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Analytical beam propagation model of micro-lensed fibers for wavelength selective switch☆

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HIGHLIGHTS

- Scalar diffraction theory is used to analyze the beam propagation in WSS.
- A method for measuring the coupling efficiency of fiber coupling micro-lens.
- The experimental coupling efficiency can reach up to 70%.
- The theoretical calculations agree well with experimental results.

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ABSTRACT

Micro-lensed fibers require some features such as low coupling loss and wide tolerance to function in wavelength selective switch (WSS). In this paper, Fourier optics and scalar diffraction theory are used to analyze the major beam propagation and transformation by switching different focus length micro-lens in WSS. A hemispheric micro-lens array is then etched with designed optimum focal length. In experiment, a method is proposed for measuring the insertion loss (IL) and coupling efficiency of a fiber coupling micro-lens in WSS. The theoretical calculations of the spot size at any distance from micro-lens agree well with experimental results. The experimental coupling efficiency can reach up to 70%.

1. Introduction

The wavelength selective switch (WSS) based next-generation reconfigurable optical add-drop multiplexer (ROADM), as an essential network component of current and next-generation dynamic optical networks, has been implemented in many flexible transport networks. Liquid crystal on silicon spatial light modulator (LC-SLM) technology based WSS has the advantages of flexible spectrum coverage, adaptive optical alignment and robustness without mechanical movement. The WSS with higher port count is desirable for providing higher number of add/drop ROADM nodes, but current WSSs are limited with respect to insertion loss(IL) and high port count numbers [1]. Nowadays, most of WSSs with LC-SLM technology employ fiber coupling micro-lens array as input/output ports, so the fiber coupling micro-lens array with more ports and lower IL is expected to contribute for these limitations of WSS. However, there have only been a few studies concentrated on adding the numbers of ports, so that most of WSSs based on LC-SLM technology have fewer than 15 ports [1–4]. Masaki Iwama's group [5,6] applied a spot size converter (SSC) array with 127 μm spacing based on planar lightwave circuit (PLC) technology into the 1×95 WSS, but it used additional anamorphic prisms instead of the conventional micro-lens array for beam expansion and collimation. The micro-lens array with 127 μm pitch up to now has not been reported yet. Therefore, high port count fiber coupling micro-lens array that expands the beam directly without other beam expansion components [5,6] is essential for improving the number of ports and not introducing extra-loss in WSS.

Since the smaller size of one port means more ports can be placed in limited range of steering angle, the micro-lens size of one port and the beam steering angle of LC-SLM determine the number of ports in WSS. At present, the beam steering angle of a 4K solution LC-SLM (GAEA device, provided by HOLOEYE company) is confined in the range of 4°. If the typical fiber array with 127 μm pitch which is configured up to 128 channels in linear array can be used in coupling micro-lens array, the port count number of WSS will easily exceed 100. In addition, the

☆ Fully documented templates are available in the elsarticle package on CTAN.
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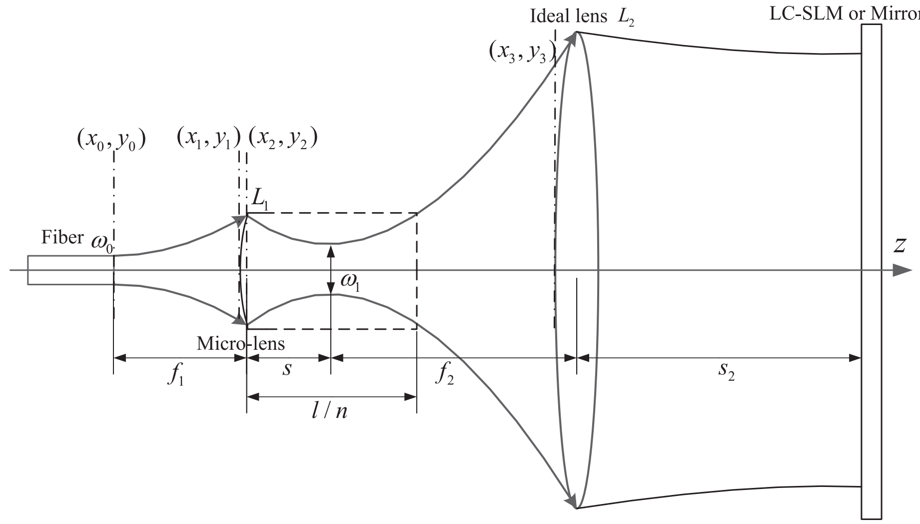

Fig. 1. Optical system configuration for Gaussian beam transformation.

beam spot size projected on LC-SLM is required to be large enough to obtain sufficient high diffraction efficiency of the Liquid crystal on silicon(LCoS). The way to address this issue is to design the appropriate focal length of the micro-lens in condition of high coupling efficiency.

In this paper, Fourier optics and scalar diffraction theory are used for analyzing the Gaussian beam propagation to design the corresponding focal length of micro-lens. A good coupling efficiency and an ideal spot size are obtained by using designed micro-lens. The experiment result has guiding significance to the development of multi-ports WSS.

2. System structure and analysis

2.1. Optical structure

As shown in Fig. 1, the basic optical structure which is extracted from the typical WSS [7,8] includes a single-mode fiber array on a 127 μm pitch, a micro-lens array L_1 with a 1 mm substrate, an ideal lens L_2, and a mirror. To only consider the transformation of Gaussian beam, this structure gives a cross-section and does not include the diffraction element of WSS such as transmission grating and multi-wavelength collimation. The z axis is the axis of symmetry, and the positive z direction is the propagation direction. The fiber end plane is the reference plane (x_0, y_0) and the $z = 0$ plane.

In general, LC-SLM is placed at the position of mirror. In Fig. 1, we only consider the Gaussian beam transformation, so the lowest insertion loss could be obtained by matching the diffraction effect of LC-SLM with the mirror tilt angle when input beam be steered to an arbitrary output port. The input Gaussian beam that is emitted from the light source passes through a single mode fiber and a micro-lens. The fiber end is placed at the focal plane of micro-lens L_1. The L_1 and ideal lens L_2 convert divergent Gaussian beam to an nearly parallel beam of which the size must be sufficiently large to keep high diffraction efficiency of LCoS and not exceed the side lengths of LC-SLM. It is necessary to calculate and design the focal length of micro-lens to ensure that the maximum efficiency of fiber coupling micro-lens and an appropriate spot size be obtained.

2.2. Analytical beam propagation model

The propagation of a Gaussian beam from fiber end surface does not fulfill the condition of paraxial optical systems because the divergence angle of Gaussian beam can up to 10°. Therefore, the problem of Gaussian beam transmission cannot be solved by the ABCD law, it needs to be analyzed by scalar diffraction theory. The field distribution of a Gaussian beam from optical fiber can be written as:

$$U_1(x, y) = A_0\frac{w_0}{w(z)}\exp\left[-\frac{x^2+y^2}{w^2(z)}\right]\exp\left[i\left(-kz-k\frac{{x_0}^2+y_0^2}{2R(z)} + \arctan\left(\frac{z\lambda}{\pi w_0^2}\right)\right)\right] \quad (1)$$

where the beam spot radius $w(z) = w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2}$, the wave front curvature radius $R(z) = z\left[1+\left(\frac{\pi w_0^2}{\lambda z}\right)^2\right]$, and w_0 is the minimum waist radius of the Gaussian beam.

The phase of Gaussian beam is changed while amplitude keeps constant when light waves pass through the micro-lens. The micro-lens can be treated as a thin lens and a plate glass. As shown in Fig. 2, the thin lens with focal length f is regarded as an optical phase transformer whose transmission coefficient $t_1(x, y)$ is given by:

$$t_1(x, y) = \exp[j\phi(x, y)] = \exp[jkL(x, y)] \quad (2)$$

where the optical path $L(x, y) = \Delta_1 + \Delta_2$ produced by the micro-lens, where

$$\Delta_1 = R-\sqrt{R^2-(x^2+y^2)},\ \Delta_2 = n[d-(R-\sqrt{R^2-(x^2+y^2)})]$$

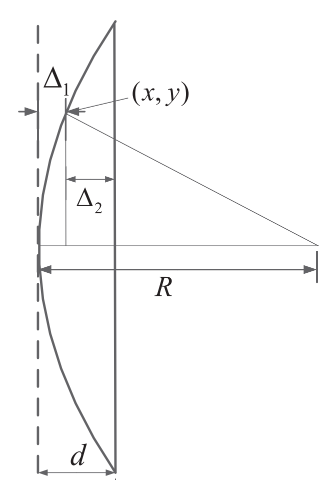

Fig. 2. The equivalent structure of a micro-lens.