3D Direct-Laser-Written Mid-Infrared Waveguide Circuits in Fused Silica and Crystalline Quartz

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Abstract: We report on the fabrication, for the first time to our knowledge, of mid-infrared step-index waveguides in fused silica substrates and mid-infrared cladding waveguides in crystalline quartz. Both types of waveguides can be designed to be multimode or single mode for wavelengths up to the transparency limits of the materials, around 4 μm wavelengths. For the case of step-index core waveguides in fused silica we demonstrate core to cladding index steps in the 0.01 range with core sizes around 10 μm x10 μm, this enabling for low coupling losses to optical fibers. We also demonstrate the capability of writing waveguide circuits deeply embedded inside silica substrates down to the mm scale, this enabling the design and 1-step fast fabrication of advanced 3D mid-IR waveguide circuits for future light processing chips for chemical sensing, astrophotonics, or any other mid-IR related application.

Introduction: In recent years there is an increasing interest in exploiting the range of longer wavelengths called the mid-infrared (MIR) range which spans from 2.5 to 20 μm [1]. Femtosecond (fs) pulse direct laser writing (DLW) is a novel technique which has been demonstrated to be capable of producing three-dimensional (3D) waveguide designs and configurations which are required for efficient and low-loss interconnection between different components, such as optical fibers and waveguide chips [2]. In this work we explore the possibility of fabricating, with this technique, MIR waveguides in fused silica and crystalline quartz, which are transparent from the ultraviolet to up to the MIR at around 4 μm.

Femtosecond pulse laser 3D fabrication: Low OH-concentration fused silica glass and standard α-quartz c-cut crystal, are employed as substrate materials for the waveguides. Fig. 1 shows examples of fabricated waveguides in crystalline quartz and fused silica. Our presentation will show how we can create lowered refractive index structures in crystalline quartz, and increased refractive index structures in fused silica glass. In the case of the crystal, we have designed and fabricated cylindrical cladding structures which can sustain light propagation in the whole transparency range of the crystal. On the other hand, in fused silica the ultrashort pulses can induce a local increase of the index, from which we benefit to design step-index core waveguides which can guide light through bends and also feature low loss butt-coupling to commercial fibers.

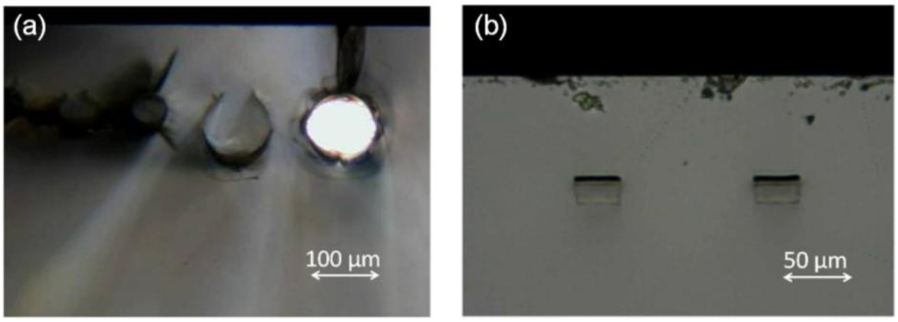

Fig. 1. Microscope images of fabricated waveguides in (a) α-quartz crystal and (b) fused silica glass.

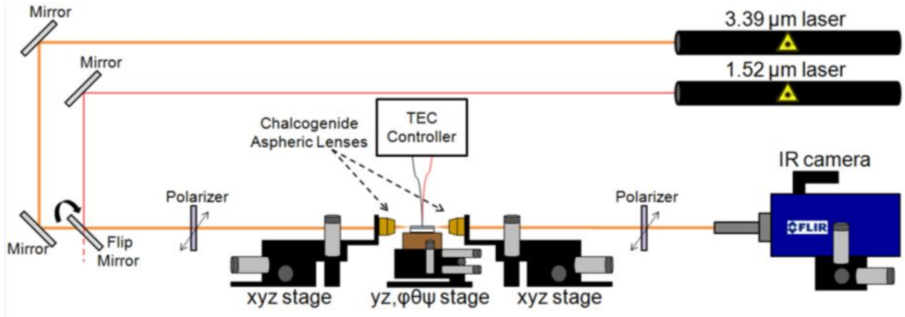

Fig. 2. Scheme of the optical setup used for modal characterization of NIR and MIR waveguides

Optical mid-infrared waveguide characterization: We have built a complete setup for NIR and MIR optical characterization of waveguides (see Fig. 2). Modal and propagation loss measurements of the waveguides are possible up to 5 µm, and spectroscopic characterization of waveguides transmission up to 12 µm with a fiber coupled FTIR spectrometer are also being performed. Some examples of modes measured at 3.39 µm wavelength in the MIR range are shown in Fig. 3. For α-quartz, two different types of cladding waveguides are shown: the first one is monomode (Fig. 3(a)) whereas the second one is much larger in size and supports a great number of modes (Fig. 3(b)). In the case of step index waveguides made in fused silica glass, we show here the observable modes for the waveguides shown in Fig.1b. Three different modes can be excited almost independently.

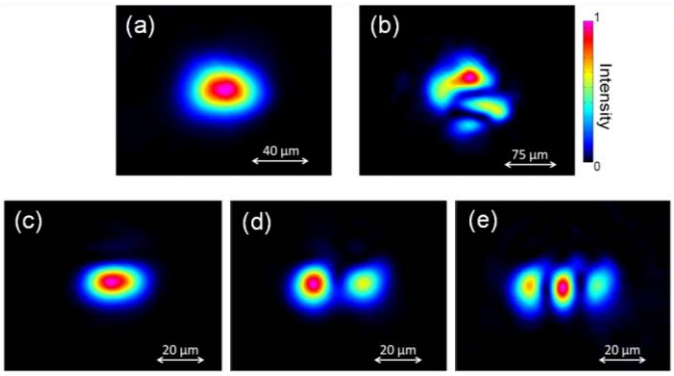

Fig. 3. Measured near-field intensity mode profiles for selected waveguides at 3.39 µm. (a) Monomode and (b) multimode waveguides made in α-quartz. (c), (d), (e) First three modes supported by a step-index waveguide made in fused silica.

Conclusions: MIR waveguides embedded in glass and crystal are being developed by the femtosecond laser writing technique. Properties such as size, light confinement, modal behavior or 3D propagation path can be easily controlled. An optical setup allows modal characterization of fabricated waveguides and testing of the performance providing feedback for fabrication optimization. The obtained waveguides will serve as MIR sensors and first results will be shown.

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