# Fabrication of planar optical waveguides by electrical microcontact printing

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This letter describes the fabrication by electrical microcontact printing (E-$\mu$CP) of planar, optical waveguides, and splitters made of poly(4-vinylphenol) doped with phloxine B. This soft-lithographic technique uses a poly(dimethylsiloxane) (PDMS) stamp coated with a thin gold film to pattern the flow of current through the film of doped polymer. The current bleaches the phloxine B, and thus creates regions of high (unbleached; waveguide core) and low (bleached; waveguide cladding) refractive index. The maximum exposure time to obtain $\Delta n = 0.025$ was 90 s. This system is useful for guiding light having $\lambda = 600-1310$ nm. These polymer waveguides preserve polarization, and are able to guide light around 90° corners with a minimum radius of curvature of 1.6 mm. E-$\mu$CP patterned a $1 \times 4$ optical power splitter in 10 s. This technique is potentially useful for rapid prototyping of planar and multilevel optical devices.  [DOI: 10.1063/1.1651329]

This letter describes the use of electrical microcontact printing (E-$\mu$CP)[1] to fabricate planar, polymer-based, optical waveguides. In E-$\mu$CP, a poly(dimethylsiloxane) (PDMS) stamp coated with a gold film is placed in conformal contact with a polymer film [e.g., poly(methylmethacrylate) (PMMA) or poly(4-vinylphenol) (PVPh)] supported on a conductive substrate (e.g., a gold film on a silicon wafer). When an electrical potential is applied between the gold film on the stamp and the conductive substrate, current flows predominantly through the regions of polymer defined by contact with the stamp. We have previously described the use of this technique to pattern areas of electrostatic potential in thin films of PMMA.[1]

E-$\mu$CP lowers the refractive index of a film of PVPh [Fig. 1(a)] doped with phloxine B [Fig. 1(b)] by irreversibly bleaching the phloxine B. We used this technique to pattern regions of low refractive index (cladding regions) on either side of regions of a high refractive index (guiding regions), and thus to create optical waveguides. We designed, fabricated, and characterized straight and curved waveguides, and an optical power splitter. The planar geometries of the waveguides produced by E-$\mu$CP can be arbitrary in design, i.e., there are no constraints on the shape, number, or size of the guides that can be patterned. This technique provides a rapid, low-cost method for fabricating planar waveguides to be used in lightwave circuits.

Photobleaching of dye-doped polymers using lasers or UV light is another technique used commonly for the fabrication of planar waveguides.[2–4] Photobleaching uses illumination through photomasks,[2,3] or laser irradiation and mechanical translation,[3–5] to pattern optical elements. Photobleaching requires long exposures (>2 h);[2,4] the exposure times for E-$\mu$CP are shorter than those for photobleaching by at least a factor of 100 for similar areas. Distributions in the intensity and limitations in the size and power of the light sources limits the uniformity of patterns over large areas.[6] Polymer waveguides have also been prepared by molding and photolithographic techniques.[6,7] These guides require a planarization step to be used in multilayer devices, such as a microfluidic biosensor that would have a channel placed on top of the guides.

We chose a system of PVPh doped with phloxine B for this work because it possesses four attractive qualities: (1) the materials are commercially available, (2) the system is processed easily into thin films by spin casting, (3) the materials are transparent to red and near-IR light (600–1310

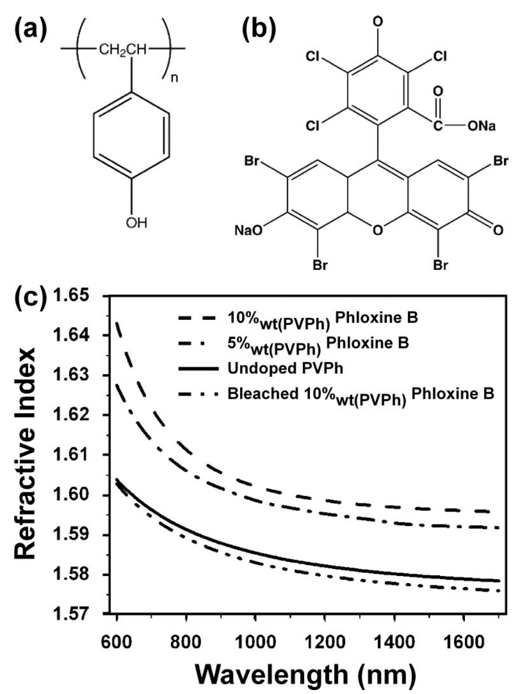


FIG. 1. (a) Chemical structure of poly(4-vinylphenol) (PVPh); (b) chemical structure of phloxine B; (c) plot of the refractive index as a function of wavelength for undoped, phloxine B-doped, and doped PVP bleached by E-$\mu$CP.

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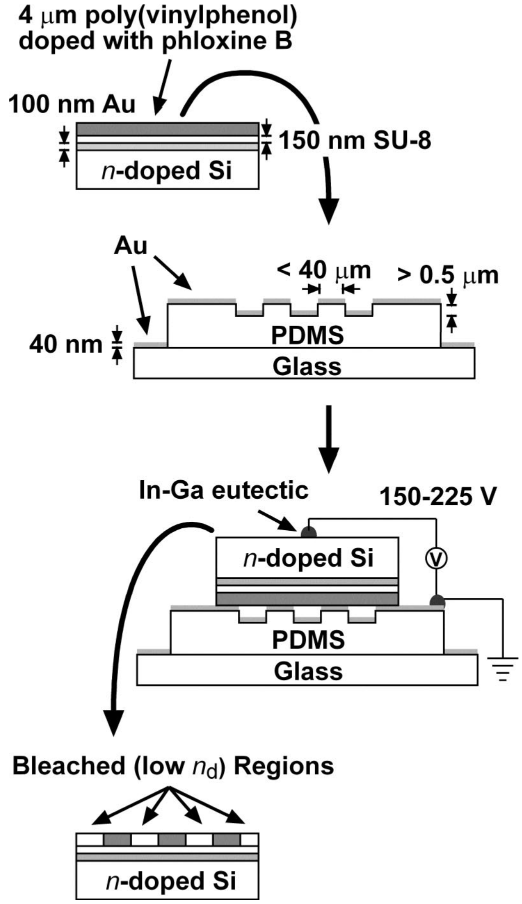


FIG. 2. Diagram describing the technique to bleach phloxine B by electrical microcontact printing (E-$\mu$CP) to form optical waveguides. The unbleached regions (dark) are the waveguides and the bleached regions (light) are the cladding for the guides. A detailed discussion of this figure is in the Supplemental Information.

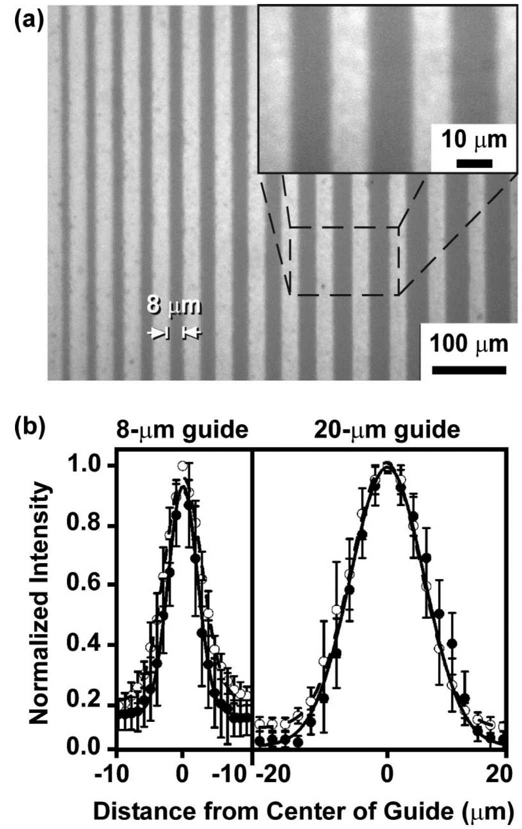


FIG. 3. (a) Optical micrographs of straight waveguides patterned by E-$\mu$CP. The light regions (low refractive index) are those that are bleached, and dark regions (high refractive index) are those that are not bleached. (b) Plot of the normalized intensity of light as a function of position of the fiber with respect to the center of the waveguides at 850 nm (closed circles) and 1310 nm (open circles). The input fiber and the collection objective were kept stationary while the guides were translated along the axis perpendicular to that of the input fiber. The solid (850 nm) and dashed lines (1310 nm) are Gaussian fits of the data.

nm), and (4) the difference in the refractive index of the doped- and undoped-polymer films is greater than 0.01 for these wavelengths [Fig. 1(c)].[8] This system is optically transparent to commercially important wavelengths, e.g., $\lambda = 850$ nm (data communications) and 1310 nm (telecommunications). In addition, previous research described waveguiding in photobleached, phloxine B-doped poly(vinylpyrrolidone).[9]

Figure 2 describes the process that uses E-$\mu$CP to print optical structures by bleaching the phloxine B. The supplemental information (EPAPS) discusses the experimental details for the process that uses E-$\mu$CP to print optical structures by bleaching the phloxine B.[10] We also include a discussion of the characterization of the surface of the polymer film after bleaching and the possible mechanism of the bleaching process.

We used E-$\mu$CP to prepare straight waveguides with widths of 4–20 $\mu$m. The guides shown in Fig. 3(a) are representative of those formed by bleaching the phloxine B completely (bleaching time of 90 s). The light was edge-coupled ($\lambda = 850$ and 1310 nm) from a single-mode, polarization-preserved fiber (6–8-$\mu$m-diameter; OZ Optics, Carp. Canada) into straight guides. The smallest guide into which we were able to efficiently couple light was ~6 $\mu$m in width. The polarization of the light was set to be parallel to the surface of the doped-polymer film. The coupling efficiency was measured to be ~20%.[11] Figure 3(b) shows the intensity of the transmitted light through guides of 8 and 20 $\mu$m in width as a function of location of the input fiber with respect to the center of each guide. The statistics were generated from data for 10, nonconsecutive guides and three separate samples. The light coming out of the guide remains polarized in the input direction to ~100:1; this ratio is equivalent to that of the light from the fiber. Figure 3 in EPAPS shows these data.[10]

The intensity of the light in 20-$\mu$m-wide waveguides (bleaching time of 90 s) guided around 90° corners with radii of curvature from 0.15 to 6.3 mm was measured for $\lambda = 780$ nm and 1064 nm [Fig. 4(a)]. The design and optical micrographs of these guides are shown in Fig. 1 in EPAPS.[10] We did not generate statistics for these data. We chose to characterize curved, multimode waveguides of 20 $\mu$m width because it was relatively easy to couple light into them, and to measure the output intensity of the guided light, while minimizing the background scattering. The critical radius of curvature for $\lambda = 780$ nm was ~1.6 mm and for $\lambda = 1064$ nm was ~1.7 mm.[12] The behavior of these guides was close to that predicted by an analytical approximation of coupled-mode theory.[13]

We also fabricated S-curve-shaped, 1×4 optical splitters by E-$\mu$CP. The design for the splitters was modeled using Free BPM (Fig. 2 in EPAPS[10]).[14] The input guide in the

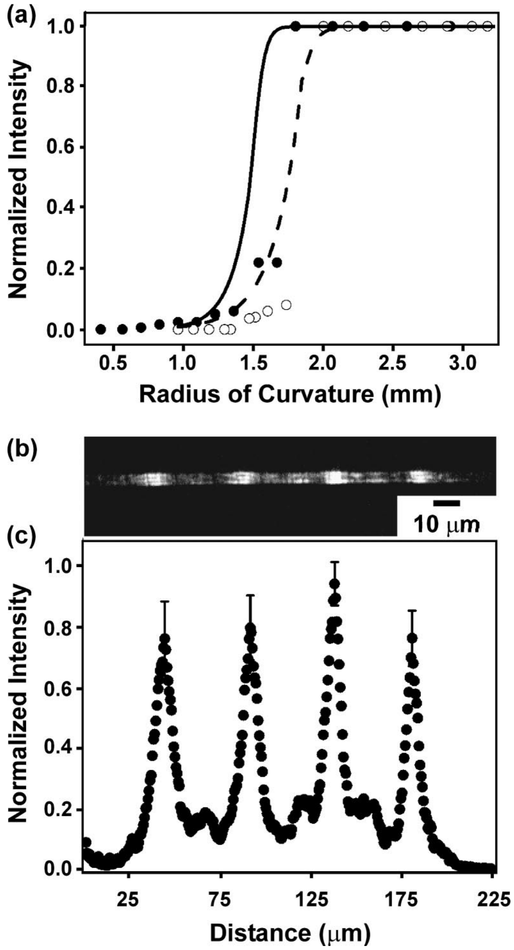


FIG. 4. (a) Plot of the normalized intensity as a function of the radius of curvature at 780 nm (closed circles) and at 1310 nm (open circles). The solid (780 nm) and dashed (1310 nm) lines are the theoretical calculations of the optical loss vs radius of curvature; (b) optical micrograph of the cross section of the output side of the $1\times4$ optical splitter; (c) plot of the intensity of the output beams as a function of distance along the edge of the guides. The individual peaks correspond to the individual outputs shown in (b).

power splitter has lateral dimensions of 20 $\mu$m and the output guides have lateral dimensions of 10 $\mu$m. This splitter was fabricated by E-$\mu$CP with an exposure time of 10 s, i.e., the phloxine B was not bleached completely. The difference in the refractive index for these guides was $<0.005$.[15] We demonstrated the function of this device at 780 nm [Figs. 4(b) and 4(c)] and it performed as predicted (Fig. 2 in EPAPS[10]).

Electrical microcontact printing can pattern optical waveguides of arbitrary shapes over areas $>1$ cm$^2$. These waveguides operate at commercially useful, visible, and near-IR wavelengths. The fabrication process is rapid ($<1.5$ min) and is low cost because it does not require the use of specialized equipment (e.g., high-power lasers or high-voltage (kV) power supplies). The bleaching process is effectively irreversible under ambient conditions; guides prepared by this technique that were over four months old retained their patterns without any measurable change in refractive index contrast or in performance.

The technique has three limitations: (i) the bleaching of featureless, large ($>0.5$ cm$^2$), areas uniformly is difficult; the exposure of these areas tends to leave regions of unbleached material. We believe the unbleached regions result from nonuniform contact of the stamp with the surface of the polymer film. This fact does not affect the performance of the guides as long as the regions immediately lateral ($\sim$200 nm in width) to the guides are bleached, but may increase the amount of background light guided by the polymer matrix itself. Incorporation of rectangles (with their long axis aligned perpendicular to the length of the guide) can reduce the amount of unbleached area and the amount of background light. (ii) The time required to pattern the polymer film increases with both thickness of the film and concentration of the dopant. The thickness of the films must be $<5$ $\mu$m and concentration of the dopant must be $<10\%_{\mathrm{wt(PVPh)}}$ for reasonable exposure times (1.5 min). (iii) The polymer system is not well suited for guiding of 1550–1650 nm light (long-haul communications) because of absorption due to C–H vibrational overtones.[6]

We believe these waveguides may be useful for the rapid prototyping of multilayer devices—e.g., optical biosensors and three-dimensional lightwave circuits—as these applications require topologically planar surfaces.

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[8] Refractive index of the polymer films was measured on a J. A. Woollam VASE spectrometer.
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[10] See EPAPS Document No. E-APPLAB-84-006409 for experimental details and additional discussion. A direct link to this document may be found in the online article's HTML reference section. The document may also be reached via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html) or from ftp.aip.orgin the directory /epaps/. See the EPAPS homepage for more information.
[11] Coupling efficiency was measured by dividing the value of the intensity of light emitted from the end of the guide by that emitted from the end of the fiber.
[12] Minimum radius of curvature necessary for guiding light around a corner is related to the difference in the refractive index between the core and the cladding of the guide. This value ($\Delta n_{(780)}=0.023$ and $\Delta n_{(1064)}=0.019$)was similar to that for $\lambda=850$ nm and $\lambda=1310$ nm ($\Delta n_{(850)}=0.021$ and $\Delta n_{(1310)}=0.019$), and thus we expect these wavelengths to have cutoff radii similar to those measured.
[13] T. Tamir, *Guided-Wave Optoelectronics*, 2nd ed. (Springer, New York, 1998).
[14] This freeware uses the beam propagation method to model the behavior of light in 2D waveguides. The software is available at http://www.freebpm.com
[15] Modeling software suggested that a small change in refractive index would yield high-quality splitters based on our design.