Three-Dimensional On-Board Optical Interconnects Enabled by Femtosecond Direct Laser Writing in Polymer

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We demonstrate a novel method to fabricate free-form symmetric three-dimensional single-mode waveguides in photopolymer. Combining femtosecond direct laser writing and external monomer diffusion yielded a refractive index contrast of 0.013. This technique could pave the way for three-dimensional optical interconnects at board level with high complexity and bandwidth density.

1 Introduction

Optical interconnects are indisputably needed for transmitting information in telecommunications, local area network, and rack-to-rack links. Recently, bringing the optical domain to board level has emerged as a potential solution for the physical limitations of electrical interconnections in terms of bandwidth density and power consumption [1].

Femtosecond direct laser writing (3D-DLW) has witnessed tremendous advances in fabricating three-dimensional micro and sub-micro structures over the last years [2]. The nonlinear two-photon absorption occurs in a tightly confined volume in order of the light source wavelength which permanently changes the physical and chemical properties of the exposed volume. Photopolymerization in organic polymer, however, induces only an insufficient refractive index difference which restrains the possibility to fabricate embedded waveguides with compact feature size and matching mode field.

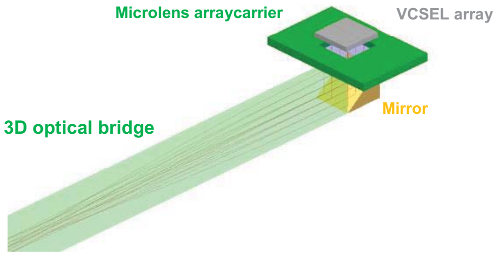

Fig. 1*The concept of the optical bridge to perform all the optical interconnections on board and in three dimensions equipped with vertical-cavity surface-emitting lasers (VCSEL) and mirrors.*

This paper reports on a new approach taking advantage of the external diffusion of gaseous monomer to tackle this challenge. The work aims for three-dimensional optical on-board hybrid integration (Fig. 1) that adds an extra dimension to planar interconnects.

2 Femtosecond Direct Laser Writing

The direct laser writing system (GT Photonic Professional, Nanoscribe GmbH) was utilized to inscribe three-dimensional waveguides. An ultrashort pulse laser of 100 fs at the wavelength of 780 nm and a high repetition rate of 80 MHz emitted from an Erbium-doped fiber laser assure a large peak power and a fast light-matter energy transfer. Fig. 2(a) illustrates the schematic setup of the 3D-DLW system. A 63× inverted microscope objective focuses the laser beam directly into the photopolymer resist. Its high working distance of 1.7 mm allows for non-contact writing in a thick layer of photoresist. The substrate is mounted on a sample holder which is moved by three precise computer-driven translation stages. The integrated focus system determines the position of the resist interface and corrects its tilt angles.

It is crucial to accurately drive the laser focal point along the resist depth. Therefore, we derived the defocus factor (D), i.e. the shift of the laser focal point due to the mismatch between the refractive indices of the air (n_1) and the photoresist (n_2), using Snell's law as:

$$D = \frac{\sqrt{n_1^2 - NA^2}}{\sqrt{n_2^2 - NA^2}} \tag{1}$$

where NA is the numerical aperture of the microscope objective.

3 Fabrication

A novel photopolymer was spin-coated on a 2-inch silicon wafer to form a resist layer with the thick-

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ness of 400 µm. The core structure of the waveguide was inscribed into the solidified photopolymer applying 3D-DLW.

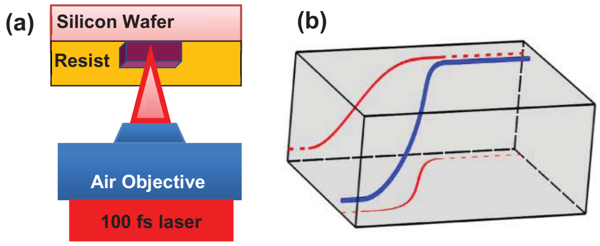

Fig.* 2(a) The non-contact 3D-DLW using air objective; there is an air-gap of around 1 mm between the microscope objective and the resist. (b) The layout of a three-dimensional waveguide (blue continuous curve) and its projections (red dotted curves).*

Fig. 2(b) shows the design of a 3D waveguide and its projections of sine functions. Due to the insufficient refractive index contrast between the core and the cladding, low index gaseous monomer (n =1.445 at 589 nm) was diffused into the host oligomer (n =1.590 at 589 nm). The subsequent UV flood exposure at 365 nm cross-linked the diffused monomer into the cladding matrix by means of single-photon absorption. The whole sample was finally hard-baked at 140 °C for 10 minutes to fully cure the whole structure and to stabilize the buried waveguide.

This technique requires only one resist layer. Furthermore, neither a mask nor a wet process is needed.

4 Results and Discussion

In order to analyze the guiding performance, refractive index profile and physical dimensions of the core were measured. The dispersion characterization of the photopolymer was measured by an m-line spectroscopy. Fig. 3 plots the measured refractive indices at different wavelengths between 400 nm and 1600 nm and their fitting curves using Cauchy equation before and after the external diffusion. Fig. 3(b) shows that the external monomer hardly diffused into the cross-linked core.

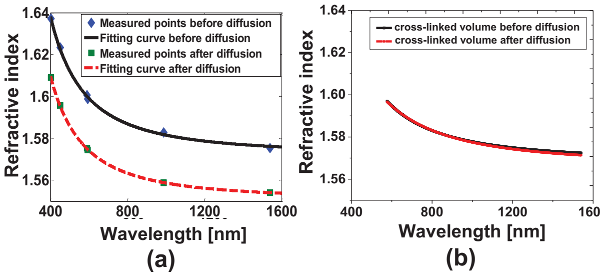

Fig. *3 Dispersion curves of the photopolymer before (black) and after (red) the external diffusion of gaseous monomers in the uncross-linked cladding (a) and in the cross-linked core (b)*

Fig. 4(a) demonstrates the end facet microscope photo of a single sweeping line, i.e. the voxel (volume picture element) size in this cross section. Fig. 4(b, c) show the gradient index profile and an index contrast of 0.013 which doubles that of a standard single-mode fiber.

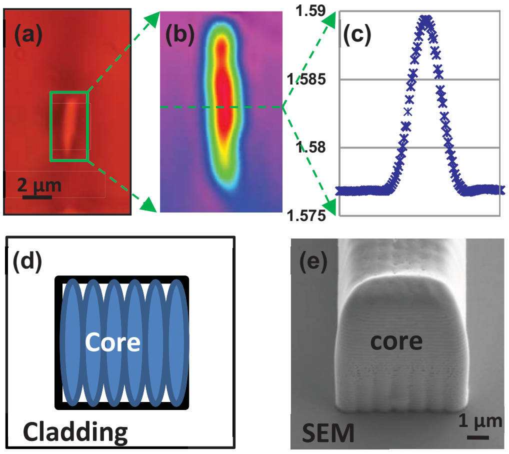

Fig. *4(a) Microscope picture of the end facet of a voxel size and (b) its refractive index profile in false color; (c)horizontal index profile showing a Gaussian distribution (d)multi-sweeping (e) SEM pictures of a waveguide core with multi-sweeping.*

Owing to high aspect ratios of the voxels, we exploited the multiple-sweeping to fabricate symmetric waveguides as depicted in Fig. 4(d). The smooth surface shown in Fig. 4(e) is attributed to the proximity effect which rounds out the gap between the inline voxels. In this SEM (scanning electron microscope) image, the cladding was not cured but rather developed by wet etching to reveal the waveguide core surface. The adjustable physical core dimensions with a matching mode field of single-mode waveguides were demonstrated [3]. Various trajectories of the 3D waveguides were also fabricated such as sine^3 or cosine^4. Their lengths of several centimeters are suitable for on-board interconnects.

In conclusion, a new concept of on-board 3D optical interconnect was introduced which could help to solve the bottleneck of electrical counterpart in data communication. Nevertheless, a further improvement of the fabrication process and a complete characterization are still needed to improve the performance.

5 References

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