

Photonic Crystal Fibers

Advances in Fiber Optics

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Abstract

I find it fascinating how communicating effectively has shaped the evolution of man as a species. In our struggle to communicate we have continually pushed the barriers to that communication. The ability to communicate over long distances has significantly reduced the effective size of this planet we call home. In that struggle several achievements propelled the science of communication forward, from written dispatches on horseback, to electricity and magnetism and Morse-code. The development of high efficiency electrical signal generation and transmission systems dominated the field of communication for decades. The transition to optical systems was a giant leap forward.

These fiber optic lines carry signals at the speed of light, are very efficient compared to other types of line communication and are immune to electromagnetic interference that plaques electronic signal lines. These fiber optics are not however perfect. The next breakthrough in high speed, high efficiency communication is now in its infancy. New types of fibers called **Photonic Crystal Fibers** are currently being researched and manufactured by scientists and universities. As of yet there are no commercial applications or companies producing these fibers commercially.

Fiber Optics

A fiber optic is composed of three general components shown in Figure 1. The light signal is transmitted down the central portion called the **core**, which is composed of silica. The core is surrounded by a second layer called the **cladding**. The **buffer coating** protects the internal structure from damage.

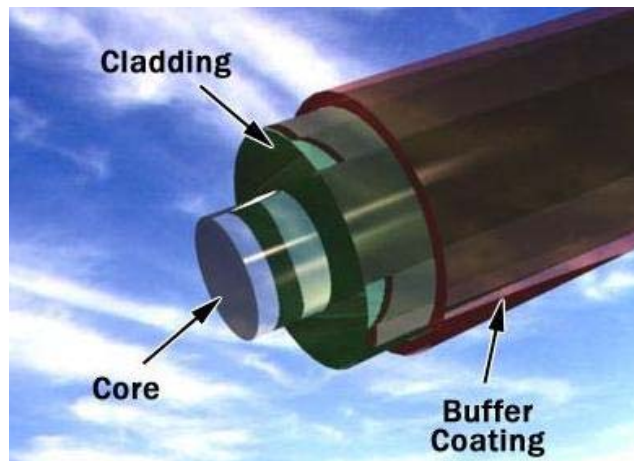


Figure 1: Fiber Optic Structure

The light wave travels the length of the fiber through the core by reflecting from the core-cladding interface, shown in Figure 2. This effect is called **total internal reflection**.

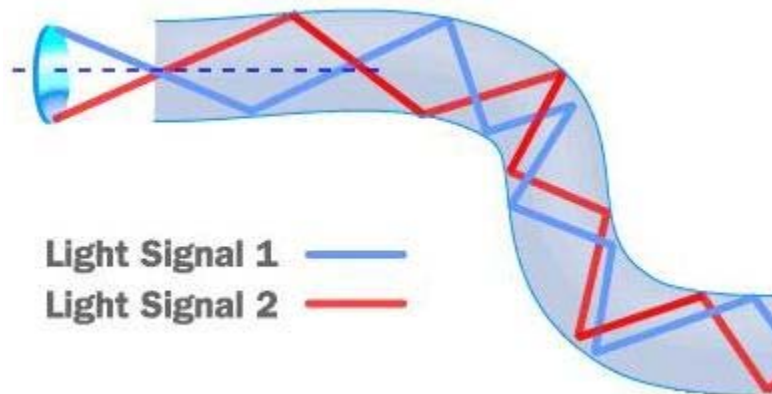


Figure 2: Total Internal Reflection Signal Transmission

Although this is a good approximation, it is only that. The higher the refractive index contrast between the core and cladding the more closely the signal is totally reflected. The fact that some portion of the signal is still passed through the interface and into the cladding accounts for significant loss over long distances.

The first generation of optical fibers, called **multi-modal** were large, with core diameter 50-200 μm and cladding 20 μm thick. The large core made the fiber durable. They are easily coupled and easily infused with a light wave. Typically multi-mode fibers are used to transmit infrared light ($\lambda=850 - 1,300 \text{ nm}$) from light-emitting diodes (LEDs). Figure 2 also demonstrates a second problem with these types of fibers. Over long distances these **modes** or signal paths have different transit lengths and therefore different signal transit times. This causes the signal to be distorted at the receiver. The solution to this problem was to narrow the core diameter until only the transverse mode, along the dashed axis, is allowed to propagate.

These fibers, known as **single-mode**, do have significant disadvantages. First the diameter of the fiber is significantly smaller, about 9 μm resulting in a weaker fiber more susceptible to physical damage. The small diameter also introduces problems in coupling these fibers to light sources and in aligning the junction properly so that the fiber is infused with light. These fibers transmit infrared laser light ($\lambda=1,300 - 1,550 \text{ nanometers}$).

The other major cause of loss through the fiber comes from the imperfections in the core or cladding and the nature of their interface. In attempting to increase the transmission effectiveness a new area of research has begun to engineer new cladding materials that enhance the nature of that interface.

Photonic Crystal Fibers

The newest approach to solving the problem of signal degradation came on the heels of a prediction in the early 1990's by Eli Yablonovitch. He predicted that certain three-dimensionally periodic photonic crystal structures contained complete **photonic bandgaps**. The presence of these bandgaps meant that for certain frequency range there were no propagating modes through the material. This means that if used as a cladding material, the signal would not be able to propagate into and through the cladding. This prediction opened the field of fiber optic manufacturing to the possibility of producing a core-cladding interface that produces total internal reflection.

These three dimensionally periodic crystal structures are however incredibly complicated to fabricate, requiring the correct refractive index contrast, pitch and structural integrity to achieve the desired interface behavior. The solution was to create a two-dimensionally periodic material that is periodic in the plane perpendicular to the axis of the fiber but constant along its length. This new technique in fiber development creates optically an excellent approximation of this 2-D structure by imbedding microscopic holes running the length of the cladding parallel to the core axis as shown in Figure 3.

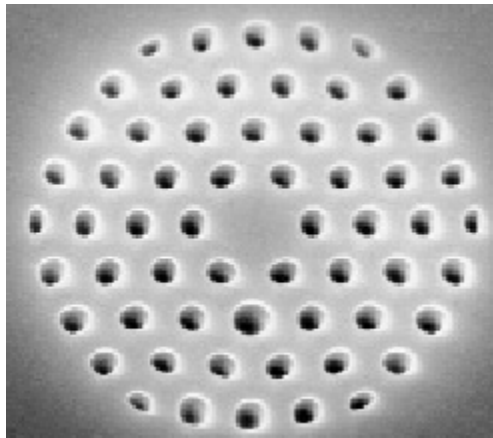


Figure 3: Photonic Crystal Fiber cross-section

The optical properties of the cladding material are highly engineerable through the manipulation of the hole size, separation and pattern the **birefringent** nature of the new cladding material can be changed. A refractive index contrast between the core and cladding can be achieved two orders of magnitudes above that of conventional fibers. Figure 4 shows two different hole arrangement patterns. The other parameters are displayed in the left image hole separation (Λ) and hole diameter (d).

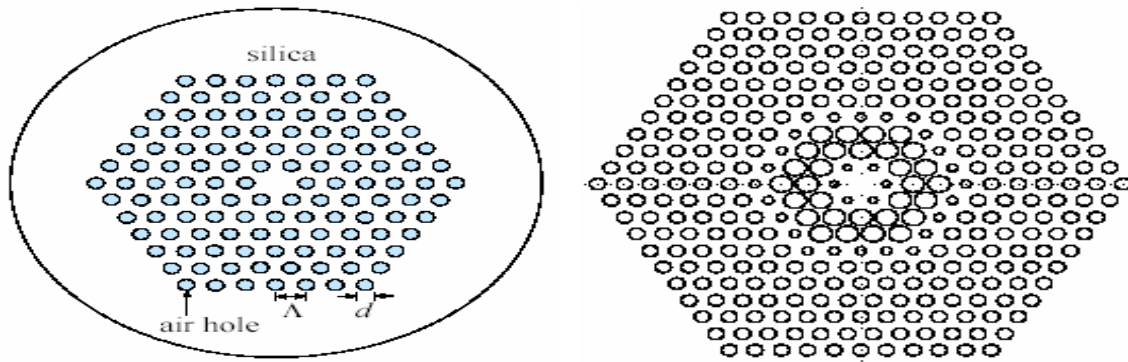


Figure 4: Differing Photonic Crystal Fiber cross-sections

Because the highest intensity in the silica is at least two orders of magnitude down from the peak intensity, the power-handling capability of such fibers will also be better, by several orders of magnitude, than in conventional fibers. The interactions resulting from the nonlinear response of silica found in conventional fibers will be reduced correspondingly. For the same reason, the material dispersion of silica will not strongly affect the dispersion of the fibers. The limitations of this type of fiber have yet to be established.

Conclusion

Through photonic bandgap manipulation cladding material can be engineered that does not support any modes for certain frequencies, creating total internal reflection. The engineerable birefringence allows for relatively high refractive index contrasts. This allows a mode to be confined in a core much smaller than previously possible, less than the wavelength of the light. The current performance of single-mode optical fibers results from many years of intensive research. There appears to be no reason why the losses in Photonic Crystal Fibers cannot be reduced to or below that of standard optical fibers. Similar development effort could lead to explosive growth in photonic crystal fiber technology over the coming years.

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