Ultrafast Laser-Written Sub-Components for Space Division Multiplexing

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Abstract: The increase in Internet data demand has resulted in the development of novel optical fibers. Ultrafast laser inscription is a powerful tool to create 3D waveguide circuits that can interface with these new fiber types.

1. Introduction

With society's ever-increasing data demand, new technologies are required to surpass the non-linear Shannon capacity limit of single-mode optical fibers. After exhausting wavelength, polarization and phase, the utilization of space to increase capacity has emerged as the most promising approach for future fiber optic communication networks [1,2]. So called space division multiplexing has driven the development of novel fibers that can carry many data streams in parallel within one common cladding [3]. Such fibers include few-mode fibers with circular or elliptical cores, multicore fibers with uncoupled or coupled single-mode cores or even fibers with multiple cores where each core is few-moded. In single-mode multicore fibers each core is used as an individual channel for data transmission, while few-mode fibers exploit the different modes as different data channels. In either case, the data transmission capacity scales proportionally with the number of parallel spatial channels. This has resulted in data transmission capacities exceeding 10 petabits per second across 114 parallel spatial channels (19 cores × 6 modes) [4]. Single-mode multicore fibers are most compatible with current technologies, whereas few-mode fibers require sophisticated digital signal processing to unravel mode crosstalk although they reduce the non-linear impairments due to the larger mode-field area [5].

Interfacing with these new types of fibers is challenging due to their increased complexity compared to single-mode fibers. Mode-multiplexers are required to excite and detect the individual modes of few-mode fibers while multicore fibers require 3D waveguide fan-outs to access the individual cores that are arranged in 2D patterns.

2. Ultrafast Laser Inscription

A technique that is seamlessly compatible with 3D waveguide geometries is Ultrafast Laser Inscription [6–8]. Ultrafast laser inscription is based on a femtosecond laser beam that is tightly focused into the bulk of the substrate material, typically a silica glass. The high peak intensity at the focal spot results in nonlinear photoionization of the material. This causes a localized modification of the glass structure and a change in its optical properties, i.e. refractive index. The refractive index change can either be positive or negative. Depending on the inscription parameters and the material itself, the refractive index change can be a result of a change in fictive temperature, the generation of color centers, defect induced densification, rarefaction and compaction of the glass network, and compositional changes due to ion migration [9,10]. Ultrafast laser inscription has a wide parameter space, such as laser wavelength, polarization, pulse duration, pulse repetition rate, focusing geometry and feedrate at which the sample is translated through the focused laser beam. The most significant influence is the laser repetition rate. Repetition rates of the order of kilohertz result in an athermal modification of the material, where the size and geometry of the refractive index modification are related to the intensity profile of the focused laser. At high repetition rates, where the laser pulses arrive on a timescale shorter than the thermal diffusion time of glass, an accumulation of heat occurs with subsequent melting of the material. This regime is characterized by refractive index modifications that grow in size significantly beyond the focal spot size. Moreover, their cross section is typically near circular due to the isotropic heat diffusion within glass. The different regimes lead to different structural modifications and different waveguide morphologies.

3. Directional Coupler based Mode-Multiplexers

In alumino-borosilicate glass the high repetition rate regime results in circular symmetric modifications with an approximately graded-index profile. By adjusting the average power of the laser, the waveguide size can be tailored to be single-mode or few-mode. Utilizing this inscription regime, efficient mode-selective mode-multiplexers based on asymmetric directional couplers have been demonstrated [11]. Asymmetrical directional couplers require precise phase-matching between the fundamental mode of the single-mode waveguide and the desired higher order mode in the few-mode waveguide. By bringing the waveguides in close proximity over a predefined distance, nearly 100% power transfer is achievable (Fig. 1(a)). In contrast, tapered velocity couplers only require phase-matching somewhere within the tapered coupling region to achieve high mode-conversion efficiency [12,13]. By gradually down-tapering the single-mode waveguide and simultaneously up-tapering the few-mode waveguide an operational bandwidth exceeding the C and L-bands is possible (Fig. 1(b)). A fully pig-tailed tapered velocity coupler typically features insertion losses of 1.7 dB with mode-extinction ratios in excess of 18 dB.

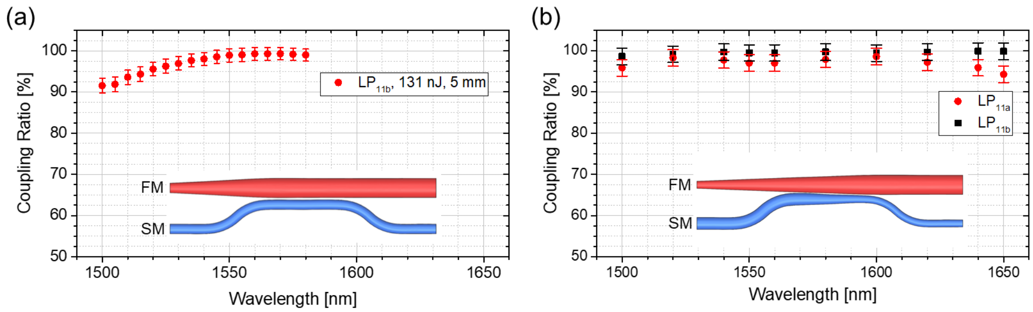

Fig. 1. (a) Coupling ratio as a function of wavelength for an asymmetric directional coupler designed to multiplex the LP_{11b} mode. The inset shows the geometry of the device with a few-mode waveguide (FM - red) and single-mode waveguide (SM - blue). (b) Broadband mode conversion efficiency for coupling into the LP_{11a} and LP_{11b} modes using a three-core tapered velocity coupler.

4. Photonic Lantern based Mode-Multiplexers

Photonic lanterns are 3D waveguide devices that convert *N* single-mode inputs to a single multimode output that supports *N* modes [14]. Like tapered couplers, photonic lanterns are based on an adiabatically tapered transition. Photonic lanterns are most commonly based on fibers, but ultrafast laser inscription is attractive as it enables relatively straightforward scaling of the number of ports [15]. A uniform photonic lantern with all cores of the same size does not map a particular input to a specific mode at the multimode output. However, by introducing asymmetry through making the individual single-mode inputs dissimilar, one-to-one mode-mapping or mode-group selective mapping can be achieved [16,17]. Ultrafast laser inscription has been used to demonstrate a 3-mode mode-group-selective lantern by changing the physical size of the individual single-mode waveguides [18]. Figure 2 shows the mode-profiles of a 6-mode mode-group selective photonic lantern. The lantern was inscribed in the athermal regime to merge all single-mode input waveguides into a single homogeneous multimode waveguide. This is challenging to achieve using the thermal inscription regime. The 65 mm long device with a 50 mm long transition from individual single-mode waveguides to the uniform multimode waveguide has an insertion loss of 4.7 dB.

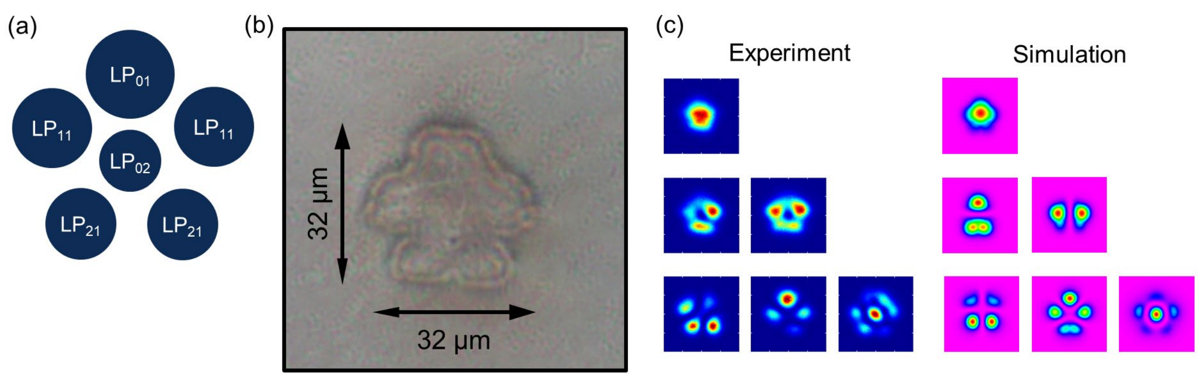

Fig. 2. (a) Cross sectional geometry of the mode-group-selective photonic lantern. (b) Microscope image of the lantern cross section. The inscription laser was incident from the top. (c) Comparison between the measured and simulated mode-profiles at 1550 nm.

5. Multicore Fiber Fan-Outs

Ultrafast laser inscription is a powerful tool to create waveguide circuits that map from an arbitrary 2D arrangement of waveguides to a linear array [19]. Thomson *et al.* fabricated the first dedicated fan-out for a multicore optical fiber with 4 cores in the athermal regime [20]. The device suffered from relatively high insertion losses of 5 dB.

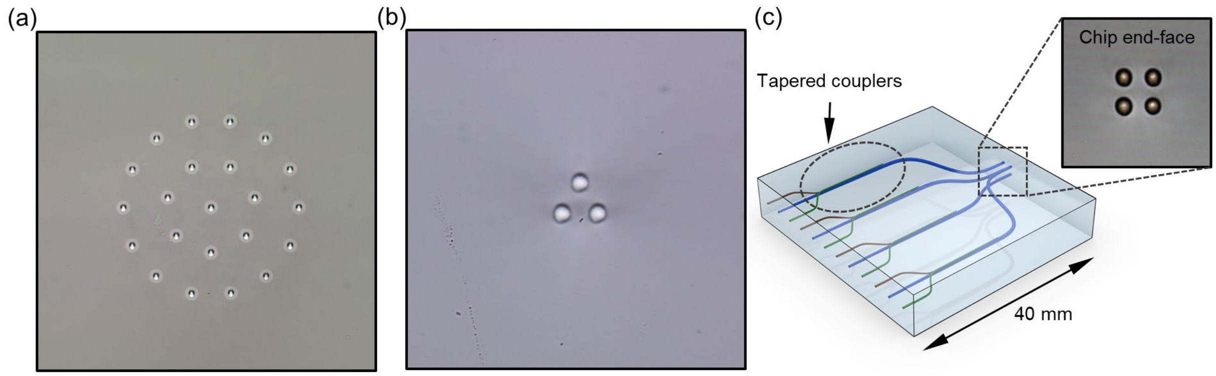

Fig. 3. Cross sectional microscope images of ultrafast laser inscribed fan-out for a 22-core multicore fiber (a) and a 3-core coupled-core fiber (b). (c) Sketch of a monolithic chip that acts as a fan-out and mode-selective mode-multiplexer for a 4-core 3-mode fiber.

Figure 3(a) shows the cross section of a fan-out for a 22-core multicore fiber inscribed in the thermal regime. This device, pigtailed to a multicore fiber on one side and a linear fiber array on the other, exhibits average insertion losses of 1.2 dB across all 22 cores with a standard deviation of 0.3 dB and a worst-case insertion loss of 1.8 dB. The internal losses of the chip are < 0.5 dB, with the remainder of the losses being attributed to mode-mismatch and misalignment at both fiber interfaces. Ultrafast laser inscription can also be utilized to create fan-outs for coupled core fibers. Figure 3(b) shows the cross-sectional microscope image of a fan-out designed to couple to a 3-core coupled core fiber. Ultrafast laser inscribed fan-out circuits are not limited to single-mode waveguides. By combining a fan-out with mode-selective mode-multiplexers, a monolithic chip for interfacing with a 4-core, 3-mode fiber has been demonstrated [21]. This device has enabled data rates of 1.2 Petabit/s across a fiber with a diameter similar to existing single-mode fibers [22].

6. Acknowledgement

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