Femtosecond laser written integrated photonics on sapphire

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Abstract: This paper presents the compact integration of photonics devices on a sapphire chip in the telecommunications waveband. The devices include waveguides, a waveguide array, a directional coupler and a splitter. © 2022

1. Introduction

Sapphire (Al_2O_3) is an exceptionally hard and resilient material. It has a very wide transmission window from 150 nm to 5500 nm, good thermal conductivity, a high optical damage threshold and it is electrically insulating. Furthermore, it is resilient to radiation, ultrahigh temperatures and corrosive chemicals. Compared to glass, sapphire is also more scratch resistant. These optical and mechanical properties make sapphire an attractive platform for integrated photonics applications in the space, aerospace, nuclear, healthcare and industrial sectors.

Femtosecond laser direct writing has enabled the fast prototyping and flexible design of compact optical devices on transparent substrates. In glass, waveguides can be created by inscribing a permanent positive refractive index change in the material through nonlinear ionization. However, in sapphire, the femtosecond laser damages the crystal lattice resulting in a negative refractive index. This necessitates a much more complex waveguide design as simple stripes cannot be used. Femtosecond laser written photonics has been demonstrated in various crystalline materials such as lithium niobate and YAG [1], but there has been little work in sapphire. Recently, we reported single-mode waveguides in sapphire at 1550 nm [2] using depressed cladding waveguides (DCW). We now extend this work to more complex photonic structures as a precursor to a fully integrated sapphire photonics chip.

2. Method

Devices were fabricated on 10×10×1.2 mm and 40×10×1.2 mm *M*-plane sapphire substrates, such that the waveguides were predominantly along the *c*-axis. A regenerative femtosecond laser system (Pharos SP-06-1000-PP) delivering 515 nm and 170 fs pulses was used for fabrication. The linearly polarized laser beam was focused onto the substrate through a 40× 0.75 NA objective at 200 µm depth. A spatial light modulator was used to adaptively correct for the spherical aberration. An optimized pulse energy of 30 nJ and a repetition rate of 1 MHz was chosen for crack mitigation. The sample was mounted on a three-axis motion stage and written at a speed of 11 mm/s. These parameters were found through an experimental process following the method discussed in [2].

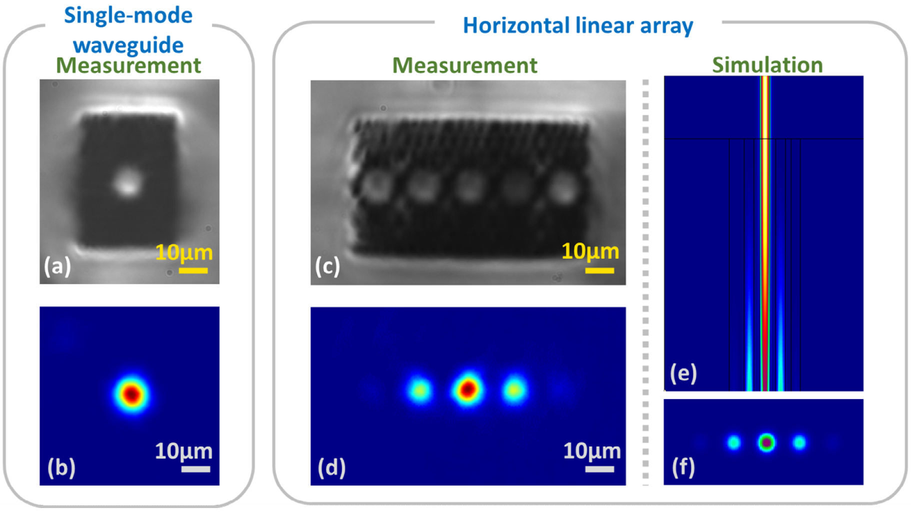

Fig. 1. Microscope image and mode profile of a DCW (a, b), those of a waveguide array (c, d); and the simulated results observed from the beam propagation direction (e) and end facet (f).

A DCW with a square outer cladding shape (35×48 µm) and a circular core with a diameter of ~10 µm was designed and fabricated [Fig.1(a)]. To characterize the DCW, 1550 nm light from a tunable laser source was butt-coupled to the DCW, and the near-field mode profile [Fig. 1(b)] was recorded by imaging onto an InGaAs camera. The propagation loss was measured by inscribing the same structure onto a 1-cm chip and a 4-cm chip and determining the difference in loss. The loss was measured to be 1.60 dB/cm and 1.50 dB/cm for transverse electric (TE) and transverse magnetic (TM) modes respectively.

The refractive index change was found using a method described in [3]. A horizontal evanescently-coupled waveguide array was designed with a coupling length of 4 mm and center-to-center spacing of 16 µm. Simulations were performed using FIMMWAVE (Photon Design Ltd.) to obtain the diffraction patterns at different refractive index changes. A waveguide array was fabricated [Fig. 1(c)] consisting of a 6 mm input waveguide feeding the central waveguide of an array of five 4 mm coupled waveguides. The propagation pattern was recorded in Fig. 1(d). By correlating the experimental measurement and simulation results, the refractive index change was found to be -0.0035 in this case [Fig. 1(e) and (f)]. The *V*-number was calculated to be 2.24, confirming the waveguide to be single-mode.

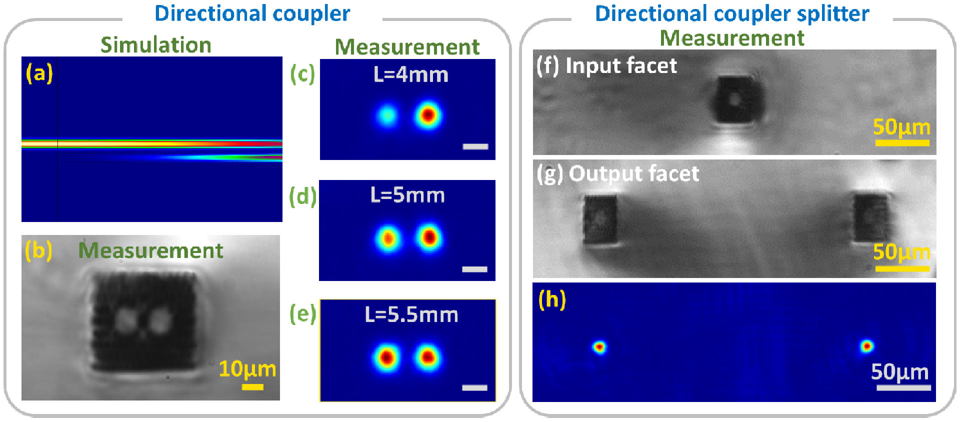

Fig. 2. (a) Simulation of a DC waveguide in the beam propagation direction, the microscope image (b) and mode profile (c-e) measured at the output facet for different designs (L: coupling length, scale bar indicates 10 µm); and the input facet (f), output facet (g) and mode profile (h) of a DC splitter.

With the above results and information from the simulations [Fig. 2(a)], a directional coupler (DC) was designed and fabricated, shown in Fig. 2(b). Different coupling lengths were scanned and their mode profiles are shown in Fig. 2(c-e). To interface the DC with a silicon device such as a V-groove, we fabricated a 50:50 splitter with two output DCWs which are separated 250 µm apart [Fig. 2(f, g)]. The design is similar to that presented in the YAG crystal [4]. It has a 1 mm straight input waveguide, followed by a DC with the optimized coupling length of 5.5 mm, a 3 mm-long branch splitter, and two 0.5 mm straight output waveguides. Figure 2(h) shows the mode profiles of the two DCWs at the outputs at 1550 nm with the power splitting ratio measured to be 49:51.

3. Conclusion

We have presented here the fabrication of waveguide devices in sapphire, demonstrating a 1×2 splitter as an example. We believe this technology shows promise for future integrated sapphire photonics chips.

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