

# Precise design of integrated diffractive optical mode converter for fiber-to-waveguide coupling

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Received November 1, 2004

Integrated diffractive optical mode converter, consisting of a diffractive optical element (DOE) and a slab waveguide, is used for fiber-to-waveguide coupling. The phase of the DOE is generally designed by optimization algorithm. In this paper, the precise design, a new method with one more restrictive way, is adopted to design the diffractive optical mode converter for fiber-to-waveguide coupling. Through this method, the intensity of any point on the output plane is fully filled with the required demand. Compared with what previously published, the coupling loss of the precise designed converter is lower.

OCIS codes: 060.1810, 050.1970, 130.0130.

In modern telecommunication, data-signal are transported over optical fiber and processed in integrated optical circuits (IOCs). To be able to process the light in the IOC, the light has to be coupled from the fiber into the IOC. High refractive index contrast, high- $\Delta$  waveguide is superior in large-scale and high-density integrate planar lightwave circuits (PLCs), because small waveguide radii make reduction of chip size. The size of single-mode fiber (SMF) is much larger than that of single-mode waveguide and the mismatch between the waveguide and SMF always leads to very high coupling loss<sup>[1,2]</sup>.

As mode converters<sup>[3,4]</sup>, diffractive optical elements (DOEs) have been introduced into PLCs to connect waveguides and fibers for high coupling efficiency<sup>[5-9]</sup>. To find the phase of DOEs, many methods, such as ray-tracing approach, optimization algorithm and so on, have been applied.

A kind of integrated diffractive optical mode converter, consisting of a DOE and a slab waveguide, has been designed in Ref. [6]. An improved algorithm of Gerchberg-Saxton (GS) algorithm, named GSST algorithm, was applied to design the DOE. However, after optimized by GSST algorithm, the points between the sampling points of the desired output field are not as required. As calculating with another group of points on the output field, the performance of coupling decreases. In order to avoid this demerit and improve coupling efficiency, the precise design<sup>[10,11]</sup> is adopted to calculate the phase distribution of the DOE. Any point on the output field, besides the chosen sampling points in the optimization, is consistent with the requirement. Therefore, the coupling efficiency is improved.

Be similar to the Fraunhofer diffraction beam-shaping optical system<sup>[6]</sup>, a DOE combined with a slab waveguide can convert the mode-field of SMF to the smaller size mode-field of high- $\Delta$  single-mode waveguide. The structure of this integrated diffractive optical mode converter is shown in Fig. 1. To satisfy far-field diffraction condition, the length of the slab waveguide is chosen to be 2 mm.

The mode-field  $f_0(x, y)$  of SMF is the incident field of the converter, which is modulated by the DOE. The output field after the DOE is

$$f(x, y) = f_0(x, y) \exp([i\Phi(x, y)]), \quad (1)$$

where  $\Phi(x, y)$  is the phase function of the DOE.

The expression  $g(x', y')$  denotes the light field on the output plane, i.e., the field at the waveguide end face. The relationship between  $f(x, y)$  and  $g(x', y')$  is

$$g(x', y') = \text{FT}\{f(x, y)\}, \quad (2)$$

where FT denotes Fourier transform.

To achieve a good match with the waveguide,  $g(x', y')$  should be highly close to the mode-field of the waveguide. In Ref. [6], GSST algorithm has been applied to design the phase of the DOE. The intensity values of the sampling points were designed to satisfy the requirement, but the intensity of other points did not have the same performance, then the coupling loss was actually large. To make any point on the output plane be consistent with the requirement and decrease the coupling loss, the precise design, with which the sampling interval on the output plane is chosen as half of the traditional sampling interval, is adopted. With this new sampling interval, good performance cannot be obtained with GSST algorithm. Then the hybrid algorithm merging hill-climbing (HC) and simulated annealing (SA)<sup>[12]</sup> is used to carry out the precise design of the DOE, because the sampling interval can be chosen as any value. With the DOE optimized by the hybrid algorithm, the intensities of any point on the output plane can be consistent with the requirement.

The parameters of the SMF at 1550-nm wavelength are: 9- $\mu\text{m}$  diameter core, 1.46 cladding refractive index,

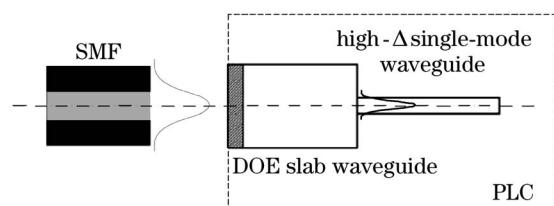


Fig. 1. Illustration diagram of the integrated diffractive optical mode converter.

and 0.33%-\$\Delta\$. The high-\$\Delta\$ waveguide has a \$3.0 \times 3.0 \mu\text{m}^2\$ square cross-section core with \$n\_{\text{cl}} = 1.46\$. In our designs, the dimension of the slab waveguide is 2 mm (length along axis) \$\times\$ 30 \$\mu\text{m}\$ \$\times\$ 30 \$\mu\text{m}\$, and the dimension of the DOE is 500 \$\mu\text{m}\$ (length along axis) \$\times\$ 1 mm \$\times\$ 1 mm with the phase relief in the central section.

For simplicity, one-dimensional simulation is discussed. Firstly, a DOE is optimized by the GSST algorithm. The sampling interval on the output plane is \$\Delta = \lambda f / D\$, where \$f\$, \$\lambda\$, and \$D\$ are the length of the slab waveguide, the incident wavelength, and the aperture size of the DOE, respectively. The intensity distributions of mode-field of SMF, mode-field of 1.86%-\$\Delta\$ single-mode waveguide, and output field of DOE mode converter are shown in Fig. 2.

In Fig. 2, there is almost no difference between the sampling points of the output field of DOE mode converter and the required mode-field of the waveguide. However, if the sampling interval on the output plane is chosen as another value, for example, as \$\Delta' = \Delta / 2\$, and re-calculating the intensity distribution on the output plane with the optimized phase, the new intensity distribution is shown in Fig. 3. Because the intensity of some points is not controlled in the optimization, the characteristic of the uniformity is sharply destroyed.

To avoid the demerit, the precise design is adopted, and the sampling interval on the output plane is decreased.

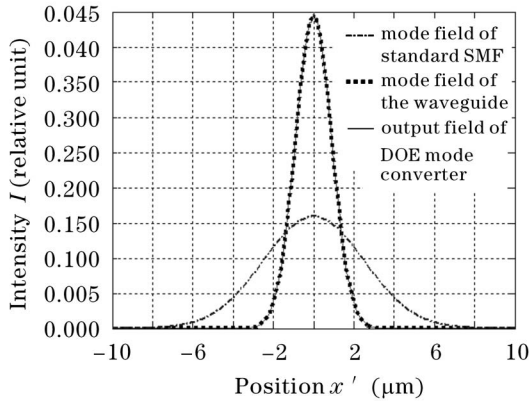


Fig. 2. Intensity distribution of mode field of SMF, mode-field of 1.86%-\$\Delta\$ single-mode waveguide, and output field of DOE mode converter.

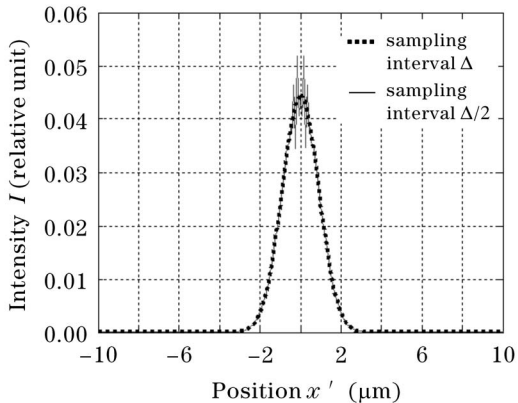


Fig. 3. Intensity distribution on the output plane.

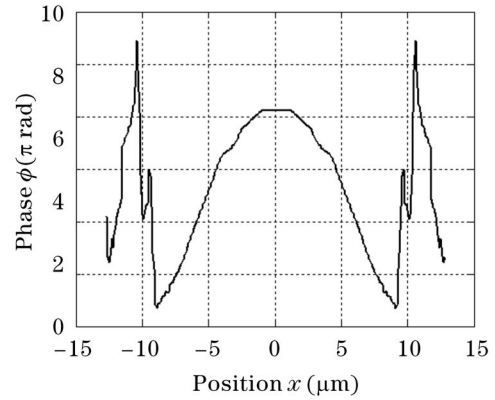


Fig. 4. Phase distribution of the DOE (optimized by the hybrid algorithm with the precise design).

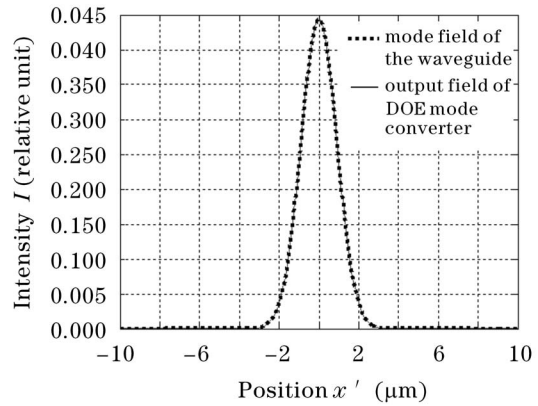


Fig. 5. Intensity distributions of mode-field of waveguide, and output field of DOE mode converter.

Then, the GSST algorithm is not fit anymore. The hybrid algorithm merging HC and SA is employed because the sampling interval can be set to any value. By the request of precise design, the sampling interval on output plane is changed to \$\Delta' = \Delta / 2\$. The designed phase and the intensity on the output plane are shown in Figs. 4 and 5, respectively. We can see the intensity distribution of the output field is consistent with that of the mode field of waveguide.

Furthermore, if the sampling interval on the output plane is changed to \$\Delta' = \Delta / 4\$, the intensity distribution is held. We can conclude that any point on the focal plane, besides the sampling points used in the optimization, is consistent with the requirement.

Waveguides are frequently used in multi-wavelength PLCs, such as wavelength multi/demultiplexer. As a phase-only element, DOE is wavelength dependent. The coupling loss will increase when the operation wavelength is not the design wavelength. That is to say, the coupling loss of the DOE designed at 1550 nm is a function of wavelength from 1450 to 1650 nm.

When the sampling interval is chosen as \$\Delta' = \Delta / 2\$, the coupling losses of DOEs designed by GSST algorithm and hybrid algorithm are calculated with different wavelengths respectively, as shown in Fig. 6. The coupling loss of the precise designed DOE reaches the minimum value 0.012 dB at 1550 nm as predicted and the maximum coupling loss is under 0.43 dB. Compared with the coupling loss of the DOE optimized by GSST algorithm, the

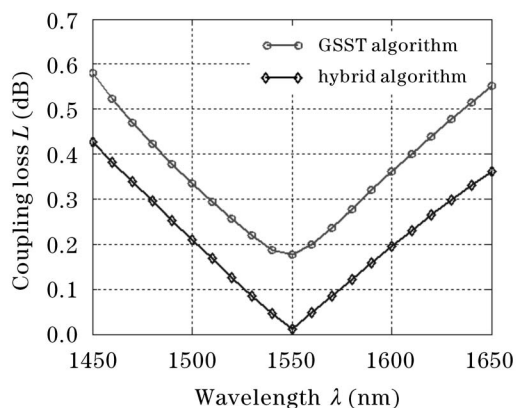


Fig. 6. Coupling loss as a function of wavelength.

coupling loss of the precise designed DOE is obviously lower. The advantage of the precise design is shown. The other capabilities of the converter are the same as those shown in Ref. [6].

Laser-beam direct writing or electron-beam direct writing can be adopted as the fabrication technology of DOE. The continuous phase relief of DOE can be quantized to multilevel phase relief<sup>[13,14]</sup>. The typical fabrication technology of multilevel DOE is a combination of photolithography and reactive ion etching.

The precise design, with the sampling interval as half of the traditional sampling interval, is adopted to design the DOE for realizing a high coupling efficiency of the integrated diffractive optical mode converter. The intensity of any point on the output plane is consistent with the requirement. Compared with what previously published, the coupling loss of the precise designed converter is obviously lower. Of course, the precise design is valid for circular-symmetric cases.

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