yet we did not take photoelasticity effects into account).

When a beam consists of the main mode mostly, it is obvious that some power will leave the fiber and some power will transfer to higher modes (see Fig. 6). But if a beam itself is a higher mode, an outcome is more complicated.

When the LP-01 mode propagates through a fiber bending it has no sense to take the mutual orientation of the mode and bending direction into account (as the mode has radial symmetry). But as the LP-11 mode has a strong rotational symmetry, its mutual orientation with bending direction can be essential. Two contrary orientations were simulated. In the first one (orientation one) the mode symmetry axis lied in the same plane as the bended fiber, in the second one (orientation two) the mode symmetry axis was orthogonal to the fiber plane.

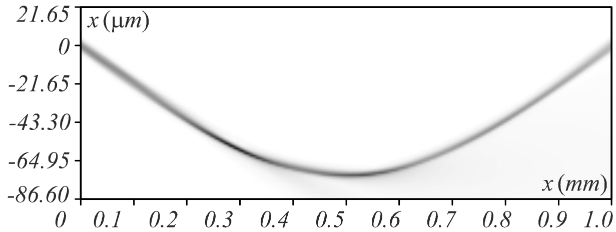

Fig. 6. Amplitude distribution in fiber section for LP-01 mode propagating through fiber microbending (with bending depth of 70 μm)

Deeper investigation of beam profiles during their propagation showed that in orientation one both spots in beam propagated through bending with power loss, but saved the beam structure (see Fig. 7).

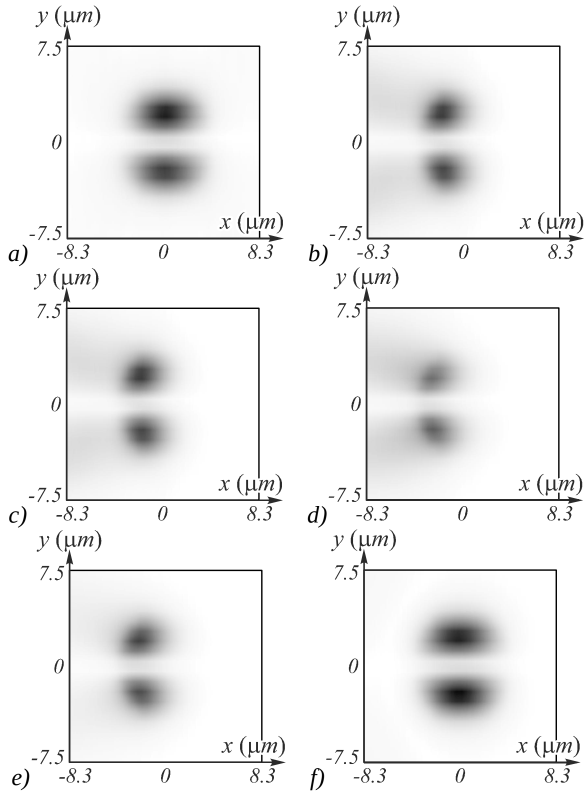

Fig. 7. Amplitude distribution in cross-section (orthogonal to the fiber axis) for the LP-11 mode in orientation one with bending depth of 74 μm for different propagation distances: 0 mm (a), 0.2 mm (b), 0.4 mm (c), 0.6 mm (d), 0.8 mm (e) and 1 mm (f)

In contrast, in orientation two the outer spot (regarding the fiber curvature center) leaved the fiber core while the inner one preserved and mutated almost to the main mode with loss of power (see Fig. 8).

Obviously, these two orientations should show different characteristics in propagation through a fiber bending.

The LP-21 mode has a rotational symmetry also, but due to its amplitude distribution structure the effect of different fiber bending and mode mutual orientations should not be so significant. For the sake of completeness it is necessary to add that simulation for LP-21 mode was made for the case when one symmetry axis lied in the fiber plane and the other was orthogonal to the plane.

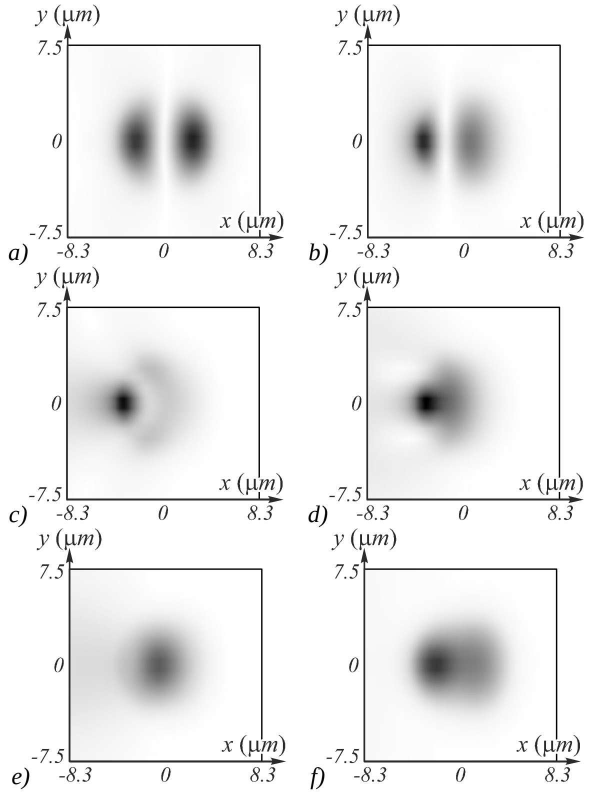

Fig. 8. Amplitude distribution in cross-section (orthogonal to the fiber axis) for the LP-11 mode in orientation two with bending depth of 74 μm for different propagation distances: 0 mm (a), 0.2 mm (b), 0.4 mm (c), 0.6 mm (d), 0.8 mm (e) and 1 mm (f)

Fig. 9 shows dependencies of beam and mode powers remained in the fiber core on the bending depth.

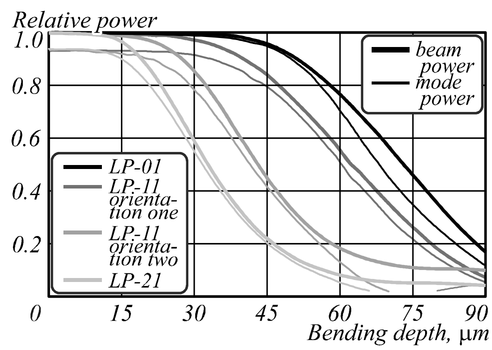

Fig. 9. Beam power in the fiber core depending on microbenging depth for LP-01 (the first from the top), two orientations of LP-11 (the second and the third from the top) and LP-21 (the first from the bottom). Thick lines represent full beam powers and thin lines represent mode powers

It can be seen that the main mode LP-01 is the least sensitive while LP-11 is more sensitive and LP-21 is even more sensitive. So, modes with higher numbers have higher sensibility. It can be explained by the fact that the higher is the mode number, the greater part of mode power propagates closer to fiber cladding. Consequently, bending affects them more than lower modes.

Also it can be seen that two orientations of LP-11 mode showed significantly different sensitivity to bending. Obviously, other orientations will give results between the obtained ones.

Another effect is revealed by gaps between beam power and mode power graphs. The gap for LP-01 increases as some power transfers to higher modes. But gaps for higher modes decrease because there are less higher modes to transfer power into. Also the product of higher mode propagation through a bending is scarcely to be similar to lower modes, especially the main one. The exception is the situation when bending is so strong, so most of the beam power leaves the fiber and the leftovers can be considered as a mode mixture noise (see graphs for LP-11 orientation two and LP-21). So, here full beam power is close to the power of the mode.

Conclusion

In summary, transverse mode converter based on binary microrelief implemented directly on an end-face of a few-mode fiber was investigated. Results of numerical simulation demonstrate high efficiency of LP-11 and LP-21 mode forming by the converter. Difference between illuminating beam amplitude and amplitude of mode to be formed results mainly in excitation of unguided modes and, consequently, amplitude-phase coding is not required to obtain high mode purity (more than 92 %) of a beam in case of illumination by a Gaussian beam. In case of illumination by a planar wave effectiveness is much lower, but mode purity is higher the higher is an excited mode.

Transformations of excited modes by fiber microbending were numerically investigated. It was shown that excited beams save their mode purity even in a strong bending, as arising parasitical modes are mostly unguided by the fiber. It was also demonstrated that resulting beam power and mode content depend on beam and bending mutual orientation for beams with strong rotational symmetry.

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