

Nonlinear Microstructure Fibers

Alex K. Raub

Center for High Technology Materials, University of New Mexico

Albuquerque, NM 87106

Email: alex.raub@chtm.unm.edu

Abstract: Due to the long interactive length that light has with the glass media of an optical fiber there tend to be nonlinear optical effects. With the advent of microstructure fibers it is possible to tailor the fiber to reduce or enhance the nonlinear effect of light propagating down a fiber. This paper will give an overview on microstructure fibers and how they are used in nonlinear optics application.

Keywords: Microstructure fiber, holey fiber, photonic crystal fiber, photonic bandgap fiber, nonlinear optics, optical continuum.

1. Introduction

Conventional fibers have a high index glass core surrounded by a lower index glass cladding. The response on any dielectric to light becomes nonlinear for intense electromagnetic fields, and optical fibers are no exception. Even though silica is intrinsically not a highly nonlinear material, the waveguide geometry that confines the light to a small cross section over long fiber lengths makes nonlinear effect quite significant.

In a microstructure fiber the cladding contains holes, and the core can either be solid glass or open air. The arrangement, shape, and size of the holes in the fiber will determine the wave-guiding properties of the fiber. Microstructure fibers allow for the tailoring of waveguides in such a way that the nonlinear effects caused by fibers can be either enhanced or reduced depending upon the design. Unlike standard fibers, microstructure fibers can also be designed with high birefringence. By designing a microstructure fiber so that it has some or all of the following properties: small cross section, handle high optical power or pump power without breakdown, and utilize birefringence for phase matching; a highly nonlinear fiber optic can be formed. These nonlinear fiber optics can then be utilized for many nonlinear optical applications. They also have the advantage of being capable of forming compact systems at relatively lower costs.

The most common nonlinear effect that utilizes nonlinear fibers is optical continuum generation; which is used for the application of ultra-fast spectroscopy, multiple wavelength sources for wavelength division multiplexed (WDM) communication systems, optical frequency metrology, optical pulse compression, and optical coherency tomography. Other nonlinear fibers effects used for applications are self-phase modulation (SPM), stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), cross-phase modulation (XPM), four-wave mixing(FWM), third harmonic generation (THG), and second harmonic generation (SHG).

2. Microstructure Fibers

Microstructure fibers open up creative possibilities in the design of exotic optical fibers and their applications. The most distinguishing feature of a microstructure fiber as opposed to conventional fibers is that the low-index cladding has been replaced by holes. These holes are usually air holes; although they can be filled with liquid or a low-index glass. Unlike standard fibers which either have a step or graded radial index, microstructure fibers typically made entirely from a single index glass. Even if the microstructure fiber is made from varying index glasses the wave guidance property of the fiber is not directly due to the index of the glass itself, but rather due to either an effective radial index change of the fiber or a radial photonic bandgap created by the microstructure

fiber. Figure 1 shows the difference between a conventional fiber and microstructure fibers with a solid core and air core.

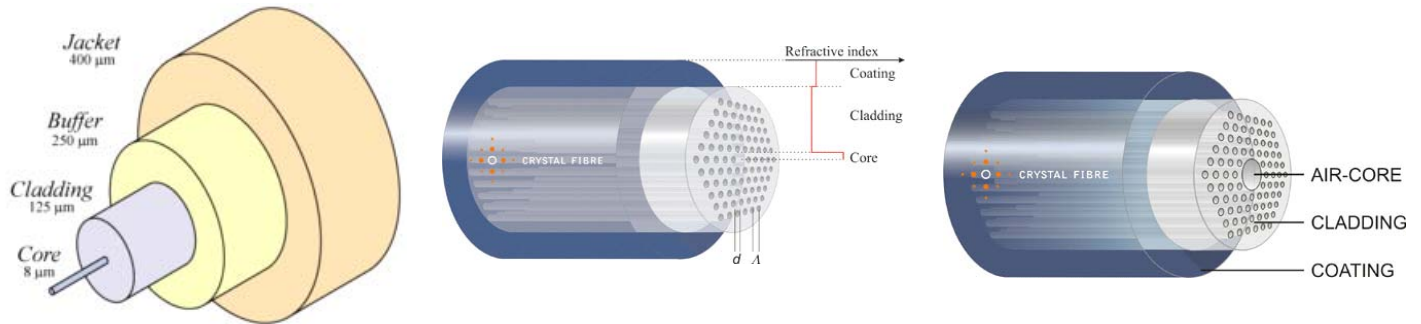


Figure 1 - Conventional step fiber, solid core microstructure fiber, air-core microstructure fiber

Microstructure fibers are categorized into two categories depending on their wave-guiding properties. The first and most common type is effective index guiding. Effective index guiding fibers have common names of holey fiber (HF), microstructure fiber (MOF), and photonic crystal fiber (PCF). The second type of microstructure fiber uses bandgap guidance, and has the common name of photonic bandgap fiber. Table 1 summarizes the microstructure fibers nomenclature.

Guidance Principle	Distinguishing Features	Common Names
Effective Index Guidance	<ul style="list-style-type: none"> Holes alone define cladding Solid core Single glass material 	<ul style="list-style-type: none"> Holey Fiber (HF) Microstructure Fiber (MOF) Photonic Crystal fiber (PCF)
Bandgap Guidance	<ul style="list-style-type: none"> Holes define periodic cladding Core formed by a defect. Core is air or glass. 	<ul style="list-style-type: none"> Photonic Bandgap Fiber

Table 1 - Microstructure fiber nomenclature

Figure 2 depicts the difference between a conventional step fiber, an effective index guiding holey fiber, and a bandgap guidance photonic bandgap fiber. The field in a microstructure fiber cladding sees both glass and air so that the effective index of the cladding falls somewhere between air and glass. The exact position of the holes does not make much difference. In contrast a photonic crystal fiber the periodicity of the holes introduces a photonic bandgap where light is coherently reflected back into the core. For photonic bandgap guidance the core index can be lower than the average cladding index. In fact, the core can be hollow.

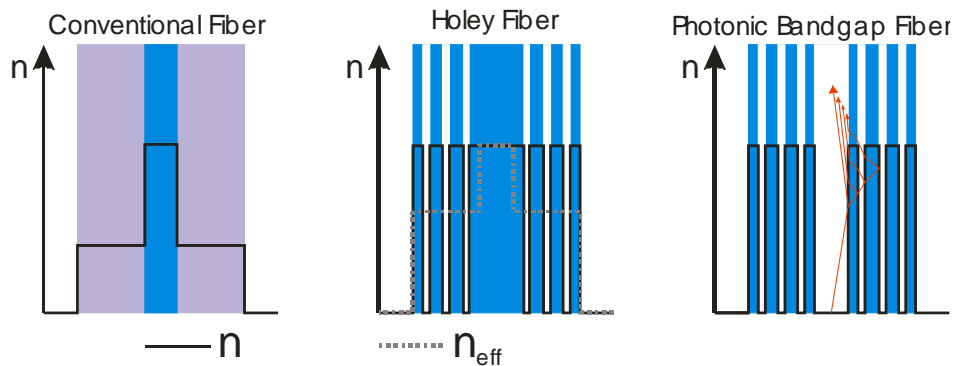


Figure 2 – Index and guiding mechanism between different types of microstructure fibers

To fabricate a microstructure fiber you start with a glass rod or tube which will form the core of the fiber. Capillaries are then stacked around the core rod or tube, which will form the cladding. The position orientation, number, outer diameter, and inner diameter size of the capillaries will all determine the wave-

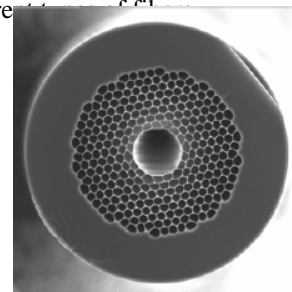


Figure 3 – Air-Core-Photonic Bandgap Fiber.

guiding properties of the microstructure fiber. Also all the capillaries do not need to be of the same shape and sizes, as is the case for birefringence polarization maintaining microstructure fibers. The stacked capillary bundle is then inserted into a glass preform tube. The preform is drawn to a cane or even a final fiber in a conventional high-temperature drawing tower. As this preform is heated it reduces radially and lengthens longitudinally. Once the cane is formed it is inserted into a jacket, and further drawn down to a fiber by another high-temperature drawing tower. Hair-thin photonic crystal fibers are readily produced in kilometer lengths. Figure 4 depicts the microstructure fiber manufacturing process. Through careful process control, the air holes retain their arrangement all through the drawing process and even fibers with very complex designs and high air filling fraction can be produced. The final fibers are comparable to standard fiber in both robustness and physical dimensions and can be both stripped and cleaved using standard tools.

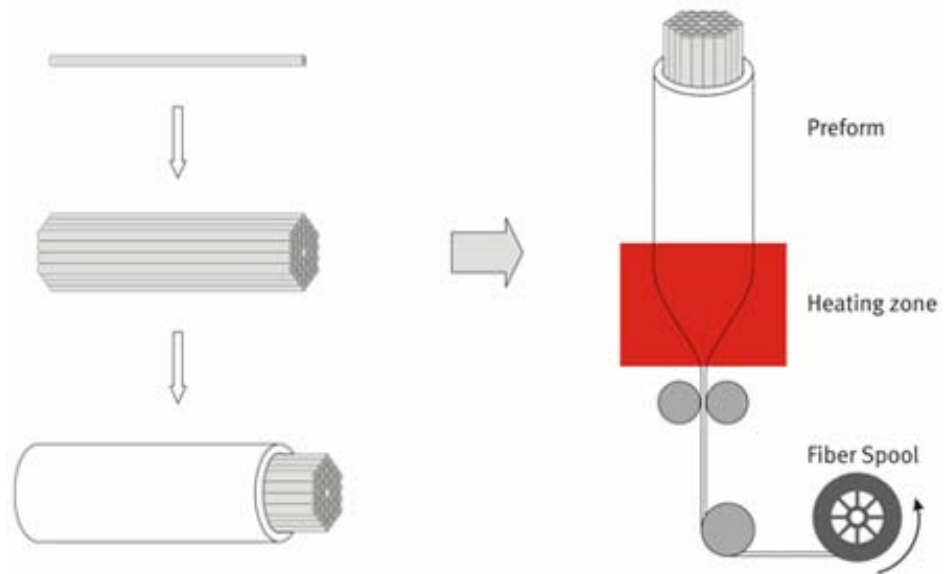


Figure 4 – Microstructure fiber manufacturing process steps.

3. Properties of Microstructure Fibers

The significant feature of microstructure fibers is the greater freedom in tailoring the various fiber properties. It is possible to have a fiber with an extremely small spot size to enhance nonlinear effects or to design a single-mode fiber with very large spot size to carry high optical power without nonlinear interactions or optical damage.

The index dispersion zero wavelength can be shifted from the infra-red to the visible. It is possible to get wavelength regions of flattened, large positive or negative dispersion from microstructure fibers. By dispersion engineering fibers can be made utilizing both microstructure fibers and conventional fibers which will exhibit near or zero group velocity and zero dispersion over very long distances. It is even possible to create a soliton pulse at any wavelength with proper dispersion engineering.

The photonic bandgap fiber can guide in a low-index core. This means that the fiber can be made with water or even air cores. An air core fiber has extremely high breakdown energy level. Air core photonic bandgap fibers will also have lower light absorption than solid core fibers, especially in the visible and UV part of the wavelength spectrum. Hollow photonic bandgap fibers can have surprisingly low bend loss. Bending loss has been reported to be negligible for 5mm bend radius and is still small for bend radii as small as 2mm.

Finally, high birefringence is relatively easy to obtain in all microstructure fiber designs. This simplified control over the state of polarization for device applications. The simplest way to introduce birefringence is by utilizing a non-circularity of the core. Another method is to vary the

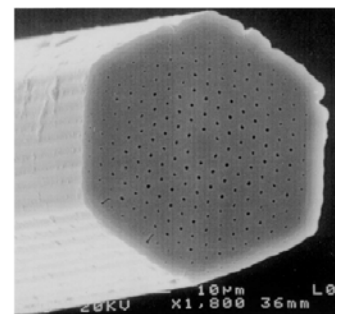


Figure 5 – Endless Single-Mode Fiber

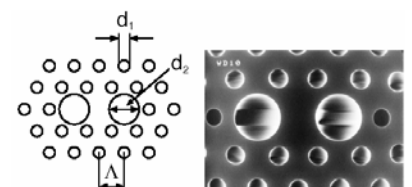


Figure 6 – Polarization-Maintaining (PM) Fiber

asymmetry of the effective index of the cladding, this is achieved by putting in either larger air holes on each side of the core, or filling in air holes on either side of the core, see Figure 6. The maximum birefringence in conventional fibers is around 4×10^{-4} . Birefringence of 0.025 has been reported from an air-guiding fiber with a core aspect ratio of only 1.16.

4. Optical Continuum Generation

The first and most ubiquitous application for effective index guiding microstructure fiber is continuum generation. Continuum generation is the formation of broad continuous spectra by propagation of high power pulses through nonlinear media, and was first observed in 1970 by Alfano and Shapiro. The term continuum does not cover a specific phenomenon but rather a plethora of nonlinear effects, which, in combination, lead to extreme pulse broadening. A short intense optical pulse is coupled into a fiber and is spectrally broadened by nonlinear interactions. The distinguishing characteristic on a nonlinear interaction is the creation of new frequencies and the magnitude of a given nonlinear effect increases with optical intensity (peak power/effective spot area) and interaction length L . The core diameters of nonlinear microstructure fibers can be less than $1 \mu\text{m}$ giving $A_{\text{eff}} \sim 1 \mu\text{m}^2$. This compares to a range of $50\text{--}80 \mu\text{m}^2$ for transmission fibers and approximately $20 \mu\text{m}^2$ for specially-designed high nonlinearity conventional fibers. It is possible to get $400\text{--}1600\text{nm}$ “white” light from a 850nm ~ 200 femto-second pulses with 4 nJ per pulse.

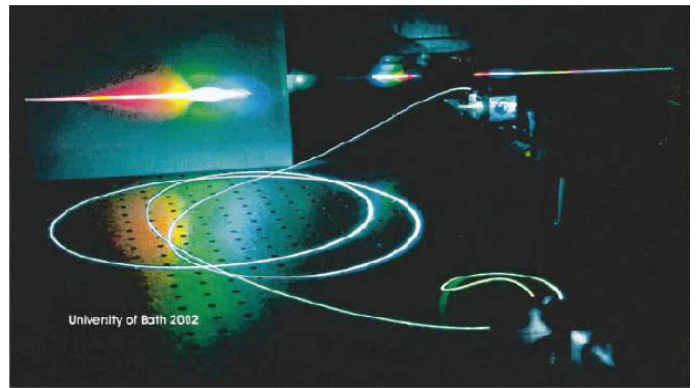


Figure 7 – White light continuum generation

The most straight-forward application for continuum sources is a replacement for the common, and often tungsten-based, white-light sources used in many characterizations setups like interferometer-based dispersion measurements, broadband attenuation characterization and numerous spectroscopy and microscopy setups. The continuum source have the special attribute of high brightness and easy coupling to single mode fibers and it is possible to create sources with the spectral width of a tungsten lamp and the intensity of a laser. Continuum sources can also have very short pump times less than a pico-second with very high intensities. Continuum sources are also coherent.

Because of the short pump times and wide spectral bandwidth of continuum generation the most obvious application is ultrafast spectroscopy. Multiple wavelength sources for wavelength division multiplexed (WDM) communication systems can be obtained by spectrally slicing an optical continuum. The noise properties of the individual channels are much improved starting from a coherent continuum as opposed to using the incoherent continuum from a white light source.

The first application of a microstructure-generated continuum was in optical frequency metrology. The essential idea is that a continuum generated by a mode-lock laser is actually a comb of discrete spectral lines separated in frequency by the inverse of the period of the input optical pulse train. This comb of frequencies can be used to precisely relate spectral line of different optical frequencies.

Optical pulse compression utilizes the fact that the continuum can have a nearly linear chirp in which the frequency of the pulse changes from the leading to the trailing edge of the optical pulse. An appropriate dispersive delay can

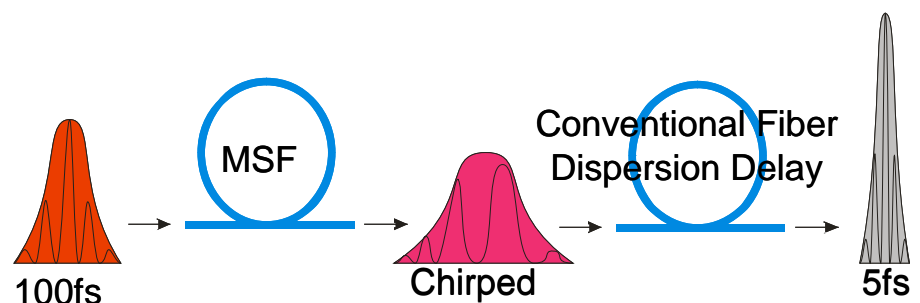


Figure 8 – Optical Pulse Compression

overlap these different frequency components producing a transform limited optical pulse much shorter than the pulse that entered the fiber, see Figure 8. Optical pulses of a few femto-seconds have been produced in this way.

Optical coherency tomography can view a few mm below the skin. The detected intensity will be higher for light scattered from a depth that matches the optical path length of a reference beam. The transverse resolution is set by the focal properties of an input lens and the longitudinal resolution is determined by the spectral band width. Thus a relatively low-power means of producing a broad spectral band around the 1.3 μm region of maximum skin transmission is highly desirable.

5. Nonlinear Application of Microstructure Fibers

One primary source of nonlinearities in microstructure fibers is self-phase modulation (SPM). In self-phase modulation the refractive index increases slightly with optical intensity. This phenomenon leads to a phase shift between the peak of the pulse, and its low-intensity leading and trailing tails which grows with propagation distance. The phase modulated pulse out of the fiber can have a spectral width of 100's on nm if one starts with an input pulse of the order of 100 fs. The spectral broadening of nonlinear microstructure fibers can be used in conjunction with conventional fibers for dispersion management.

Stimulated light scattering due to inelastic scattering mechanism will have frequency shifted scattered photons. Stimulated Brillouin scattering (SBS) uses acoustic phonon to back scatter light, and the light is shifted in frequency by about 10 GHz. In Stimulated Raman scattering (SRS) optical phonon scatter the light in both forward and backward directions, and the light is shifted in frequency by about 13 THz and has a wide gain spectrum that extends over 20-30 THz. By utilizing stimulated Raman scattering it is possible to create a small frequency downshifted wavelength from the pump wavelength.

Four-wave mixing (FWM) is another way to generate new wavelengths. By utilizing the third-order nonlinearity of silica light can be converted to upper and lower sidebands. Four-wave mixing is often used for de-multiplexing individual channels when time-division multiplexing is used in the optical domain. FWM can also be used for wavelength conversion. In optical fibers four-wave mixing can be used for generating a spectrally inverted signal through the process of optical phase conjugation.

A particular case of four-wave mixing where three of the frequencies being mixed are the same, third harmonic generation is accomplished. This is very useful for generating UV light in fibers. Second harmonic generation is also possible in all silica microstructure fibers. Normally second harmonic generation should be forbidden in glass due to its symmetrical structure, but it is observed in microstructure fibers, probably from quadrupole interactions of surface effects.

6. Conclusion

It can be seen how the creative possibilities in the design of microstructure fibers can lead to very nonlinear fibers. This is even true when using just pure silica fibers by utilizing air holes with just the right arrangement, shape, and size. It is the ability for microstructure fibers to have small cross section that have high birefringence and the ability to handle high optical power that make them great candidates for nonlinear optics. Not only do they have large nonlinearities, but they are easy to use, small in size, and relatively cheap to produce. That is why microstructure fibers are ideal for many nonlinear applications.

It has been demonstrated how useful microstructure fibers are for generating optical continuum. By utilizing optical continuum generation the use of ultra-fast spectroscopy, multiple wavelength sources for wavelength division multiplexed (WDM) communication systems, optical frequency metrology, optical pulse compression, and optical coherency tomography; were made feasible by nonlinear microstructure fibers. Many long distance communication applications are possible due to the ability of nonlinear microstructure fiber to perform dispersion management due to the high chirp of self-phase modulation (SPM). Wavelength frequency downshifting is made possible due to stimulated Raman scattering (SRS) of nonlinear microstructure fibers.

Generation of new wavelengths is capable by utilizing nonlinear microstructure fibers that exhibit four-wave mixing (FWM), third harmonic generation (THG), or second harmonic generation (SHG).

As more exotic nonlinear microstructure fibers are designed many new nonlinear optical application will be created. This is currently only limited by the engineers imagination on microstructure fiber fabrication, and application implementation..

7. References

- [1] Tanya M. Monro, "Holey Optical Fibers: Fundamentals and Applications", OFC Tutorial, March 2002.
- [2] R. H. Stolen, "Microstructure Fibers", teaching module on microstructure fibers, Virginia Tech, Blacksburg, VA, November 1, 2006.
- [3] S. G. Johnson and J. D. Joannopoulos, "A Long and Winding Road, *Photonic-Crystal Fibers*", MIT Independent Activity Period tutorial series, Lecture 5, 2003
- [4] "Fiber 101 selected concepts", Corning Discovery Center, <http://www.corning.com/opticalfiber>
- [5] "TECHNOLOGY TUTORIAL", Crystal Fibre A/S, Blokken 84, 3460 Birkerod, Denmark, http://www.crystal-fibre.com/technology/technology_tutorial.shtm
- [6] "Optical Fiber", Wikipedia, http://en.wikipedia.org/wiki/Optical_fiber
- [7] "Photonic-crystal fiber", Wikipedia, http://en.wikipedia.org/wiki/Photonic_crystal_fiber
- [8] "Photonic Crystal Fibers", Newport, Photonics Products, <http://www.newport.com/store/genproduct.aspx?id=323352&lang=1033&Section=Detail>
- [9] Govind P. Agrawal, "Fiber-Optics Communication Systems", John Wiley & Sons, Inc., New York, 2002