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# Modeling and characterization of novel, low-cost, direct-write waveguide

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*M.A. Mignatti, M.I. Campbell, R. Ruizpalacios, K.L. Wood and J.J. Beaman*

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## Keywords

Thin films, Wave properties, Optical communication equipment, Wave physics, Wavelengths

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## Abstract

Both the current long term telecommunication trends toward optical networking and the recent growth in information bandwidth have pushed the necessity for improved optical communications. Our fabrication approach, which leverages our expertise in solid freeform fabrication in conjunction with sol-gel technology, has advantages over these other methods because of the inherent benefits of using a direct-write philosophy, such as design flexibility and minimal post-processing. However, fabrication of such novel optical components requires extensive knowledge of their light guidance capabilities. This paper shows the technical issues involved in both modeling and characterizing small optical components fabricated by locally densifying sol-gels in a modified direct-write process.

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## Introduction

The use of sol-gel technology with direct-write manufacturing techniques facilitates the construction of integrated optical devices, including three-dimensional communication devices with low-losses and increased functionality. Sol-gels are created in a low-temperature process that utilizes a colloidal silica suspension to create a porous silicate gel of high purity. The introduction of dopants in the sol-gel alters the resulting silica structure and thus can be used to produce glasses with novel optical properties (Pierre, 1998). The sol-gel process has inherent advantages over other small-scale fabrication methods since it is a low temperature process and the resulting materials are both homogeneous and of high purity.

Direct-write manufacturing techniques for fabrication of micro-scale optical components involves focusing of a laser onto the desired workpiece and writing a desired pattern or shape by moving either the beam itself or the workpiece via a high-precision multi-dimensional stage (Hansen *et al.*, 2002). The chief advantages of this process over traditional lithographic techniques such as CVD are that the direct-write process does not require the use of masks or caustic etchants. Additionally, in the direct-write process parts are made directly from CAD files, eliminating the need for tooling changes and thus increasing the flexibility of the process.

Using these direct-write techniques with sol-gel technology enables the fabrication of novel optical waveguides. Laser interaction with porous silica structures results in a localized change in the refractive index of the sol-gel, which can then be used to guide light. Additionally, the use of lasers in the process allows for the creation of waveguides with novel shapes such as unique curves and bends, and even, the creation of a truly three-dimensional waveguide. The main benefits with sol-gel are its inherent low-cost, flexibility to design and material changes (e.g. use of dopants), and unlimited geometry.

Fabrication of such a device requires extensive knowledge of both manufacturing techniques and light guidance capabilities. Extensive modeling and testing are therefore necessary to fully realize and utilize the



properties and benefits from the direct-write manufacturing technique. This paper discusses efforts completed in the last year at both the modeling and experimental characterization of a sol-gel waveguide manufactured using direct-write techniques. The organization of the paper is as follows. First, we present an overview of the manufacturing process. Next, we discuss applicable thin-film characterization techniques and associated efforts to realize characterization. This is followed by a section presenting a description of the modeling efforts to date. The final section presents preliminary results and is concluded with a discussion including future work.

### Process overview

The manufacturing process is comprised of four main steps: the sol-gel is first prepared; the sol is deposited onto a substrate using standard spin-coating techniques; the wafer and sol-gel are heat treated; and finally a path is locally densified with a laser. In general, sol-gel processes take advantage of the hydrolysis of a precursor (in the presence of a catalyst), followed by condensation and polycondensation reactions to form particulate and polymeric structures (Ruizpalacios *et al.*, 2003).

As mentioned earlier, the second step in the process is the deposition of the sol-gel onto a substrate – either silicon wafers[1] or borosilicate glass slides. This is done using standard spin-coating techniques. Spin-coating allows for quick depositions in a controlled environment with layer thickness and uniformity controlled by process variables, such as differential velocity profiles and deposition times. Deposition film thicknesses are typically between 300 and 600 nm. After successful deposition has occurred, the wafer is pre-sintered. Appropriate heat treatment represents one of the most crucial steps in the process. Heat treatment reduces film stresses which lead to cracking and it increases the global index of refraction, as sol-gel density and index of refraction are directly related (Hench, 1998).

The final step in the process is laser densification using direct-write techniques. The sample is first mounted on a two-dimensional stage with a resolution of  $0.5 \mu\text{m}$ . A 50 W  $\text{CO}_2$

laser with an operating wavelength of  $10.6 \mu\text{m}$  and a spot size of approximately  $80 \mu\text{m}$  is used for densification. Using a moving test bed allows us to characterize systematically both the laser power and scan speed, which are crucial in locally increasing the index of refraction without ablating the sol-gel film. Additionally, precise control of the laser's power and duty cycle allows for specific geometries and patterns to be written onto the film. Once laser densification has been completed, the sample is then tested for its light guidance properties.

### Waveguide characterization

To determine the exact properties of the individual waveguides created, and thus to evaluate their future potential as light guidance devices, the waveguides must be fully characterized. Specifically, characterization refers to measurements of both the index of refraction and the index profile in the guided region, film thickness and attenuation of the laser-densified sol-gel films. All global index of refraction measurements, such as index of the film (before laser-densification), are measured with ellipsometry techniques. A two-prism coupler method is used to determine the index of refraction and film thickness characteristics. Both a three-prism coupler technique and an end-fire method are used to study the attenuation of the waveguide.

Multiple-angle ellipsometry techniques are capable of measuring the global film index and initial film thickness, assuming that the film is less than a few microns thick. In ellipsometry, collimated, coherent and polarized light is incident on the surface of a thin-film; both the change in polarization and the phase shift of the reflected light are then measured (Azzam, 1995). From these measurements, the index of refraction and film thickness are calculated. Unfortunately, ellipsometry cannot be used to measure the index of refraction in the densified region due to the large spot size of the ellipsometer.

The technique used to characterize the guided region of the waveguide is the two-prism coupler method. Implementation of this method requires 2 mm scale prisms with high index of refraction, such that  $n_{\text{prism}} \gg n_{\text{film}}$ .

Figure 1 shows a schematic of the three-prism coupler; implementation of the two-prism method is identical, but uses only prisms one and three. Prism one is clamped onto the waveguide in the region where light is coupled into the guide. When light is incident on the face of the prism at a particular angle, as measured from the normal to the prism face, a specific mode becomes excited within the film (Chen, 1991). This coupling occurs because the phase matching condition is satisfied at the prism/waveguide boundary: as the horizontal portion of the incident wave approaches the propagation constant<sup>[2]</sup> of the waveguide, light will begin to tunnel into the guide. Maximum coupling occurs when the propagation constant is equal to the horizontal portion of the incident wave (Chen, 1991). The second prism is typically at the far end of the waveguide with a photodetector attached. Coupling of specific modes corresponds to peaks in the power output as measured by the photodetector. When more than three modes are present, a root mean square approach is necessary to determine the precise index of refraction and film thickness.

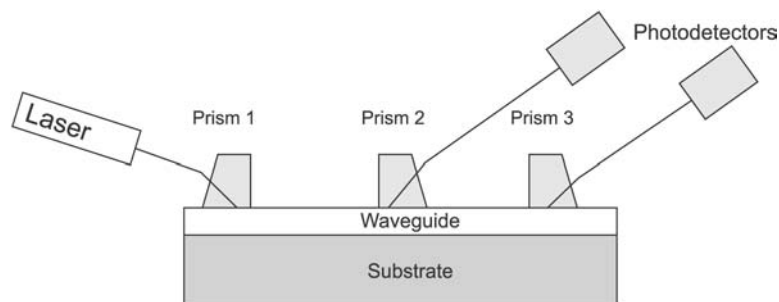
For attenuation measurements, the two-prism method is modified by the introduction of a third prism. A schematic of this setup can be seen in Figure 1. The additional prism, labeled as Prism 2 in this figure, is free to move laterally along the length of the waveguide, and has a photodetector mounted to it. The mobile prism is used to find power readings at various points along the guide, a technique which yields improved loss measurements, as the attenuation is measured as a function of the waveguide length (Tien, 1971).

The advantages of using the two-prism coupler method for index and thickness characterization lie in the accuracy of the results.

If more than two modes are excited, the accuracy of the measurements becomes self-checking (Ulrich and Torge, 1973). While this method will yield very accurate results, implementation is remarkably difficult. The size of the prisms makes handling difficult, and as they need to be optically smooth during use, any imperfections will alter the results. Clamping of the prisms to the waveguide is also challenging. The prisms cannot be clamped too tightly, else the integrity of the film will be disturbed and the waveguide itself will be warped, altering the light propagation. If the clamping is too loose, scattering will occur due to the air gap between the prism and waveguide. Additionally, the method demands accurate measurements of incident light on the prism relative to the face normal. Ulrich and Torge (1973) recommend using a rotation stage with accuracy better than one arc minute. Locating the center of the prism face at the normal angle is also a significant challenge.

Another method, known as the end-fire method, is also used to characterize the attenuation of the waveguide. In this method, light is coupled into the waveguide through a microscope objective lens which focuses a laser beam into the film and, after the light propagates through the film, the light is detected at the other end in the same manner. Coupling of light in this fashion requires that the ends of the waveguide are cut and highly polished, else the coupling losses would be substantially high and no light would be effectively coupled into or out of the waveguide. The output power is measured by a photodetector mounted at the exit. The end-fire method does not require measurements as precise as the three-prism coupler method, but it does require the ends to be optically polished so that surface roughness is less than  $0.5 \mu\text{m}$ . Polishing must be done after

Figure 1 Three-prism coupler schematic



both the film deposition and laser densification steps and, because the polishing process is destructive, there is potential for film damage. Additionally, polishing the end of a wafer (approximate thickness of 0.5 mm) is extremely challenging and requires special polishing jigs to hold the sample without damage. The other drawback of this method is that, to characterize the attenuation losses as a function of waveguide length, several samples of different lengths will first need to be prepared, cleaved, and polished. Thus, the method is performed iteratively over a number of assorted sample lengths.

Figure 2 shows a current implementation of the three-prism coupler method. The exciting laser is a HeNe with an operating wavelength of 632.8 nm. The prisms which have a 5 mm square base, are made from lithium tantalate ( $\text{LiTaO}_3$ ), and have an index greater than 2.1. In this configuration, the waveguide is mounted vertically on a rotation stage with a resolution of one arc minute. Additionally, the mounting platform must be optically flat in both the horizontal and vertical directions as any slight deviation can produce erroneous results.

## Modeling

This section focuses on a computational model we created to study light propagation through waveguides manufactured via the aforementioned direct-write process.

The development of the model is centered on the chief attributes associated with this process, namely localized refractive index change.

The model was conceived as a design tool to assist the waveguide designer in determining the utility of a novel waveguide. Figure 3 shows the changes in the index of refraction over a sol-gel component. The designer is free to choose all aspects of this profile, including the extent and locations of local index changes and the nature of these changes (graded or defined step). Once the designer has created the waveguide profile, it is then fed into the propagation model along with initial state information such as location and trajectory of the light. After the propagation has been calculated, the designer will receive output in the form of a graphical representation of the path of light through the waveguide.

The type of refractive index profile used by the designer is largely governed by the beam profile of the incident laser. The beam profile for the  $\text{CO}_2$  laser used for densification is a Gaussian, as shown in Figure 4(a). Gaussian profiles are typically measured by the beam half-width, which is the point where the average power drops to approximately 14 percent (Hecht, 1998). With a given spot-size, most of the power will therefore be at the center of the spot, decaying exponentially outward. As the densification process is thermally driven, it follows that the largest change in refractive index will occur at the center of the beam/film interface. The scan speed and laser power also play a major role in shaping the refractive profile, as slow scan speeds allow significant thermal diffusion from the beam center, and therefore the resulting refractive profile is wider than the spot size (Figure 4(b)). Additionally, as the densification process is physical in nature, there will likewise be a physical change to the film in the form of localized shrinkage, as shown in Figure 4(c).

Conceptually, the algorithm that drives the model is based on Huygens's Principle. Huygens was the first physicist to suggest that light traveled in a series of propagating wavefronts. This principle is used to model light propagation through distinct media with planar point sources. Each of these point sources will propagate a new wavefront with a trajectory based on both the current index of refraction and a discrete time step. This instantiation of Huygens's Principle allows for propagations of various light phenomena, particularly reflections and refractions. It should be noted

Figure 2 Current implementation of the three-prism coupler method

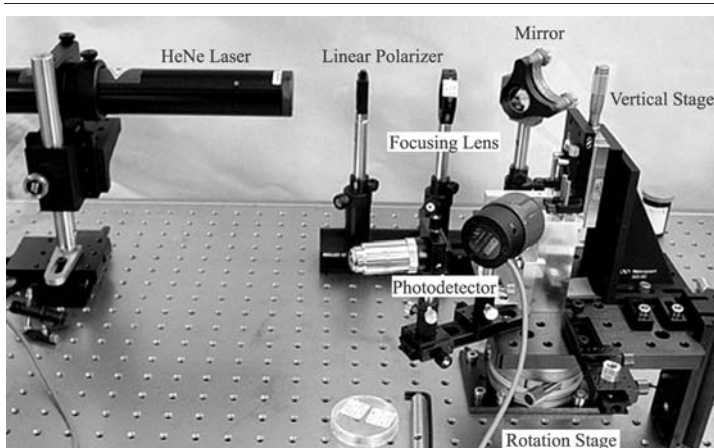
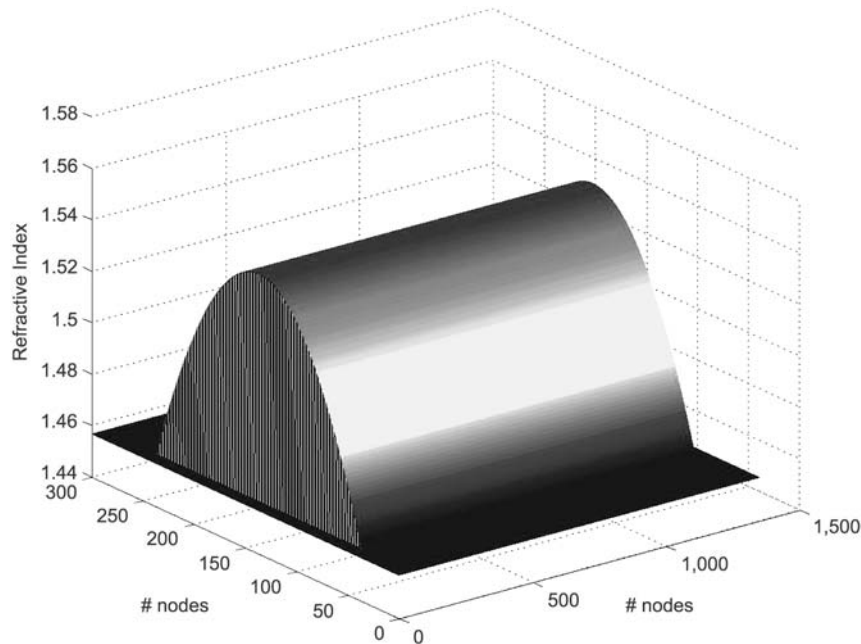


Figure 3 Waveguide modeled as refractive index profile



that, while based on the wave nature of light suggested by Huygens's Principle, this algorithm lies in the physical or geometrical optics domain. The ray is used to map the path of the wave so that it can be represented graphically.

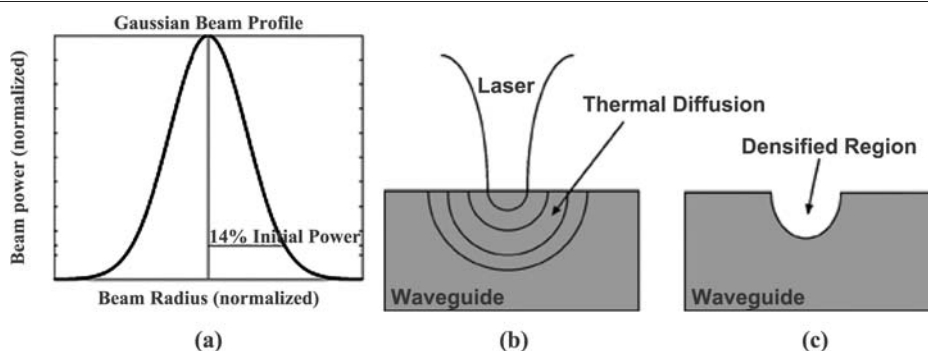
Huygens's Principle has been employed in the model using a finite-difference approach. While the algorithm has a geometrical foundation, finite-difference approaches are, strictly speaking, based on discretization of derivatives, generally differential equations. Our approach discretizes the light into a series of positions at discrete time intervals. The first step in the problem is to discretize the waveguide into a grid or mesh of nodes, with equal spacing in each direction of the grid (Note: the spacing need not be the same in all directions, but each

distinct direction needs to have uniform spacing) (Greenberg, 1998). The discretization occurs in two spatial dimensions with respect to the refractive index profile and in the temporal dimension with respect to overall propagation. Thus, the model uses the same basic framework as a finite-difference approach, but a geometrical interpretation is substituted for the differential equation.

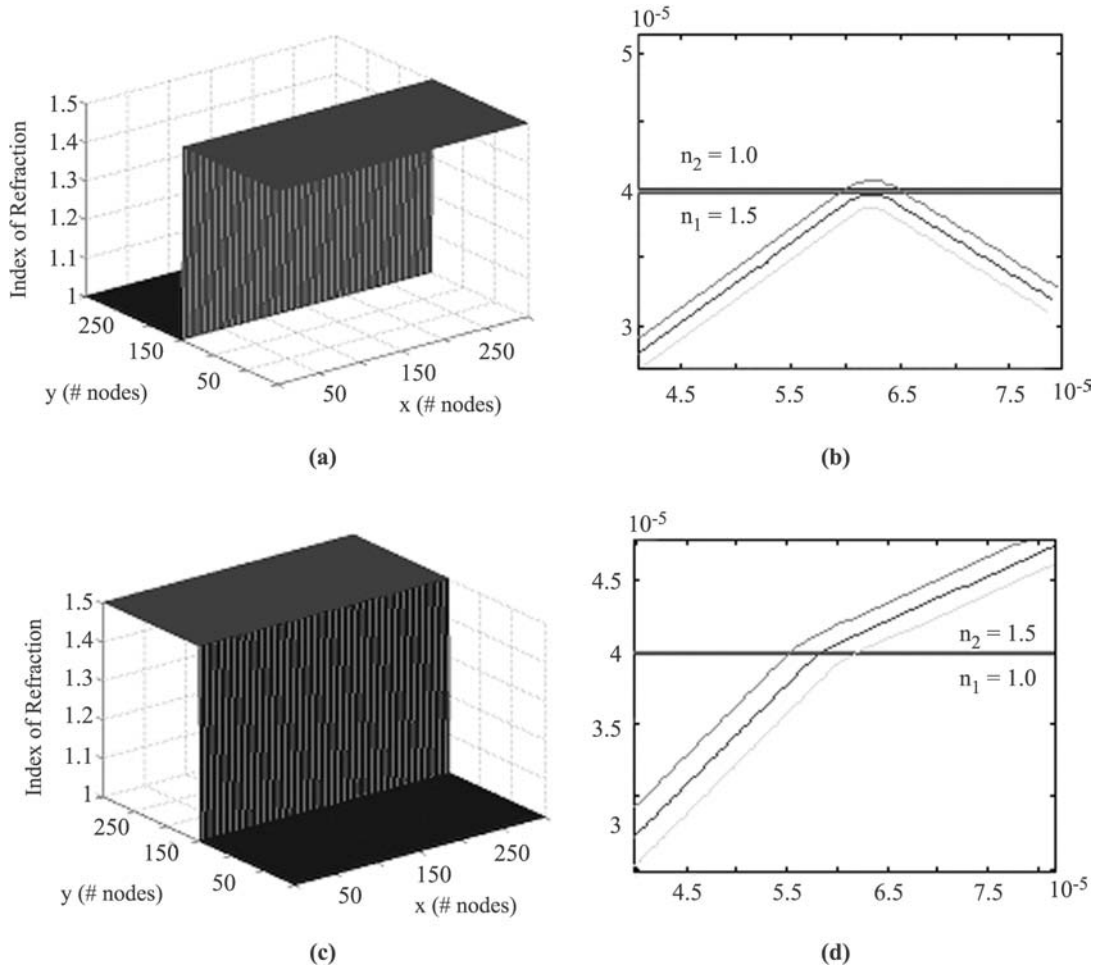
**Results and discussion**

Figure 5(a) and (c) shows two refractive index profiles and the subsequent light propagation through each profile is shown in Figure 5(b) and (d), respectively. The step down profile (Figure 5(a)) is representative of the interface

Figure 4 Gaussian profile and thermal/physical effects



**Figure 5** Step profiles and associated propagation. Figure 5(a) Shows a step-down profile and associated reflection while Figure 5(b) Shows a step-up profile and associated refraction



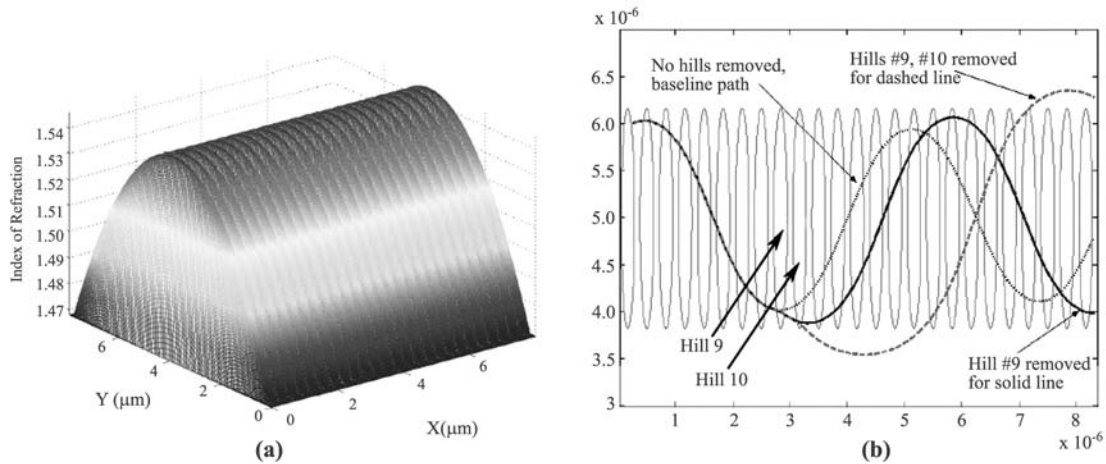
between core and cladding of a step-index fiber and its propagation is a simple reflection. The step-up profile (Figure 5(c)) is representative of the interface between air and glass and its propagation is a simple refraction. As these figures demonstrate, the model predicts both reflections and refractions with less than 1 percent error relative to Snell's Law. These results verify that the model is producing accurate results and is useful as a tool to study propagation through a waveguide.

Figure 6(a) and (b) shows plots of a unique refractive index profile and subsequent light propagation through this profile. The refractive index profile is conceptualized as an array of refractive index hills. The index of refraction is the highest at the center of each hill, and the hill size corresponds with the spot size of the incident laser, approximately  $5\text{--}10\ \mu\text{m}$ . Notice that as the light travels through the waveguide,

its path is sinusoidal in nature, and similar to that of a graded index waveguide. Strategic placement of these hills can significantly alter the trajectory of the path of the light, as shown in Figure 6(b). Conceivably, this sort of profile could be tailored to guide only particular wavelengths or trajectories of incoming light. Additionally, as this profile is only  $80\ \mu\text{m}$  in length, it remains a viable option for integrated optics applications.

Characterization efforts to date have yielded results only from the ellipsometry method as shown in Table I. Listed in the table are index of refraction and thickness results. Other characterization efforts have yet to be completed. These results are preliminary, but show a significant index difference between the film and substrate. The maximum index difference,  $\Delta n$ , is crucial to contain light within the film. Without local densification the light

**Figure 6** Refractive index profile and associated propagation path. Note that in Figure 6(b), the aspect ratio is not one-to-one and ovals represent the refractive index hills



**Table I** Representative ellipsometry results

Sample	Substrate index	Film index	Film thickness (nm)	$\Delta n$ (percent)
10 percent Ti-SiO <sub>2</sub>	1.4537	1.4837	372	2.05
10 percent Ti-SiO <sub>2</sub>	1.4537	1.4933	307.4	2.65

will not be confined to a specific region of the waveguide and significant scattering losses will occur. Typically, current optical fibers achieve a  $\Delta n$  of the order of 1 percent (Agrawal, 1996) which is half of the change in refractive index that we have been able to achieve. However, while we have been able to couple light only, we have not yet coupled light into the guided region of the film.

## Conclusions and future work

This paper describes research efforts to model and characterize a novel sol-gel based waveguide manufactured with direct-write techniques. The computational model is built on the idea of localized change in refractive index and allows the designer to create an arbitrary refractive index profile. While the designer is free to choose any refractive index, the profile should be realistic, thus the typical fully dense index range is between 1.47 and 1.49. Additionally, there are geometric and process limitations that restrict the shape of the refractive index profile. Furthermore, as characterization efforts come to fruition, real index data, including index profiles of the

guided region, will be incorporated into the model thus increasing its accuracy.

Efforts to further validate the model are currently underway. These involve determining the actual index profile created from the laser densification and creating an experimental setup to verify model predictions. Efforts are also underway to complete the characterization of the waveguides, and preliminary results are promising.

## Notes

- 1 To guide light with pure silicon wafers, an oxide buffer layer must exist between the film and the wafer. This is primarily because pure silicon has an index of refraction much greater than the film.
- 2 The propagation constant is the magnitude of the wave vector, decomposed into its  $x$ - and  $y$ -components. The wave vector describes the propagation of light waves in distinct media. Each wavelength has a unique wave vector.

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