High Pressure Chemical Vapor Deposition to make Multimaterial Optical Fibers

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Abstract: Optical fibers are manufactured by drawing technique which limits the materials that can be incorporated in them. High pressure chemical vapor deposition (HPCVD) has emerged as an important technique to deposit various materials inside pre-drawn hollow optical fibers. Using this technique, semiconductor optical fibers which guide light by total internal reflection and Bragg fibers which guide light by photonic bandgap formation have been fabricated. COMSOL Multiphysics® has been used to design these fibers and subsequently based on those designs the fibers have been fabricated to obtain high transmission over a wide range of wavelengths.

Keywords: Bragg optical fiber, photonic bandgap, high pressure, chemical vapor deposition

1. Introduction

Optical fibers have revolutionized the communication technology, but apart from communication they are being used in a variety of other areas such as medical technology, sensing, laser sources in the form of fiber lasers, amplifiers, cutting and drilling, defense applications, etc.[1] Optical fibers are manufactured by drawing technique which limits the materials that can be incorporated in them. Templated deposition inside hollow core optical fibers using high pressure chemical vapor deposition (HPCVD) has emerged as an important technique to incorporate different materials such as metals, semiconductors and insulators in fibers which has enabled the exploration of various properties of these materials.[2]

1.1 HPCVD to obtain step index optical fibers

Using HPCVD, semiconductors such silicon and germanium have been deposited inside the hollow core optical fiber to form step index fibers which guide light by total internal reflection. Silicon and germanium have a much wider transparency window compared to silica glass that extends well into the mid infrared, high linear and nonlinear refractive indices and large damage threshold. This enables the use of these fibers for the delivery of high power infrared light, nonlinear optical processes and infrared countermeasures. The size of the core and the refractive indices of the core and cladding determine the number of optical modes that can propagate in these fibers. COMSOL Multiphysics® 5.1 has been used to model various step index fibers to understand the light guiding properties of these fibers at various wavelengths and how it is affected by altering the core size.

1.2. HPCVD to obtain Bragg optical fibers

Apart from total internal reflection light can propagate in a fiber by several other mechanisms such as the formation of photonic bandgap[3], antiresonant reflection[4] etc. Bragg fiber is a special type of fiber that guides light by the formation of photonic bandgap. It consists of a hollow core bound by concentric alternating layers of high and low refractive index materials which gives rise to the photonic bandgap.[5] Thus using this fiber light can be guided in a hollow core which has certain advantages over light guidance in a step-index fiber such as reduced latency, low absorption loss and negligible optical nonlinearities. Although Bragg fiber was conceptualized in 1978 but due to the structural complexity of drawing such fiber by traditional drawing techniques very few Bragg fibers have been fabricated.[6, 7] It is even more difficult to incorporate robust refractory materials as layers for the Bragg fiber by the drawing technique. This limitation has been overcome by using HPCVD technique to deposit materials inside hollow silica capillary to fabricate the fiber instead of drawing it. The light guidance property of the fiber depends on a number of factors, predominantly among those are the diameter of the hollow core, refractive indices of the layers, the thicknesses of the layers and the number of layers. COMSOL Multiphysics® 5.1 has been used to model all these parameters to obtain a Bragg fiber design that has high transmission.

2. Use of COMSOL Multiphysics

Radio Frequency Module of COMSOL Multiphysics® 5.1 has been used for modeling of the optical fibers. The governing equation is the given by the Helmholtz equation.

$$\nabla \times (\nabla \times \mathbf{E}) - k_0^2 \epsilon_r \mathbf{E} = 0$$

Triangular meshing was used keeping the maximum size of the element at λ/4 where λ is the wavelength. Perfectly matched layer with the cylindrical definition has been used to obtain the confinement loss of these fibers.

2.1. COMSOL modeling of step index fibers

Silicon step index fibers have been modeled to obtain the maximum core size at which the fiber has single mode guidance. The number of modes propagating in a fiber is given by the V-number of the fiber

$$V = \frac{2\pi}{\lambda} a \, \mathrm{NA} = \frac{2\pi}{\lambda} a \sqrt{n_{core}^2 - n_{cladding}^2}$$

Where V < 2.405 implies single mode guidance for fibers with core diameters below 360 nm at 1.55 µm wavelength which has been corroborated by COMSOL modeling. Figure 1 shows the light guidance in a multimodal 1.8 µm diameter silicon fiber at 1.55 µm wavelength.

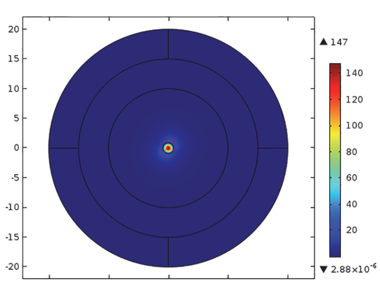

Figure 1: Mode showing light guidance in a 1.8 µm diameter silicon fiber at 1.55 µm wavelength

2.2 COMSOL modeling of Bragg fibers

Different designs of Bragg fibers have been modeled by varying all the parameters that affect the guidance properties such as refractive indices of the layers, their thicknesses and the number of layers. A wide range of material systems have been studied such as silicon (n = 3.4777 at 1.55 µm) and silica (n = 1.444 at 1.55 µm), silicon and germanium dioxide (n = 1.5871 at 1.55 µm), silicon and zinc selenide (n = 2.4556 at 1.55 µm), silicon and silicon nitride (n = 2.4629 at 1.55 µm). The size of the fiber core has been kept constant at 150 µm. The best guidance is given by the layers which have the highest index contrast. To corroborate this factor each of the different material systems were modeled by COMSOL with just one pair of quarter wave thick layers keeping the wavelength constant at 1.55 µm. The lowest order optical mode obtained corresponding to the lowest optical loss is the HE_{11} mode. The optical loss for each system has been tabulated in table 1 as shown below.

Table 1: Comparison of the optical losses of different material systems with one layer pair

Material pair chosen for the layers	Optical Loss (dB/m)
Silicon - Silica	4.45
Silicon - Germania	5.18
Silicon – Silicon Nitride	8.75
Silicon – Zinc Selenide	8.75

It should be noted that this loss corresponds to only confinement loss which is the major source of loss in these fibers. Other types of losses such as scattering loss may also affect the guiding property of these fibers which hasn't been accounted for in these modeling. Figure 2 shows the associated mode for the Silicon-Silica system. The lowest optical loss is given by the silicon – silica system owing to their highest refractive index contrast. Thus silicon and silica have been chosen as the materials for making the layers for the fabrication of the Bragg fiber. Increasing the number of layers decreases the confinement loss of the fiber which has been verified by modeling fibers with different number of layers. Figure 3 shows the confinement loss with different number of layers for a silicon-silica Bragg fiber. All the layers have been made quarter wave thick. As evident

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from the plot the confinement loss decreases with the increase in the number of layers.

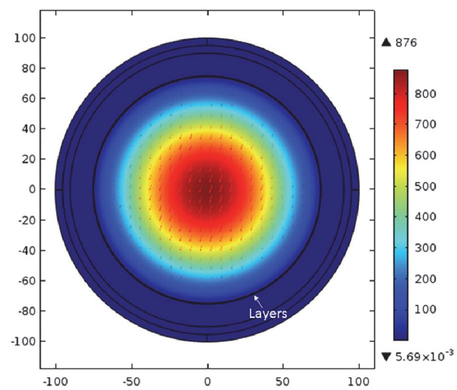

Figure 2: Light guidance in a one pair silicon-silica Bragg fiber

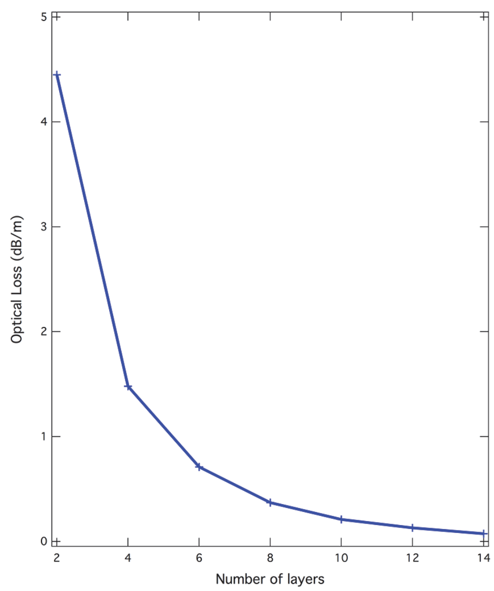

Figure 3: Confinement loss decreases with the increase in the number of layers

Figure 4 shows the mode when the Bragg fiber has 14 layers. Similar effect is observed in fibers with different materials used in layers but the rate of decrease of confinement loss with the increase in the number of layers is much less. Thus for a fiber which has higher index contrast between the layers, lower loss can be achieved with fewer number of layers as compared to one with low index contrast.

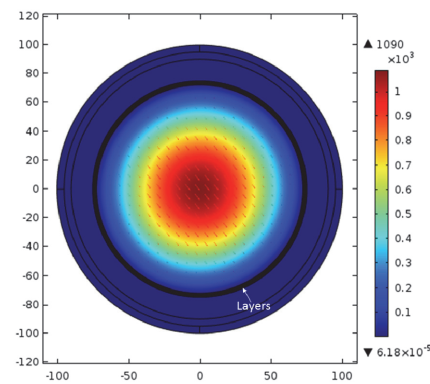

Figure 4: Light guidance in a 14 layered silicon-silica Bragg fiber

So far the diameter of the core has been kept constant at 150 µm. The confinement loss of the fiber also increases with the decrease in the core size which has been demonstrated through modeling four layered fibers of different sizes as shown in Figure 5. The thicknesses of the layers have been kept same while the core size has been varied.

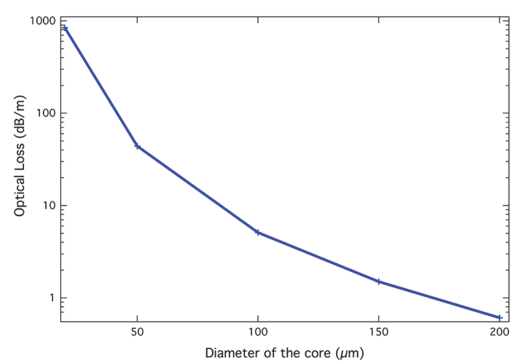

Figure 5: Variation of loss with the change in core diameter

Wavelength scaling of the Bragg fiber has been done to obtain relatively low loss region. Figure 6 shows that a four layered fiber has a wide bandwidth of around 300 – 400 nm over which it has low loss.

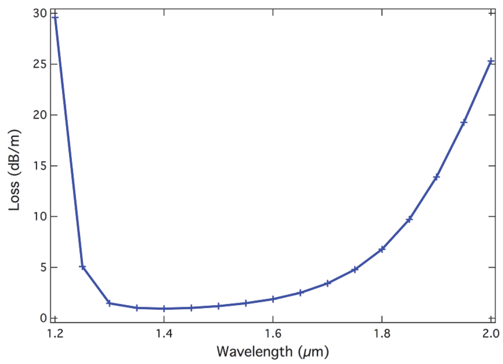

Figure 6: Wavelength dependence on a four layered Bragg fiber

3. Experimental and Results

HPCVD technique has been used to fabricate step index fibers and Bragg fibers. Silane (SiH_4) gas along with helium under a total pressure of 35 MPa has been introduced inside a hollow core silica fiber while it is being heated externally. Under these circumstances the silane decomposes and deposits along the inner walls of the fiber. This deposition continues until the core is completely filled with silicon to form a step index fiber.[8] Fibers with different core sizes can be obtained using this technique (Figure 7).

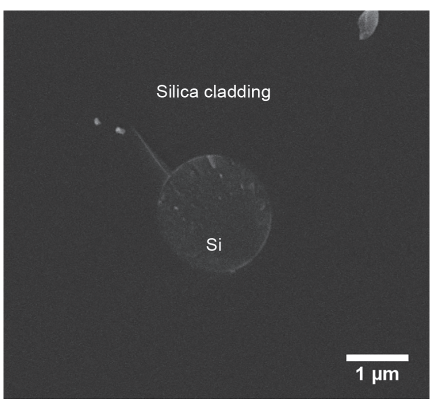

Figure 7: Scanning electron microscope (SEM) image showing a 1.8 μm core diameter silicon step index fiber

As obtained from numerical calculations and COMSOL modeling when the core size is below 360 nm in diameter the fiber becomes single mode at 1.55 μm. It should be noted that if the core size is further decreased, at a certain point the core will no longer be able to support a confined mode and it will leak into the cladding. Germanium step index fibers can be fabricated using the same technique by using germane (GeH_4) as the precursor gas.[8]

To obtain a Bragg fiber, a 150 µm core diameter hollow fiber (Figure 8) has been taken and a thin film of silicon deposited by the HPCVD technique instead of filling it up completely like in step index fibers.[9] Tuning the deposition conditions can precisely control the thickness of the silicon layer. This is followed by partial oxidation of the silicon layer under a temperature of 850 ºC to form a pair of silicon-silica layers. This process is then repeated to increase the number of layers. The thickness of silicon deposited is adjusted taking into account the increase in volume during oxidation. The thicknesses of the layers required for good transmission is based on the modeling result obtained from COMSOL. Figures 9 and 10 show the SEM images of layers deposited using this technique.

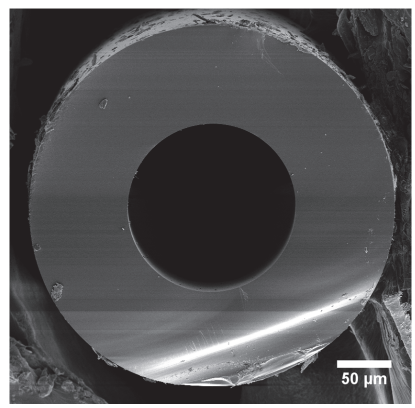

Figure 8: SEM image showing a hollow 150 µm core diameter silica fiber

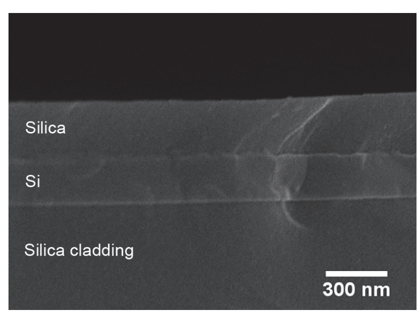

Figure 9: SEM image showing a 2 layered fiber. The silica has been partially etched out with hydrofluoric acid to show the contrast in heights between the layers

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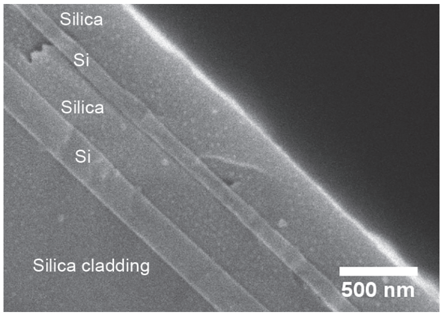

Figure 10: SEM image showing a four layered fiber. The silica has been partially etched out with hydrofluoric acid to show the contrast in heights between the layers

4. Conclusion

COMSOL is a very powerful modeling technique which has been used to design step index and Bragg fibers. Based on those designs different fibers have been fabricated by using the HPCVD technique. Using COMSOL different parameters can be tuned to obtain fiber designs that can have good transmission at various other wavelengths. These fibers have potential applications in high power delivery of various wavelengths of light, ultrafast physics, sensing, medical applications etc.

5. References

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