Photopolymer Waveguide to Fiber Coupling via 3D Direct-Write Lithography

Charles D. Anderson, Robert R. McLeod
Department of Electrical Engineering, University of Colorado, Campus Box 425, Boulder, Colorado 80309
charles.anderson@colorado.edu

Matthew W. Grabowski, Amy C. Sullivan
Department of Physics, University of Colorado, Campus Box 390, Boulder, Colorado 80309

Abstract: We demonstrate a novel fiber to waveguide coupling in which fiber ends are encapsulated in photopolymer and located by specialized microscopes. Optical waveguides are formed directly off of the fiber cores via 3D direct-write lithography.

OCIS Codes: (160.5470) Polymers, (160.2900) Holographic recording materials, (130.3130) Integrated optics materials, (130.6750) Integrated optics systems, (130.2790) Integrated optics guided waves, (200.4650) Optical computing: Optical interconnects.

1. Introduction and motivation

Integrated optical circuits are typically butt-coupled to single-mode fibers held in precision silicon V-groove arrays. This operation requires time-consuming active alignment and is a common point of failure since the joint must be constrained against sub-micron motion only by the epoxy, solder, or laser-welding between the elements. Previous research into mechanically-constrained passive fiber connections has formed sockets in the circuit substrate either by ion etching of 125 mm grooves in polymer [1] or by selective etching of the silica waveguide core and fiber cladding [2]. After the placement of the fiber in the etched socket, the groove is filled with polymer or epoxy to hold the fiber in place and to index match across the fiber/waveguide interface. These methods can thus be thought of as forming the precision "V-groove" directly on the waveguide substrate after the waveguides are created.

Here we demonstrate an entirely different approach in which cleaved fibers are loosely positioned, then encapsulated in an optically-writeable polymer and finally connected to the circuit with waveguides written by 3D direct-write lithography. In contrast to both butt-coupling and the previous research, here the attachment of fiber has very loose tolerances since the waveguide is aligned to the fiber after curing of the polymer. This waveguiding medium is directly adhered to the fiber face and sides, so thermal- or stress-induced motion of the polymer should displace both the waveguide and the fiber, significantly reducing environmental sensitivity. The waveguides are not constrained to a plane and the method is extensible to other passive and active components, potentially enabling dense, fully hybrid optoelectronic circuits [3].

This technique is somewhat similar to earlier research [4,5] in which fiber is embedded in photopolymer and light from the fiber itself is used to expose short waveguides and fiber-to-fiber interconnects via a soliton-like self-writing. The major limitations of this method are an inability to control the waveguide path and the need to match the operational wavelength to the visible band in which photopolymers can be exposed. Recently this method has been used to create visible WDM circuits with encapsulated fibers and thin-film filters, illustrating the potential of these polymer materials to form inexpensive, hybrid circuits [6].

In this paper, we demonstrate deeply-buried waveguides in photopolymer written directly from the core of a single-mode fiber via 3D direct-write lithography. The waveguide is routed in 3D across more than 20 millimeters of polymer and into a second, multi-mode fiber offset both transversely and in depth. The second fiber is multi-mode due to the shape of the waveguide written by the translating focused beam; we address this shape and methods for its control elsewhere [7]. In this paper we develop the methods for locating the fiber tips and aligning the polymer waveguides to the detected locations.

2. 3D direct-write lithography with integrated 3D microscopy

Direct-write lithography into photopolymer is similar to femtosecond machining of glass waveguides [8] except that the large sensitivity of diffusion photopolymers [9] allows the use of CW lasers with microwatts of optical power. The additional requirement for this application is the need to determine the 3D location of encapsulated fiber tips within micron accuracy. This is accomplished by an integrated detection system operating at a longer wavelength outside the sensitivity band of the material. To meet the stated goal of micron accuracy, the detection and writing optics must use the same objective to avoid mis-registration between separate optical trains.

The depth location of the fiber in the polymer can be detected from Fresnel reflections generated by the small index mismatch between the polymer and the upper and lower cladding boundaries. By confocally filtering the return through the objective, these reflections can be precisely localized in depth, indicating the center of the core halfway between the two reflection peaks; in some cases the core itself can be directly detected. Longitudinal chromatic aberration of the objective or mismatch in the collimation of the two beams will cause a significant offset between the focal depths of the detection and writing wavelengths. A knife edge was thus encapsulated in a polymer sample and used to precisely measure the axial position of each color. The stage position during writing is offset by the difference just prior to writing.

This confocal microscope is not sensitive to the transverse spatial frequencies associated with the in-plane fiber edges and face and thus is not useful in locating the fiber in *x* or *y*. A second phase-contrast microscope is thus implemented through the same objective. Differential transmission scanning microscopy [10] uses a position-sensitive detector (PSD) to sense the deflection of the transmitted beam caused by transverse index gradients. This PSD also provides a highly accurate method to insure the detection and writing beams are registered transversely.

The resulting lithography system is shown in Figure 1. A HeNe laser is focused through a 0.55 NA molded aspheric objective corrected for 1.2 mm of spherical aberration. Reflections are confocally filtered and transmission is Fourier-transformed onto the PSD to implement the two microscopes. The 3D direct-write portion of the system is simply a doubled NdYAG at 532 nm blocked by a computer-controlled shutter. In order to access one millimeter of polymer without significant spherical aberration, the lens is stopped down to 0.3 NA. The sample is mounted on three-axis Newport PM500 stages and two NewFocus Picomotor tip/tilt stages. Confocal detection of the polymer surface is used to automatically align it normal to the beam.

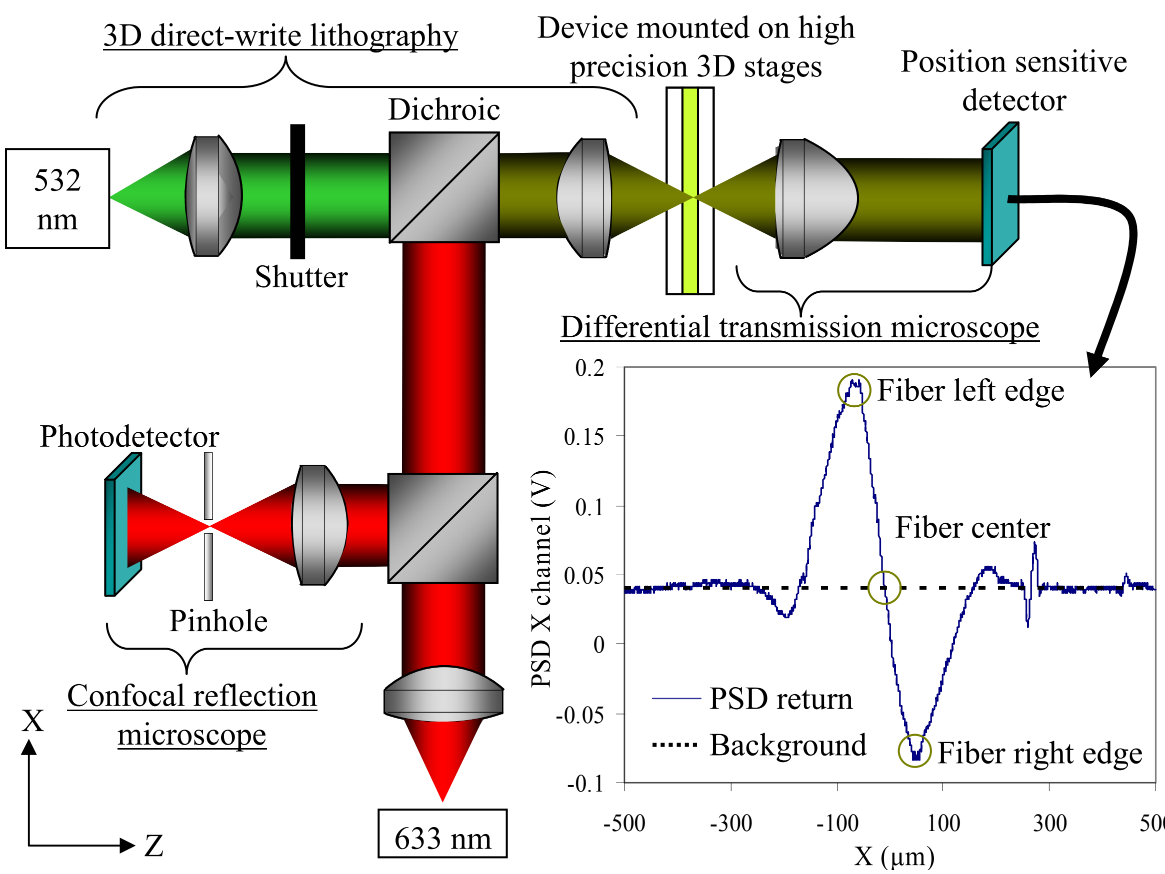

Fig. 1. Optical layout for detection and direct lithography system. Confocal reflection and differential transmission microscopes are implemented through the writing objective at 633 nm where the polymer is insensitive. The inset plot shows how the x coordinate of the fiber is located by the transmission microscope. Once the xyz coordinates of the two waveguide endpoints are determined, deeply buried waveguides are written by the 532 nm light as device is moved relative to the focus by the 3D stages.

3. Experimental demonstration

Single- and multi-mode 630 nm optical fibers are cleaved and loosely positioned facing one another on a 0.3×35×35 mm glass slide. The liquid precursor of InPhase Technologies Tapestry™ HDS3000 photopolymer [9] is cast over the slide, encapsulating several millimeters of the fiber ends as the upper cover layer is brought down to form a total polymer thickness of 0.7 mm. The polymer matrix then sets into a tough rubbery solid that adheres to the fiber and glass substrates, permanently positioning the fibers. As shown in the phase-contrast image of Figure 2a, the polymer is extremely optically uniform including regions near the fiber. Shrinkage stress around the fiber is sufficiently low that no detectable birefringence is present in the polymer. Once the *xyz* locations of the opposing fiber faces have been located, 125 µW of writing light focused to a 0.75 µm $1/e^2$ radius is moved between them at a velocity of 2 mm/second. The circuit is then exposed to uniform white-light illumination which bleaches the remaining sensitizer and fully polymerizes the sample, rendering it insensitive to further optical exposure.

Figure 2a shows a preliminary result in which a waveguide has been written directly off of the fiber face, demonstrating that the writing light can focus well at the fiber face and that the polymer responds uniformly up to this boundary. This waveguide is routed through two bends to the multi-mode fiber on the opposite side of the sample. In this experiment, coupling losses were quite large, as explained by the combined phase-contrast and bright-field microscope image in Figure 2b.

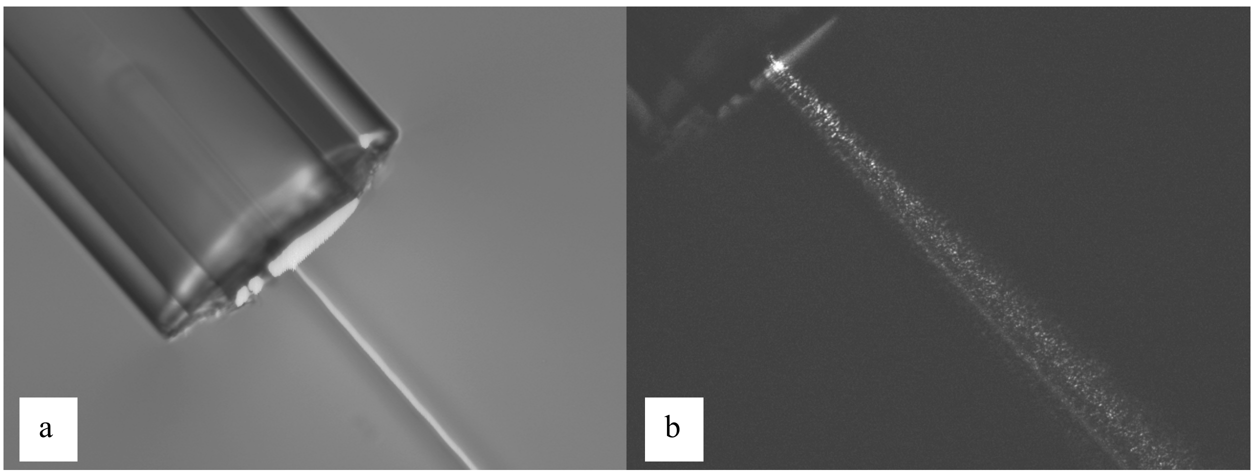

Fig. 2a. Phase image of the index structure written from the core of a single mode 630 nm fiber buried in 1 mm of glass (0.3mm) and polymer (0.7mm). Part b shows that a 4 um location error has caused most of the light to miss the guide.

4. Conclusions

We have demonstrated that optical fiber can be encapsulated in thick photopolymer and precisely located by a combination of reflection and transmission microscopes. Optical waveguides can then be written directly off of the fiber core without any traditional active alignment to implement a simple and robust hybrid optical circuit element.

Acknowledgements: The authors would like to thank InPhase Technologies for the use of the Tapestry ™ material and the Army Aeromedical Research Lab for financial support. Amy Sullivan is supported by an NSF IGERT.

1 B.L. Booth, "Low Los Channel Waveguides in Polymers," Journal of Lightwave Technology, 7, 1445-1452, (1989)
2 B. Gibson, S. Huntington, and J. Love, "Self-aligning method of fiber-to-waveguide pigtailing," Opt. Lett. 30, 2858-2860 (2005)
3 R. R. McLeod, A. C. Sullivan, M. W. Grabowski, T. Scott, "Hybrid Integrated Optics in Volume Holographic Photopolymer," in SPIE Annual Meeting 2004 (Denver, CO), Proc. SPIE (2004).
4 A. S. Kewitsch, A. Yariv, "Self-focusing and self-trapping of optical beams upon photopolymerization," Optics Letters 21, 24-26, (1996)
5 T. Yoshimura et. al., "Self-Organizing Lightwave Network (SOLNET) and Its Application to Film Optical Circuit Substrates," IEEE Transactions on Components and Packaging Technologies 24, 500-509, (2001)
6 M. Yonemura, A. Kawasaki, S. Kato, M. Kagami, "Polymer waveguide module for visible wavelength division multiplexing plastic optical fiber communication," Optics Letters, 30, 2206-2208 (2005)
7 M. Grabowski, A. C. Sullivan and R. R. McLeod, "3D direct-write waveguides in diffusion photopolymers," submitted to Integrated Photonics Research 2005
8 K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, "Writing waveguides in glass with a femtosecond laser," Optics Letters, Vol. 21, N. 21, Nov. 1, 1996.
9 L. Dhar, A. Hale, H. E. Katz, M. L. Schilling, M. G. Schnoes, and F. C. Schilling, "Recording media that exhibit high dynamic range for digital holographic data storage", Optics Letters 24, 487-489, (1999).
10 M. R. Ayres, R. R. McLeod, "Scanning transmission microscopy using a PSD," in preparation