Precision Laser Direct Writing of Polymer Optical Waveguides and Optofluidic Systems

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A flexible fabrication setup for laser direct writing of µm-sized structures in photopatternable polymers is presented. As a demonstration, multimode polymer waveguides on printed circuit boards were fabricated along with fluidic structures using mask-based lithography to form an optofluidic system.

1 Introduction

Polymer optical waveguides find their applications in optical interconnect solutions for data communication or in integrated measurement devices for physical properties of liquids or gases [1]. Both applications may be realized using printed circuit board (PCB) material as the underlayer, typically *FR4*, which in its copper-clad version can be populated with electronic circuits, though glass or polymers are suitable materials as well.

In our approach, the structures to be formed are build up layer by layer, involving standard photopatternable polymers differing in refractive indices, and dry resists. Precision laser direct writing (LDW) is used for the functional elements requiring high resolution such as waveguide structures, while conventional mask-based lithography with chrome or foil masks is used for large-scale or lower-resolution features.

2 Laser Direct Writing System

Our self-build laser direct writing system (Fig. 1) consists of four major components: 1) a motorized XY translation stage (Aerotech, Inc.) covering 300 x 300 mm² with a bidirectional repeatability of ± 0,1 µm and a step size of 0,01 µm, 2) a modulatable ultraviolet diode laser source (20 mW @ 375 nm, omicron GmbH) with focusing optics and a fiber-based spatial filter yielding a nearly perfect circular intensity profile (Fig. 1 c)), 3) a CMOS camera for write process monitoring and laser alignment to already existing structures, 4) a pneumatic vibration isolation table.

During exposure, the substrate is moved relative to the stationary laser head. Coordinated X- and Y-axis motion is possible to ensure a constant exposure dose along arbitrarily shaped waveguide paths. The laser emission can be switched on and off or be modulated in synchronization with the programmed coordinates. The setup is situated in a clean room equipped with further facilities for photolithography, such as a spin coater, a hot plate, a dry resist laminator, and a mask aligner.

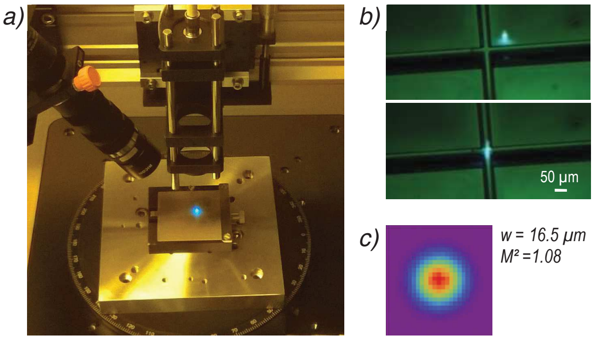

Fig. 1 *a) Photopolymer-coated PCB being processed on the laser direct writing system, b) camera image showing the writing spot on prefabricated alignment structures, c) writing spot as recorded by a laser beam profiler showing a beam quality factor M² close to 1.*

3 Waveguide and Structure Widths

To assess the experimentally accessible parameter range of waveguide widths, trajectories have been written with different velocities and different spot sizes in *SU-8 50* negative resist [2]. The results are compared to a model [3] for waveguide or structure widths b:

$$b = w\left[2\ \log\left(\sqrt{\frac{2}{\pi}\frac{P}{D_0 w\, v}}\right)\right]^{1/2} \qquad (1)$$

where v denotes the writing velocity, w is the 1/e² beam radius, D_0 is the resist's threshold exposure dose, and P is the laser power reaching the resist.

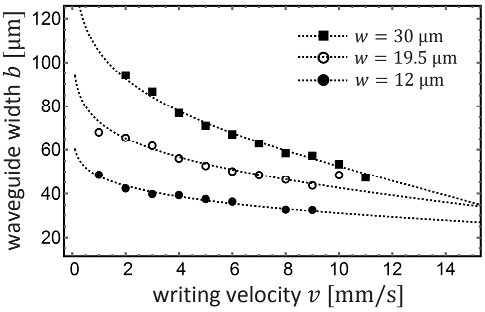

Fig. 2 *Waveguide widths as a function of writing velocity. Dashed lines: predicted widths by equation (1) for three different beam radii* w*. The markers denote the measured waveguide widths* b*.*

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Since writing velocity, laser power and spot size diameter (related to the distance between laser head and polymer) can be programmed, waveguide widths can be dynamically changed during exposure. That allows for fabricating lateral waveguide tapers to adapt mode field diameters of external light sources or fibers to the light-fluid interaction regions in microfluidic devices. The laser spot size can be further reduced to a couple of micrometers to suit single mode waveguide fabrication and coupling, as well.

4 Fabrication Procedure

The fabrication of optical polymer waveguides on printed circuit boards starts y spin coating the optical undercladding *EpoClad* [2] onto the *FR4* substrate. In a second step, the waveguide core layer made of higher index polymer *SU-8* or *EpoCore* [2] is applied and waveguide paths are exposed by LDW. In a third step, the upper cladding layer polymer, again *EpoClad*, is applied. Each step is finalized by thermal curing and development which removes unexposed areas (negative tone resists). As a result of steps one to three, a polymer waveguide core fully embedded in a poly-mer cladding is formed. Propagation losses of straight waveguides have been measured by a cutback method to be around 0,5 to 0,6 dB/cm at 850 nm wavelength which is reasonably low compared to literature [1], [2].

In order to integrate fluidic structures for fluid-light interaction, subsequent mask lithography steps are performed on the core layer and the upper cladding layer right after the LDW exposures, respectively. Finally, the fluidic channels are covered by laminating an additional dry resist layer.

5 Optofluidic Device

We adopt a measurement principle similar to attenuated total reflection (ATR) spectroscopy widely used in clinical diagnostics [4]. In ATR, light is guided in a waveguide whose cladding is formed by the fluid to be studied. While most of the lightfield is located in the waveguide core, a small portion (the evanescent field, Fig. 3 a)) extends beyond into the fluid and gets absorbed according to its absorption spectrum. Measuring the drop in optical power for one or more distinct wavelengths allows one to derive information about the fluid.

The fabricated device is shown in Fig. 3 b). Coupling to an external fluid pump is made by vertically attached tubings. Fiber coupling to light sources and detectors is aided by micropositioning stages and mechanical guiding structures exposed into the resist layers (Fig. 3 d)). The connections are finally glued into place. First measurements confirm the functionality of the device.

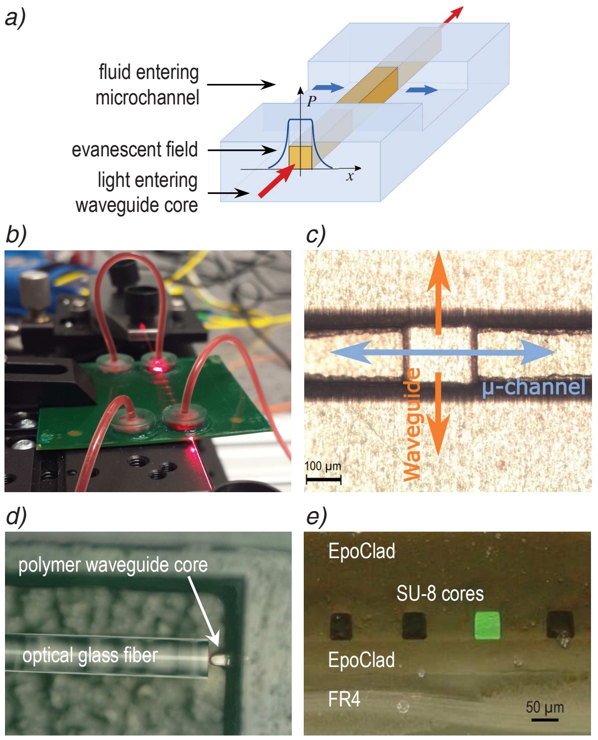

Fig. 3 *Optofluidic device. a) Schematic sketch illustrating fluid-light interaction and evanescent field, b) PCB comprising fluidic and optical structures in a measurement setup, attached to an external fluid pump, light source and detector, c) fluid-light interaction region, d) light coupling from optical glass fiber to polymer waveguide, e) three layer structure on FR4 showing SU-8 waveguide cores measuring 42 x 50 µm² and 50 x 50 µm² (width x height) surrounded by EpoCore cladding. Light has been coupled to one of the waveguides for demonstration purposes.*

6 Conclusion

We have demonstrated the fabrication of an optofluidic device by means of a self-build laser direct writing system. The combination of LDW with conventional mask-based lithography offers both speed and accuracy. The system represents a versatile and flexible tool for research in electrooptical printed circuit boards as well as in optomicrofluidics.

References

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