Development of Random Hole Optical Fiber and Crucible Technique Optical Fibers

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Abstract

This dissertation reports the development of two new categories of optical fibers. These are the Random Hole Optical Fiber (RHOF) and the Crucible Technique Hybrid Fiber (CTF). The RHOF is a new class of microstructure fiber which possesses air holes which vary in diameter and location along the length of the fiber. Unlike all prior microstructure fibers, these RHOF do not have continuous air holes which extend throughout the fiber. The CTF is a method for incorporating glasses with vastly differing thermal properties into a single optical fiber. Each of these two classes of fiber brings a new set of optical characteristics into being. The RHOF exhibit many of the same guidance properties as the previously researched microstructure fibers, such as reduced mode counts in a large area core. CTF fibers show great promise for integrating core materials with extremely high levels of nonlinearity or gain. The initial goal of this work was to combine the two techniques to form a fiber with exceedingly high efficiency of nonlinear interactions.

Numerous methods have been endeavored in the attempt to achieve the fabrication of the RHOF. Some of the methods include the use of sol-gel glass, microbubbles, various silica powders, and silica powders with the incorporation of gas producing agents. Through careful balancing of the competing forces of

surface tension and internal pressure it has been possible to produce an optical fiber which guides light successfully.

The optical loss of these fibers depends strongly on the geometrical arrangement of the air holes. Fibers with a higher number of smaller holes possess a markedly lower attenuation. RHOF also possess, to at least some degree the reduced mode number which has been extensively reported in the past for ordered hole fibers. Remarkably, the RHOF are also inherently pressure sensitive. When force is applied to an RHOF either isotropically, or on an axis perpendicular to the length of the fiber, a wavelength dependent loss is observed. This loss does not come with a corresponding response to temperature, rendering the RHOF highly anomalous in the area of fiber optic sensing techniques. Furthermore an ordered hole fiber was also tested to determine that this was not merely a hitherto undisclosed property of all microstructure fibers.

Crucible technique fibers have also been fabricated by constructing an extremely thick walled silica tube, which is sealed at the bottom. A piece of the glass that is desired for the core (such as Lead Indium Phosphate) is inserted into the hole which is in the center of the tube. The preform is then drawn on an fiber draw tower, resulting in a fiber with a core consisting of a material which has a coefficient of thermal expansion (CTE) or a melting temperature (T_m) which is not commonly compatible with those of silica.

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Introduction

Goals

The initial goal of this work was to generate a new optical fiber which could be used to obtain extremely efficient nonlinear interactions. The basic method used was to combine a structure which would result in very high optical intensities with a material which has a tremendously high nonlinear refractive index. The two approaches used for each of these tasks were, respectively, the holey fiber and fibers containing non-silicate glasses. In order to approach this problem, each task was addressed independently. My research work with each of these fibers also represents a significant increase in the state of the art for their respective applications. Some of the areas in which these fibers can be used are sensing systems, optical gain fiber (both Raman and more localized forms of gain), nonlinear applications, and low cost-short distance communications links.

With regard to random hole optical fibers, the goal of my research was to investigate methods, as needed, to develop a repeatable mechanism for fabricating microstructure fibers which are significantly different from the previously developed ordered hole fibers. The hope of this work was that such a structure will share many of the intriguing characteristics which have been found in ordered hole fibers. The work conducted under the heading of crucible technique fiber fabrication was intended to explore the question of whether it is possible to incorporate core materials which have desirable properties into a predominantly silica fiber, despite the core material's extreme physical characteristics. In both cases, my target achievement was to fabricate samples of fiber which exhibited guidance of optical power over at least a short distance.

Background

Microstructured optical fiber

Holey fibers have been studied over the last several years because of their collection of properties which are very different from those found in conventional fibers. Typically, holey fibers are fabricated entirely of a single material, commonly bulk fused silica. Rather than doping the glass to obtain variations in the refractive index, holey fibers are produced by incorporating air holes into the cladding region.[1] The earliest related fiber was the "single material fiber" developed at Bell Labs in 1973.[2] In this case the core was a rod of silica which was suspended in the center of a large outer tube by a pair of thin bridges. A schematic of this structure can be seen in Figure 1. This is an example of the multimode sample of fiber. A single mode structure was also fabricated by using a much smaller core rod.

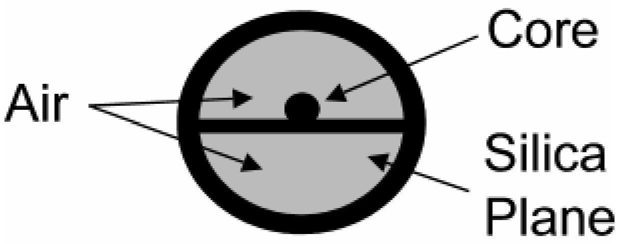

Figure 1: Schematic of "Single Material Fiber" from Bell Labs (1973)

Subsequent holey fibers have been developed to possess far more complex structures, including the photonic crystal fiber (PCF) which is a subset of microstructure fibers. In many cases this has been done by arranging a collection of tubes around a solid central rod. Through various techniques employed during the fiber draw, the structure of this preform is maintained.[1,3] The light which is guided in the solid core of these holey fibers experiences the inhomogeneous cladding as a nearly homogeneous material with an index of refraction which is a weighted average of that of the two materials (silica and air).[1]

The most discussed property of the holey fiber is its ability to demonstrate single mode behavior over very large spectral ranges.[4,5] Individual fibers have been found to demonstrate single mode behavior over a range of wavelengths from 377 nm up to 1550 nm.[5] This can be observed as resulting from the single mode condition for an optical fiber, in which the normalized frequency, $V = (2\pi\rho/\lambda)(n_{co}^2 - n_{cl}^2)^{1/2}$, must be less than 2.405. Due to the increase in the confinement factor of a fiber as one shifts to shorter wavelengths, less of the optical field extends into the air spaces within the optical fiber. As a result, the effective index of the cladding rises much more rapidly than would be experienced in a conventional fiber.[4] By properly selecting the ratio of the diameter of the air holes to their pitch, the single mode cutoff wavelength can be selected, independent of the overall scale of the fiber.

A similar argument applies to the usage of air holes for controlling the dispersion characteristics of the fiber. Zero group velocity dispersion has been reported at wavelengths as low as 765 nm, with anomalous dispersion occurring at longer wavelengths.[6] As a result, holey fibers become an intriguing host for a variety of optical processes which require either dispersion compensation or phase matching. Holey fibers can also possess multiple cores, and act as directional couplers, allowing the consideration of a host of device applications.[7]

Interest has begun to arise in the area of holey fibers which possess a random distribution of air holes. Theoretical analyses indicate that such random hole optical fibers (RHOFs) would exhibit properties which are very similar to those of ordered holey fibers.[8] Neither the traditional ordered hole fiber, nor the random hole optical fiber, is likely to demonstrate one property of the photonic crystal fiber. This property is the PCF’s ability to guide light at both a high index defect of the structure (a solid core), or a low index defect of the structure (an air hole of different size than the others).[9] To obtain a photonic crystal fiber, the air holes are required to be periodically spaced.[1] In the majority of these cases the periodic spacing occurs on either a triangular or hexagonal grid. In a few cases, however, a photonic crystal fiber has been generated whose structure is radially arranged.[10]

Fibers containing non-silicate materials

An additional area of interest is fibers that contain non-silicate glasses. Although the vast majority of optical fiber development has been based on the ultra-pure chemical vapor deposited silica fibers (lightly doped with assorted elements), there has been prior work in fibers which are not silica based, for specialty applications. One such class of materials are the chalcogenide glasses which are used for transmission in the mid to long infrared region of the spectrum. Another potential application of the non-silicate glasses are in the field of fiber nonlinear optics. Silica is a material of tremendous strength, which makes it very desirable to use in fiber systems. Silicate glasses possess small nonlinear responses, however, which render it a less suitable host for nonlinear interactions. Some alternate glasses can have values of n_2, the nonlinear refractive index, which are fifty times that of silica, or even greater.

The disadvantages of fibers fabricated entirely from non-silicate glasses is in their intrinsically low physical strength compared to silicate glasses, and in the difficulties involved in merging them into a standard telecommunications style of optical fiber. All of these materials have melting temperatures which are far lower than those found in silica, and coefficients of thermal expansion (CTEs) which are far greater.

Ideally, one would wish to be able to fabricate a fiber with the optical properties of the non-silicate glass, and the physical properties of silica. The natural approach to this is to construct a system in which the core is comprised of the specialty glass, enclosed in a surrounding region of silica cladding. This has been done extensively, with some materials. One such example is the inclusion of borosilicate-based stress regions in a polarization maintaining fiber, whether in elliptical geometry or in the PANDA structure. [11,12] Many of the non-standard materials, such as phosphate glasses, have not been possible to incorporate into a silicate fiber using existing techniques. When standard methods, based on chemical vapor deposition (CVD) or fusing of bulk glasses together, have been attempted, the result is a shattering of either the core or cladding, as the extreme difference in CTEs generates far more stress than the material can survive. A novel method, the "crucible technique", has been developed for fabricating such fibers.

Overview of work

A listing of all preforms which were drawn during the course of this research can be found in Appendix A. It is noteworthy that while some of these preforms were drawn once, approximately half of them were drawn (or attempted to be drawn) repeatedly. These repeated attempts were to investigate whether altering draw parameters would result in either an improvement of the resultant fiber or, in some cases, would result in any fiber being successfully drawn from the preform in question.

The initial attempts at fiber fabrication were intended to see if a very straightforward approach to the end goal was possible. A set of ordered hole preforms were fabricated, constructed by the rod and tube method. The central cores of these preforms were replaced with high index Lead Indium Phosphate (LIP) glass. Following this, the preform was drawn into fiber. It rapidly became apparent that such a simplistic approach was inherently infeasible. Due to the extreme low melting temperature of the LIP glass, it became fully molten and flowed throughout all of the interstitial spaces of the preform. Thus, we determined to attempt to separate the two problems and work on each of them independently, with the possible goal of recombining the results at the end. A flow chart showing the development of the parallel research avenues can be seen in Figure 2.

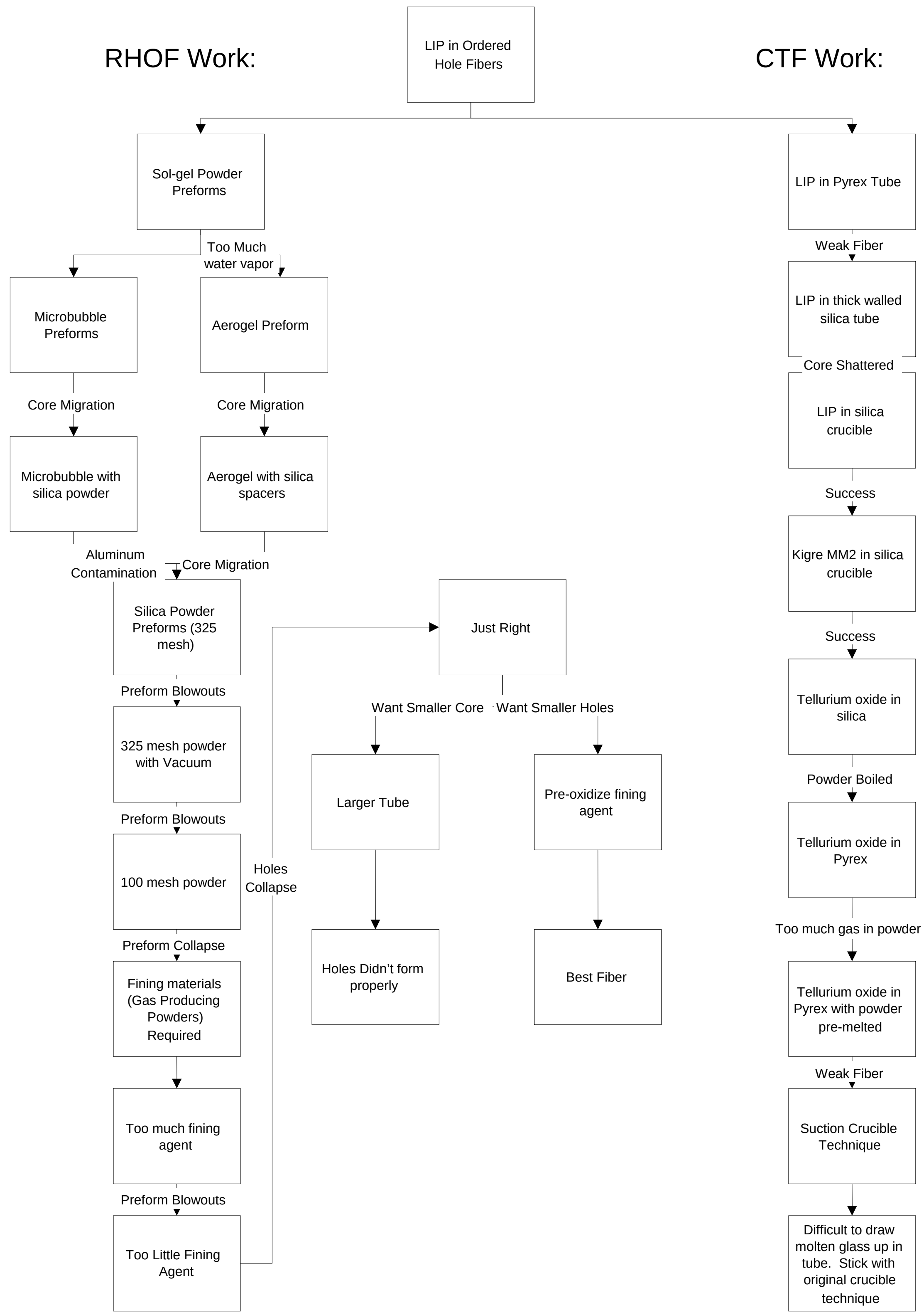

Figure 2: Research Flow Chart

This document will first cover the research in microstructure optical fiber, beginning with a survey of the major varieties of microstructure fibers, followed by a discussion of the random hole optical fiber (RHOF). Then will follow a discussion of the measurement of the properties of these fibers. Next, I will cover the development and theory of the non-silicate crucible technique fibers. Last will be some example applications of the fiber types developed in this work. Appendix A gives a comprehensive list of all preforms drawn in the course of this research. Appendix B contains an overview of some of the salient points of operation of a fiber draw tower. Appendix C presents a description of a method for measuring the refractive index profile of a fiber with extremely high delta.

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