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Laser Direct-Write of Novel Optical Components

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Abstract: The combination of direct-write techniques with the deposition of sol-gel films has the opportunity of creating low-cost optical components. Recent advancements in both fields suggest the possibility of fabricating novel components for rapid prototyping purposes. This paper presents continuing work in the integration of these two concepts for the development of a novel manufacturing process. The results concentrate on laser processing stage, as well as on the optical characterization of simple waveguides.

1. Project Summary: The recent increase in demand for information bandwidth has created the need for improving current technologies for data, voice and video transmission. New technologies have emerged addressing different aspects of networking, such as transmission protocols, communication devices, and manufacturing methods of these devices. Two particular areas of interest in the advancement of ultra-high capacity optical networks include function integration in optoelectronic components and the use of advanced materials. The combination of advanced materials derived from sol-gels with direct-write technologies, has the potential of addressing these initiatives.

Direct-write technologies are manufacturing processes characterized by the use of computer-generated patterns and shapes for direct fabrication without part-specific tooling. They represent a set of emerging technologies, with the potential to compete with conventional fabrication techniques in the microelectronics and photonics fields. They lie at the forefront in research and development as alternatives of current photolithographic technologies (Miura, Qiu *et al.*, 1997; Church, Fore *et al.*, 2000; Piqué and Chrisey, 2002). Some of the main objectives include the reduction of steps for fabricating net-shape two- and three-dimensional structures.

The deposition of sol-gel films offers great versatility to modify specific properties, such as index of refraction, through the strict control of processing parameters (concentration, pH, temperature, humidity) in combination with high-purity sol-gel precursors (Brinker and Scherer, 1990). This approach has received great attention because of the possibility of low processing temperatures and standard atmospheric conditions, together with the ability to produce highly pure materials directly from their synthesis.

On the other hand, the use of a laser as a photophysical source is equally attractive to selectively induce structural or chemical changes by increasing the density of the matrix or polymerizing the network; see for example (Shaw and King, 1990; Bae and Park, 2001). High temperatures can be achieved over small localized areas with heating rates in the order of 10^3K/s. A direct relation exists between a sol-gel's density and index of refraction (Hench, 1998); hence the ability to control the index of refraction through density changes based on laser power control is an area of keen interest.

This paper reports the work in progress done over the past year towards the development of a novel direct-write manufacturing process for optical components. We have included a description of the experimental procedures, followed by some concluding remarks.

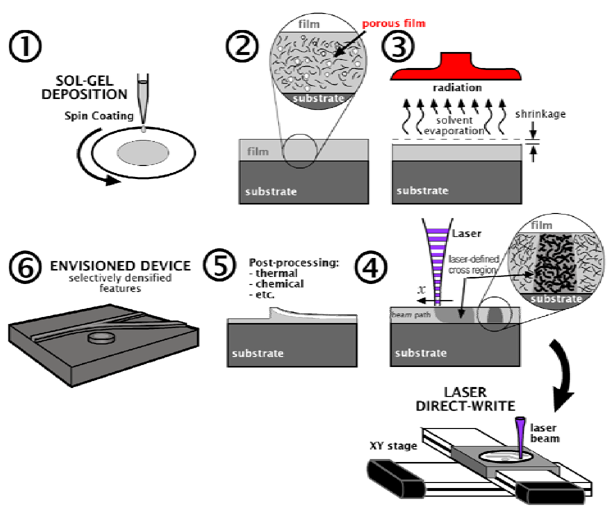


Figure 1. Proposed direct-write process

2. Proposed Direct-Write Process: The proposed direct-write process consists of combination of three simple steps: (1) deposition of the sol-gel film by spin coating, (2) thermal treatment of the sol-gel film to promote further condensation of the network while eliminating unwanted solvents, and (3) laser scanning to define the features on the sol-gel film. The process is depicted in Figure 1.

3. Experimental Procedure: This section briefly describes the experimental procedures that were followed, beginning with the synthesis and deposition of the sol-gel solution, then the heat-treating process to obtain desired film thickness, the laser densification step, and finally the optical characterization of the films. Figure 2 illustrates in general the experimental procedure that was followed.

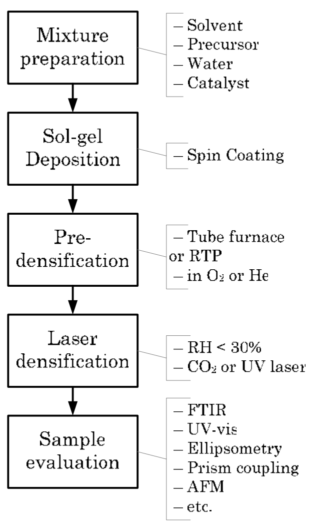


Figure 2. Experimental procedure

3.1. Sol-Gel Synthesis and Deposition of Thin Films: Organically modified silica based sol-gels were synthesized based on standard procedures (Fardad, Andrews et al., 1997). Zircomium-IV propoxide (ZPO) was used as the dopant precursor, in conjunction with methacryloxy-propiltrimethoxysilane (MPTMS) as the organic-inorganic silica source, and methacrylic acid (MAA) as chelating agent. All the reagents were used as received from Aldrich. The alkoxides were hydrolyzed with acidified water (0.05N HCl), and later diluted in ethanol (EtOH) prior deposition.

The sol-gel films were deposited by spin coating onto fused silica, and Si wafers with a grown oxide layer of 2.4 μm. Prior to deposition, the substrates were thoroughly cleaned by standard procedures with trichloroethylene, acetone, isopropanol, and de-ionized water. The films were spin coated using a single-wafer spin processor at velocities between 2500 to 4500 rpm for 30-40sec, under a solvent saturated atmosphere of N_2 and O_2.

3.2. Thermal Processing: The thermal treatment of the sol-gel film is necessary to help consolidate the film and remove undesired byproducts residing in the pores of the structure. The thermal process must avoid the development of cracks in the film due to residual stresses induced during the solvent evaporation, undesired particles, and the competition between densification and crystallization during thermal treatment. To address this problem we implemented a low-cost rapid thermal processing (RTP) furnace, which can achieve high heating rates of ~100°C/min. RTP is a standard processing technique in the semiconductor industry.

In previous work we demonstrated the importance of a pre-baking step to reduce structural inorganic components that remain in the film (Beaman, Ruizpalacios *et al.*, 2003). These have been associated with attenuation measurements (Righini and Pelli, 1997). We provided spectroscopic evidence of the advantages of this step through Fourier transform infrared spectroscopy (FTIR), for characterization of the molecular structure. This additional step was implemented during the thermal processing of the films, and involves a low temperature drying step done immediately after film deposition. We performed similar experiments to verify that this would also be beneficial for hybrid organic-inorganic sol-gel films. Temperatures of up to 550°C remove most of the inorganic compounds, while at ~900°C the structure closely resembles a fully inorganic glass.

In the case of hybrid sol-gels synthesized for photopolymerization, much milder temperatures were used: 80°C for pre-bake, and 150°C for hardbake.

3.3. Laser Processing: The final step in the process is laser densification using direct-write techniques. The sample placed inside a controlled atmosphere chamber, which is mounted to an XY stage using linear servo motors with a resolution of 0.5 µm. Figure 3 shows a picture of the setup. For densification and polymerization, a 300 mW UV laser operating at a wavelength of 244 nm and a spot size at the specimen of approximately 8 μm was used. Typical values for the scanning speeds and laser power are 0.2 – 1.5 cm/s, in combination with laser powers of 20–80 μW for polymerization and 150–350 mW for densification. Additionally, CAM software is used to generate the motion profiles defined from a CAD model of the laser's trajectory. The laser power is controlled through software developed in LabVIEW, which interacts with the XY-stage's controller. Precise control of the laser power and duty cycle allow 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.

The resultant refractive index profile is largely governed by the beam profile of the incident laser, which in this case was 94% pure Gaussian, achieved after beam correction. Gaussian profiles are typically measured by the beam half-width, which is the point where the average power drops to approximately 14% (Siegman, 1986). With a given spot-size, most of the power will therefore be at the center of the spot, decaying exponentially outward. The densification process is mainly photo-thermal, and the largest change in refractive index will occur at the center of the beam/film interface. The scan speed and laser power play a large role in shaping of the refractive profile, as slow scan speeds allow for significant thermal diffusion from the beam center, and therefore the resulting refractive profile is wider then the spot size. Additionally, as the densification process is physical in nature, there is likewise a physical change to the film in the form of localized shrinkage.

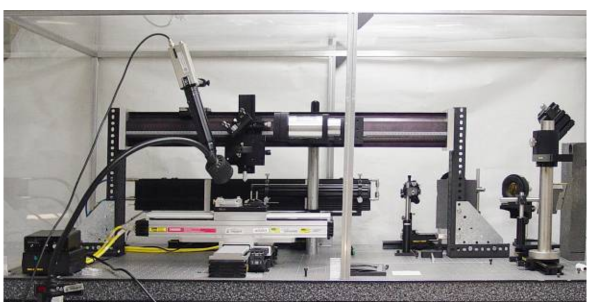


Figure 3. Laser processing station

3.4. Optical Characterization: In previous work, the film was characterized by a number of standard techniques (Beaman, Ruizpalacios *et al.*, 2003). These included variable angle ellipsometry for thickness and index of refraction measurements, atomic force microscopy (AFM) for surface roughness and film morphology, and a profilometry to measure the cross-sectional profile of the densified region.

For this paper we concentrated on demonstrating the feasibility of the process by coupling light into simple waveguides. Light from a HeNe laser (632.8 nm) was coupled into the waveguide by means of the end-fire technique. Figure 4 presents a schematic of the optical setup, which includes the end-fire (left) and prism-coupling (right) setups.

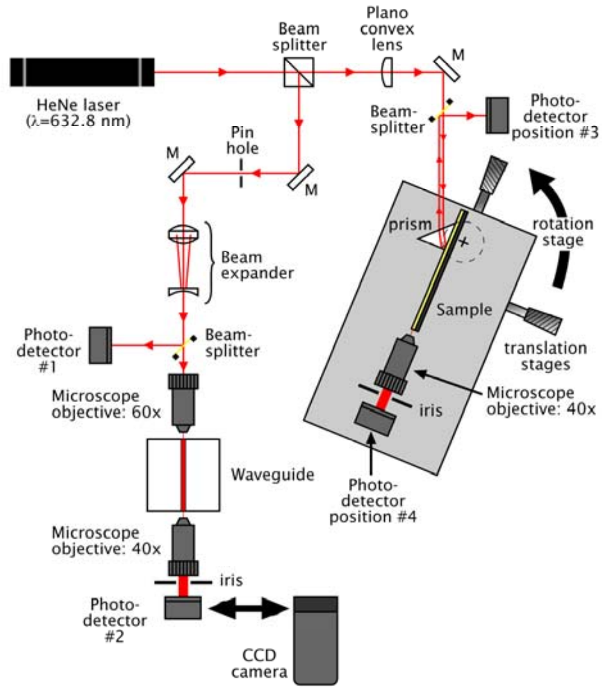


Figure 4. Set-up for optical characterization

The previous work reported on the characterization of the film and laser densified region by m-line or prism-coupler method for cut-off conditions (including thickness and index of refraction), and the three-prism coupler for attenuation measurements, based on (Kogelnik, 1975; Hunsperger, 2002). A hybrid prism coupler-end-fire technique was used to observe the near-field spot. For the end-fire configuration of Figure 4 (left), light is coupled into the waveguide by means of a microscope objective (60x) that focuses the light directly into the polished edge of the waveguide. Then the light is extracted at the other end of the sample using another microscope objective (40x), and observed using a CCD camera mounted to the objective. The CCD camera can be exchanged with a power meter to record the optical losses.

4. Results: Figure 5 shows an SEM image of a track defined by the UV laser after post-processing. As can be seen from the image, the track is approximately 24 μm wide, which is far greater than the nominal spot size. By adjusting the power and scan speed correctly, together with tight alignment and beam focusing, tracks as small as 4 μm were manufactured. The typical thickness for one layer of this particular sol-gel is between 5–10 μm, depending on the spin coating velocity and the shrinkage during the thermal treatment.

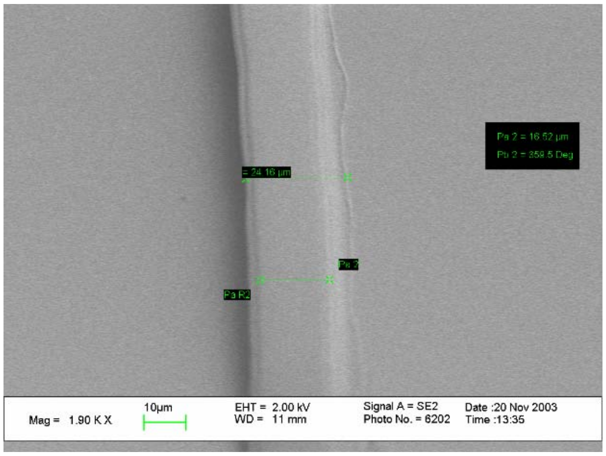


Figure 5. SEM image of a laser-defined waveguide

Figure 6 shows a close-up picture of the end-fire configuration with light from the HeNe laser being coupled into the laser-defined sol-gel waveguide. To complement this image, Figure 7 shows a top view picture of the same end-fire setup, where the light is being coupled from the left through the microscope objective. This last image shows how light is coupled into one of the multiple waveguides (straight lines). It also shows how light is quickly scattered and the signal quickly weakens. This is due mainly to imperfections in the waveguide, both interior and exterior, through inclusions and surface defects caused during the laser direct-write process. The losses were estimated in the range of ~2.5 dB/cm, which is still far from a desired <1dB/cm, but remains promising.

On the other side of the waveguide, light is collected by a CCD camera (as shown in Figure 4), and captured into a computer, where the image is automatically converted into a bitmap. The bitmap can then be post-processed to estimate the light intensity profile, which in turn can be used to approximate the spatial distribution of the refractive index.

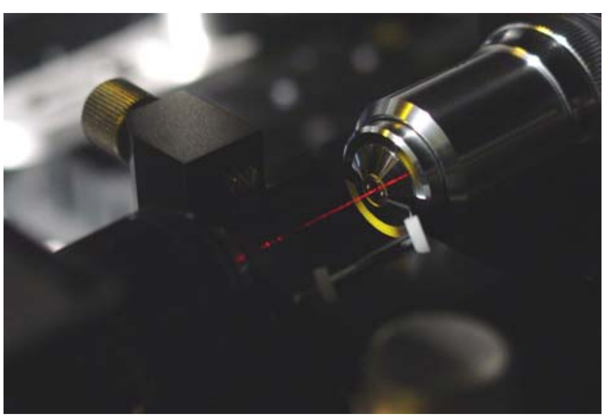


Figure 6. Light coupled by the end-fire technique

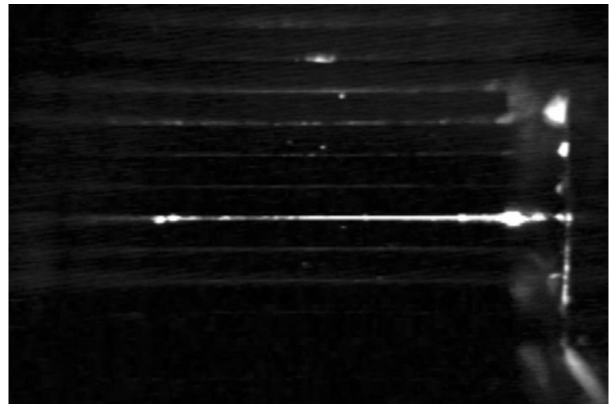
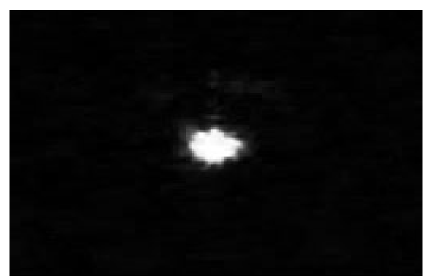
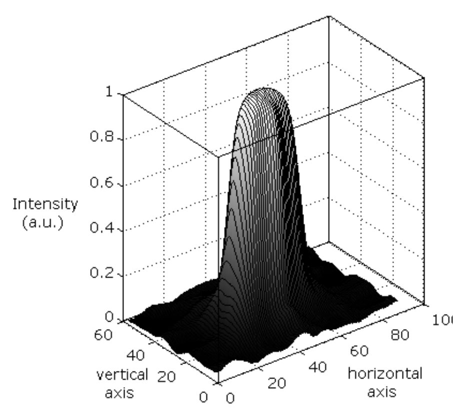


Figure 7. Top view of end-fire coupling

Figure 8a presents an image taken with the CCD camera at the end of the laser-defined waveguide. The image is presented without any alterations. As seen from the picture, the light intensity has an ellipsoidal shape, which is expected because of the difference between thickness (~5 μm) and width (~8 μm). This is further confirmed when the light intensity is visualized in a surface plot, as depicted in Figure 8b. Scattered light is eliminated for this step by means of and iris and image processing.



(a) image of light intensity as captured by CCD camera



(b) surface plot of light intensity from bitmap

Figure 8. Light collected by end-fire method

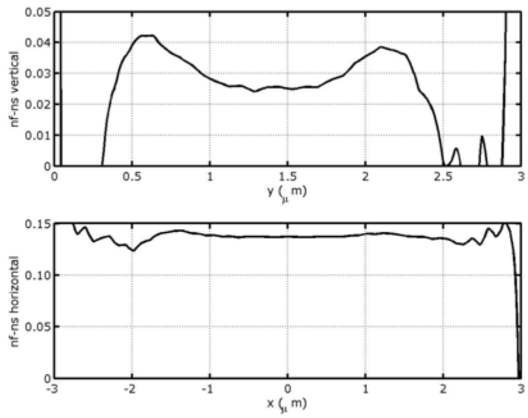


Figure 9. Numerical approximation to index difference

The refractive index difference for the vertical and horizontal directions at the central axis of the intensity plot can be calculated by employing the propagation-mode near field method proposed by (Morishita, 1986). After performing some curve smoothing operations on the light intensity data, the index difference in both directions was determined and is plotted in Figure 9. Since the method required numerical differentiation of the second order, it is particularly sensitive to small variations in the data. This is clearly seen in the jittery data of the approximated Δn for both directions (horizontal and vertical), in particular once approaching the edges of the waveguide. In this edge region the fit is neither stable nor reliable. We are working on resolving this issue by both improving the image acquisition hardware and software, as well as the numerical differentiation techniques.

5. Conclusions: We successfully demonstrated the fabrication of a straight channel waveguide through our proposed direct-write process. We were also able to couple light into the waveguide with moderate, yet promising results for the future. Several improvements can be made, in order to reduce the optical losses. Some of these include the synthesis, deposition and thermal treatment inside a clean room, which will help reduce unwanted particles in the film. On the other hand, the shape of the laser beam can be improved. This in particular will have a great impact on the geometry and surface morphology of the waveguide.

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