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Fabrication of a LP_{01} to LP_{02} mode converter embedded in bulk glass using femtosecond direct inscription

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ABSTRACT

In this paper, we demonstrate a fabrication of an integrated mode converter that converts LP_{01} to LP_{02} for the C-band. The mode converter was directly inscribed in the bulk of a borosilicate glass using a femtosecond laser. The converter has an insertion loss of less than 1 dB for the entire C-band, suggesting more than 80% conversion efficiency.

1. Introduction

Mode division multiplexing (MDM), a type of space division multiplexing (SDM), has been proposed to overcome the capacity limits of optical networks based on standard single mode fiber (SMF). The idea behind the MDM is to use the different (orthogonal) guided optical modes (fundamental mode and higher order modes) within the same multimode (MMF) or few-mode (FMF) fiber to carry different optical signals, i.e. one mode corresponding to one optical channel. The higher order modes are usually excited by converting the fundamental mode using some means of conversion, and then all modes are multiplexed into a single MMF or FMF [1,2].

Mode conversion can be achieved mainly using free-space or fiber/waveguide-based optics. Structures using free-space optics are based on matching the spatial profile of an input mode to the spatial profile of an output mode using phase mask or spatial light modulator such as liquid crystal on silicon (LCOS). They include some phase plates, beam splitters, mirrors and lenses, therefore, they are bulky and experience high insertion losses but they are wavelength insensitive [3].

Mode converter structures based on fibers or waveguides can be realized through a variety of techniques, such as grating, coupling, tapers, lanterns, photonic crystal fibers, etc. [4–9]. These converters match the propagation constant of the input mode to the propagation constant of the (desired) output mode by altering the physical characteristics of the fiber or the waveguide. In general, waveguide-based mode converters have high conversion efficiency, i.e. low insertion loss and are compact, but they are wavelength dependent to some extent [1].

The main challenge of waveguide-based structures is the ability to fabricate them. Recently, advances in femtosecond laser pulses to inscribe a 3D photonic device inside a transparent glass have received full attention from designers and researchers. This technique allows the fabrication of passive and active integrated photonic devices by focusing the light of a laser beam to induce a local refractive index change through multiphoton interaction [10–13]. This technique has also a great flexibility with the type of glasses in which inscription is performed since it does not require UV sensitive glasses like continuous-wave or quasi-continuous-wave UV exposure techniques [14]. With proper displacement, rotation and translation of the glass, almost any arbitrary shape can be written (taper, Y-junction, S-section, etc.). Moreover, different devices could be written sequentially or in parallel, allowing the integration of complex photonic devices and systems.

In this paper, we present an integrated LP_{01} to LP_{02} mode converter written in the bulk of a borosilicate glass sample (Corning Eagle 2000) using femtosecond laser direct inscription. The design is derived from a previously reported work [15]. However, the reported design could not be fabricated with up-to-date femtosecond laser techniques. Therefore, the parameters of the new design have been tailored to fit the fabrication requirements, mainly the minimum dimensions and the core-cladding refractive index difference. The next section provides an overview about the new design.

2. Design and fabrication of the mode converter

The idea behind the proposed mode converter is to match the effective refractive index of the input fundamental mode (LP_{01}) to the effective refractive index of the desired output mode (LP_{02}). This matching

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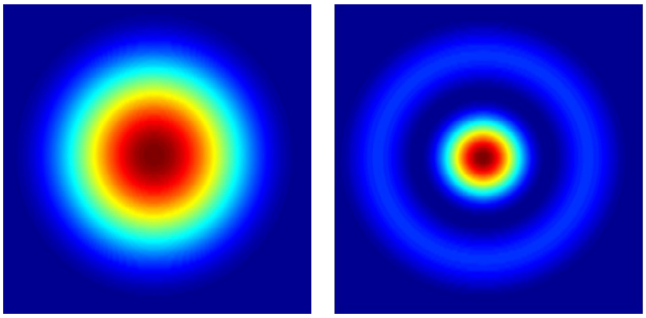

(a) LP_{01}.

(b) LP_{02}.

Fig. 1. 2D field Intensity profile of (a) LP_{01} and (b) LP_{02} modes.

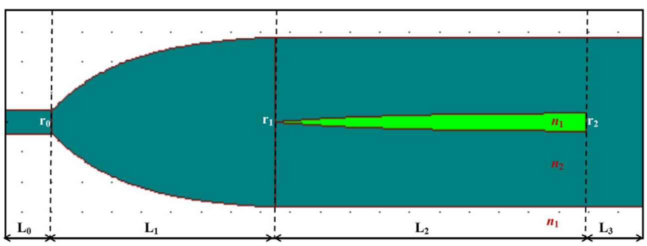

Fig. 2. Schematic diagram of the LP_{01} to LP_{02} mode converter.

Table 1
Parameters of the fabricated mode converter (L_i and r_i in μm).

Parameters	L_1	L_2	n_1	n_2	r_0	r_1	r_2
Value	1200	1020	1.4877	1.4907	5	39	4

is achieved using all-fiber optics by changing the core diameter (through adiabatic tapering) of a circular waveguide. Conversion between LP_{01} and LP_{02} has been chosen because both modes are non-degenerate (polarization insensitive) and the field intensity profiles of both modes have a common central spot, with LP_{02} mode intensity profile having an outer ring, as shown in Fig. 1.

The proposed structure of the mode converter is shown in Fig. 2. It consists basically of two tapered circular waveguides. The first taper has a length L_1, a starting radius r_0 and an ending radius r_1. The starting radius; r_1; is chosen to allow easy coupling to a standard single mode fiber. The tapering follows an exponential function to ensure smooth transition and reduce losses and reflections. The core refractive index is n_2, whereas the cladding refractive index is n_1. This taper is followed by a few mode circular waveguide of length L_2 and core radius r_1. Inside this section, a second inner core is introduced (with a refractive index n_1). The radius of the inner taper is tapered from zero to r_2 over a length of L_2. This second taper forms a ring index profile [16].

The values of the mode converter parameters are given in Table 1. The converter has a total length of about 2.22 mm, an initial radius of 5 microns and a final radius of 39 microns. The input of the converter can be easily coupled to a single mode fiber (Corning SMF-28), which has a typical mode field diameter (MFD) of about 10.4 microns.

The mode converter was inscribed in a 1.1 mm thick bulk glass sample (top surface of 2×10 mm^2, Corning Eagle2000) using a Ti:sapphire laser system (Coherent RegA). The system was operated at a wavelength of 790 nm and a repetition rate of 250 kHz. The temporal full-width at half maximum (FWHM) of the pulses was measured to be ~65 fs at the laser output and estimated at 85 fs on the sample. The beam was focused beneath the surface of glass samples using a 50 X (Edmunds M Plan APO LWD, $f = 4$ mm, 0.55 NA) microscope objective. A cylindrical lens telescope was used to produce an astigmatic beam and shape the focal volume in such way as to form traces with circular cross sections [17,18]. The samples were translated at a speed of 3 mm/s, across the focal point, perpendicular to the laser beam using motorized mechanical stages (Newport XML210 and GTS30V). In order to fabricate the mode converter, an approach similar to Gosh et al. [19,20] was used. The beam was scanned multiple times (314 times) while following slightly displaced trajectories (with 2 microns space between each adjacent trajectory) to fill in the contour of the design. After the inscription process, photo-inscribed devices were examined under an optical microscope (Olympus STM6). Fig. 3 shows the top view, the input face as well as the output face of the fabricated mode converter.

Fig. 3(a) shows the left part of the fabricated device (section L_0 and part of L_1 as shown in Fig. 2). At the left, a circular section is inserted with a diameter of ~10 microns and a length of ~47 microns. This section is used for input LP_{01} mode to be coupled to a SMF. The right section depicts clearly the tapered section L_1. The resulting inscribed taper and core-cladding refractive index contrast follow our design. Fig. 3(b) illustrates the input beam of the laser to be used for inscription. Unfortunately, the beam has a principal (desired) focus and a second (non-desired) focus. Moreover, the shape of the principal focus deviates from the targeted shape, since it does not have a perfect circular form (in fact, a D shape) and its radii are slightly above the desired 10 micron). Fig. 3(c) shows that there is an unwanted structure formed underneath the desired structure. This structure is due to the second focus of the astigmatic input beam [17]. The image of the input face of the beam (Fig. 3(b)), clearly shows that defect exists (not perfect fundamental mode). As a result, a region in which the refractive index difference is slightly higher than the rest of the structure is formed where the unwanted and desired structures overlapped. Therefore, the output LP_{02} mode is more confined in the overlap region than the rest as shown Fig. 4.

Fig. 4 depicts the output intensity profile of the resulting mode (LP_{02} mode at section L_3 as shown in Fig. 2) at four different wavelengths of 1510, 1540, 1550 and 1570 nm. Fig. 4 demonstrates that despite the presence of the defects in the inscribed device, the output mode intensity profile is very close to an LP_{02} as given by Fig. 1(b). All the intensity profiles in Fig. 4 have an internal spot surrounded by an outer ring. In some wavelengths, the ring is not continuous due to the unwanted structure formed by the defect in the input laser beam. Fig. 4 shows also that even though the converter was designed mainly for the C-band (1532 to 1565 nm), it covers a wider band, extending over both sides of the C- band.

The results shown in Fig. 4 were obtained using the set-up illustrated in Fig. 5. It consists of a tunable input laser, a 3-D adjustable stage for alignment and a high-resolution CCD camera. The input light beam from a single mode fiber (LP_{01} mode) connected to the tunable laser is directly injected into the input section of the mode converter (at air-glass interface as shown in Fig. 3(a)). The output light from the converter (LP_{02} mode) is focused through lenses and then captured by the camera, which is connected to a computer. The 3-D adjustable stage is used to align the output light from the SMF into the input of the device. It has three degrees of freedom allowing a perfect alignment to insure minimum coupling losses between the light from the output of SMF into the input of the device under test.

Fig. 6 illustrates the comparison between the simulated and measured insertion loss (conversion efficiency) of the fabricated converter. The simulation result shows a flat response of the converter over a wide range of wavelengths centered at 1550 nm, whereas the measured response has a minimum insertion loss at 1555 nm and the loss varies from 0.4 to 1.3 dB over the wavelength range from 1510 to 1575 nm. If C-band is only considered, the insertion loss is less than 1 dB, implying mode conversion efficiency of more than 80%.