and consequently it is difficult from a single measurement to ascertain the peak index change for the asymmetric waveguides written at great depth without aberration correction. However, the peak index change could be seen as approximately consistent whether aberration correction was applied or not- i.e. it has a far greater dependency on the material and laser parameters than any focal distortion. This was in agreement with measurements of the propagation loss of the waveguides, which was estimated as approximately 1.2 dB/cm at the test wavelength of 630 nm. Within the measurement uncertainty the overall propagation loss was independent of the fabrication depth and the aberration correction. The primary benefit of the aberration correction was to maintain uniform waveguide cross-section and hence single mode operation at all depths within the glass.

5. Conclusion

In conclusion, we have explored theoretically the range over which depth-dependent aberrations are important for waveguide writing in glass at three commonly used numerical apertures. Waveguides with a uniform cross-section may be expected over a depth range of 400, 140 and 50 μm for objective lenses with NAs of 0.4, 0.5 and 0.6 respectively, provided that the incident laser fabrication power is appropriately adjusted. This work considers waveguide writing in a low pulse repetition rate (PRR) regime with slit beam shaping, and we expect the results to be highly analogous for waveguides with cross-sections tailored by other methods, such as astigmatic focal shaping [7], spatio-temporal focusing [9] or using the multiscan technique [18]. It is more difficult, however, to predict the effect of the aberration on waveguide writing at higher PRR, corresponding to a cumulative heating regime where the waveguide cross-section is not so closely matched to the focal intensity [5]. Indeed, it has recently been shown that induced spherical aberration can aid waveguide writing in such systems by driving ion migration [29].

Experimentally we have demonstrated waveguides by laser writing at depths up to 1.2 mm in fused silica at a 0.5 NA. At depths greater than 0.35 mm, the quality of the laser-written waveguides was highly affected by the depth-dependent aberration, and could be greatly improved using adaptive aberration correction. Waveguides deep below the surface are highly asymmetric with irregular cross-sections. These waveguides require higher power for sufficient refractive-index modification and become multi-mode. By applying adaptive optics in our DL-W system, the corrected waveguides had circular symmetric profiles and the single-mode were well-confined during transmission. Similar waveguide profiles and performances over a large depth range were maintained, while more accurate and predictable position control could be achieved. The experimental results showed that the aberration correction could greatly facilitate the fabrication of high-quality waveguides over large depth ranges. These results are expected to be important for DLW waveguide circuits that comprise waveguides at multiple depths, for example in devices for photonic reformatting [18, 30, 31] or waveguide lattices [32–34].

Acknowledgments

The authors gratefully acknowledge the Engineering and Physical Sciences Research Council (grant numbers EP/E055818/1 and EP/K034480/1) and the Leverhulme Trust for financial support.

#260371 Received 2 Mar 2016; revised 13 Apr 2016; accepted 17 Apr 2016; published 5 May 2016