Final Report: Silica and ZBLAN Fiber for Optical Transmission

March 27, 2012

Eric Singh

Wilfrid Laurier University, 75 University Avenue West, Waterloo, Ontario, N2L 3C5

Advisers: Dr. Shaowen Song

1 Introduction

Since the first demonstration of optical fiber used for transporting signal in 1880, hundreds of crystals and glasses, doped with rare-earth ions have been fabricated and utilized to avoid attenuation and signal dispersion for telecommunication. To date, silicate optical fiber is the most common material for fabricating fibers due to their low loss, high tenability and strong strength. For the long-haul communication, the S-based fiber has been demonstrated with attenuation as low as 0.2dB/km. However, recently a new heavy metal fluoride glass has drawn much attenuation because it has some advantages over conventional silicate based glass materials. The most important advantages are that the fluoride glass has a low intrinsic loss in the mid-infrared region, where such low attenuation is hard to be obtained from silicon glass fibers. In addition, the fluoride glass has a wide transparency window in the long wavelength regions, which is more useful in modern telecommunication. And ZBLAN ($ZrF_4 - BaF_2 - LaF_3 - AlF_3 - NaF$) is the most stable fruoride glass for the optical fiber.

This paper will compare the silicate glass fiber and fluoride glass fiber in each spectral operating region and is organized as follows. Firstly, the advantages, disadvantages and basic applications of S-based glass fiber are described. Secondly, the advantages, disadvantages and fabrication of ZBLAN follow. Then, the final part will discuss the background knowledge of attenuation in the fiber and explain the reasons of low loss for silicon glass at 1550nm and low attenuation for ZBLAN at ultra-long wavelength region.

2 Silica

2.1 Introduction

Optical fiber is made with pure glass (Silica) and serves as a transport to transmit light between two points. The optical fiber was first invented in the 1970s and has been used quite extensively since that time. Since the demand for increased bandwidth for information traffic has risen quite quickly over time, a transmission medium with the capabilities of handling higher bandwidth needs of the users is essential (Massa, 2000).

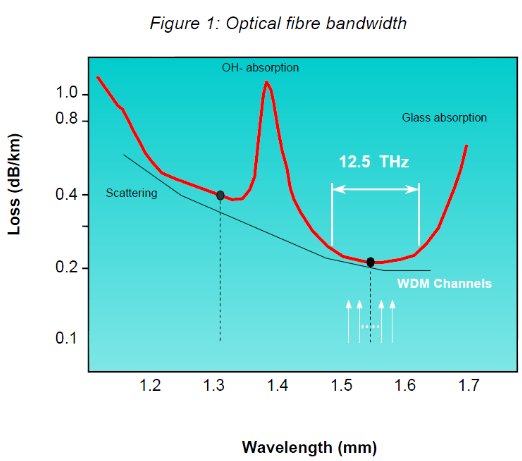
2.2 Advantages

The optical fiber has many benefits over metallic based transmission systems. The signal transmission in optical fiber has a much longer transmission distance relative to metallic based systems, allowing over 100 km transmission distance without any interval amplification. The versatility of the optical fiber is a great advantage, allowing a much larger bandwidth to be transmitted without sacrificing the space considering the lightweight and very small size of the cable. Optical fiber can also be installed in any location without being affected by outside sources such as electromagnetic interference (EMI), since it is nonconductive and has no metallic components. The optical fiber also cannot be intercepted by a device attempting the retrieve a signal being transmitted and any attempt to intervene with the cable can be detected easily by a security surveillance system. When looking at the overall benefits of optical fiber, it is very appealing mechanism to transmit information efficiently (Massa, 2000).

2.3 Disadvantages

The disadvantages of optical fiber are limited. The cost of optical fiber is greater than copper cabling, therefore more suited towards long distance applications. The installation of optical fiber is difficult and requires highly skilled persons.

Another limiting factor of optical fiber is the attenuation of signal with distance. Although the attenuation is low relative to other transmission means such as copper. The attenuation present in optical fiber is dependent on the wavelength of the transmitted light. The two figures below demonstrate the attenuation relative to wavelength (Fur, Thomine, & Le, 2003).



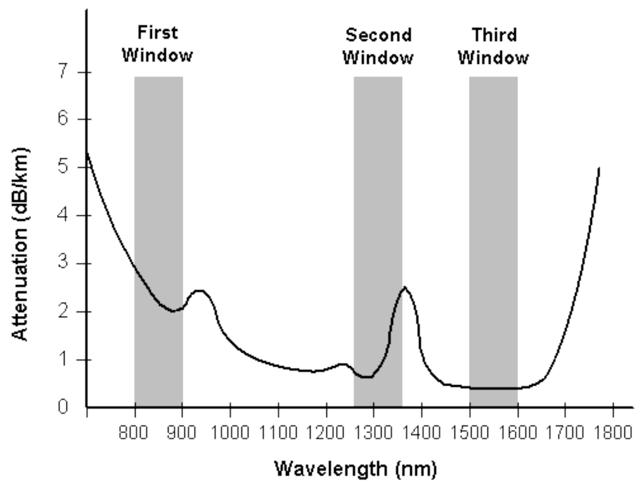


Figure 1 & 2: Attenuation relative to wavelength

As shown above, optical transmission is located in one of the three windows. This is due to one of three limiting factors of optical fiber attenuation. The biggest factor is scattering, which is the interaction of the transmission of photons with the glass molecules randomly. This causes the photon path to sometimes be ejected from the optical fiber and occurs more often with lower transmission wavelengths. OH absorption is another factor that presents itself in the form of attenuation between the wavelengths of 1400nm and 1500nm and is due to the presence of OH- ions. The last factor is that at wavelengths above 1600nm, glass molecules themselves start to absorb transmitted light (Fur, Thomine, & Le, 2003).

2.4 1600 nm and Above

The attenuation of higher wavelength light transmission, specifically above 1600 nm, is much too high since the natural properties of silica cause absorption of light.

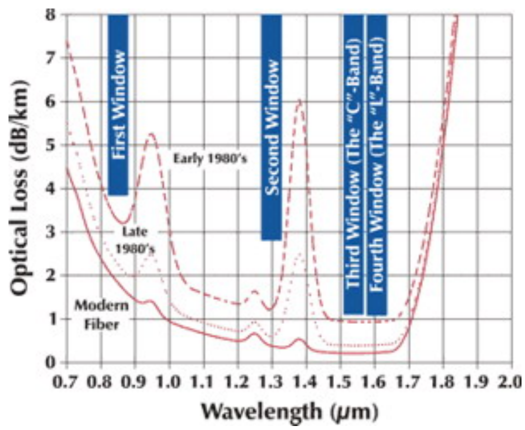


Figure 3: Attenuation for 1600nm and above

The figure above shows optical loss through the wavelengths of 700nm to 2000nm. Observing the region between the 1600nm to 2000nm, it can be seen that the optical loss is much too high to attempt to transmit light at those wavelengths.

2.5 Application

The increased demand of information traffic has in turn increased the demand of implementing optical fiber communications, where the amount of applications is limitless. The applications of optical fiber in telecommunications range from global networks to desktop computers, and mostly involve the transfer of voice, data and video over a range of distances from a couple meters to over a hundred kilometers.

Some examples of optical fiber applications are (Alwayn, 2004):

- Phone service carriers use optical fiber to carry telephone service across nationwide distances
- Multinational companies that require secure, reliable systems to transfer data and financial information can implement optical fiber communication to transfer data between buildings, between desktop terminals and globally.
- Cable providers utilize the optical fiber to carry their television and data signals, especially the high-definition signals because of the very large bandwidth provided by the optical fiber.
- Optical fiber based telemetry based systems are used for intelligent transport systems.
- There are numerous other applications for optical fiber, including space, military and automotive.

The applications for using optical fiber for transmitting wavelengths between 1600nm and 2000nm are not available. Even though the attenuation (scattering of light) of the fiber should be theoretically less at longer wavelengths, this is not the case. The attenuation is much too high for the optical fiber to be usable at higher wavelengths.

2.5 Summary

Although Silica has a much lower attenuation when compared to metallic based cables, the attenuation of the transmission of higher wavelengths is much too high. There is an alternate material to silica, a heavy metal fluoride named ZBLAN, which can successfully transmit light in the ultra-long wavelength range.

3 ZBLAN

3.1 Introduction

For decades most of glass-making research and manufacturing focused on silica family, mostly because it is easy to make, it can transmit large volumes of information with not bad attenuation. However, scientists know about better materials that are superior to silica in its transmission properties. (Sheng Wang, 2006)

Heavy metal fluoride gasses (HMF) were accidentally discovered in 1975 by Poulain and Lucas at the University of Rennes in France. HMF glasses show great promise as fibre optic materials due to its broad optical transmission window and possibility of much lower attenuation rates.

3.1 Advantages

The most promising and most stable member of HMF glasses is ZBLAN (ZrF4-BaF2-LaF3-AlF3-NaF). With its low attenuation (as low as 0.001 dB/km vs. 0.2 dB/km for Si-based material) it is far superior to silica-based fiber. A perfect ZBLAN fiber could carry light with an attenuation as low as the theoretical best allowed by matter. In addition, ZBLAN has a large spectral window (300nm to 7000nm), which is especially important in telecommunication – increased bandwidth. (Chenan Xia, 2009)

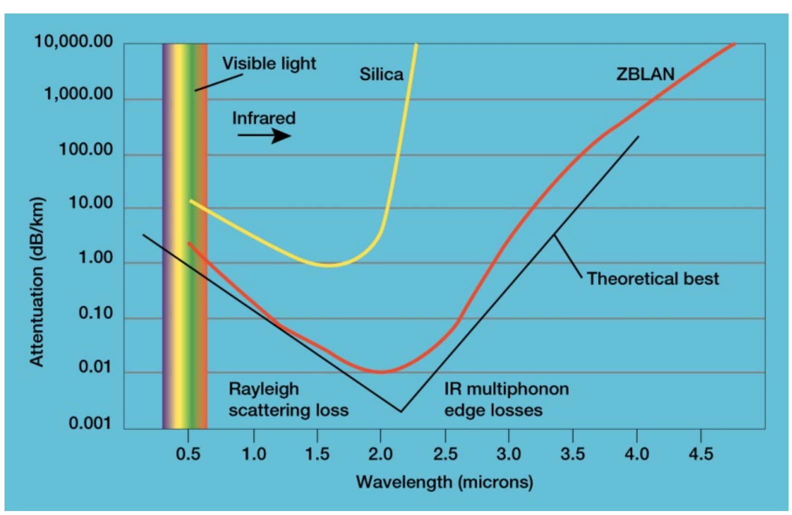


Figure 4: ZBLAN's attenuation approaches the theoretical minimum allowed by matter

3.2 Properties

Glass property	Silica	ZBLAN
Approximate transmission range (1 mm thickness, $T > 1\ 0$ %) (μm)	0.16–4.0	0.22–8.0
Maximum phonon energy (cm^{-1})	1100	600
Transition temperature (°C)	1175	260
Specific heat (J/(g·K))	0.179	0.151
Thermal conductivity, W/(m·K)	1.38	0.628
Expansion coefficient (10^{-6}/K)	0.55	17.2
Density (g/cm^3)	2.20	4.33
Knoop hardness (kg/mm^2)	600	225
Fracture toughness ($MPam^{1/2}$)	0.72	0.32
Poisson's ratio	0.17	0.17
Young's modulus (Gpa)	70	58.3
Shear's modulus (Gpa)	31.2	20.5
Bulk's modulus (Gpa)	36.7	47.7
Refractive index (@ 0.589 um)	1.458	1.499
Abbe number	68	76
Zero material dispersion wavelength (μm)	1.3	1.6
Nonlinear index (10^{-13} esu)	1	0.85
Thermo-optic coefficient (10^{-6}/K)	11.9	−14.75

Table 1: Properties of ZBLAN vs. Silica

3.3 Manufacturing Process

Compared to silica glasses, it is more complicated to make HMF glasses. To achieve high quality fluoride glasses, extremely pure starting materials are needed. In addition, complete absence of water and prevention of contamination are a must. Moreover, when fabricated in a gravity environment, tiny crystals form and significantly reduce quality and transmittance properties of material. (Aijun Jin, 2011)
In microgravity, the experiments show, the effects of crystallization are greatly reduced. Those experiments also provide great clues and insights on possible ways to avoid gravity-induced crystallization, so it is possible to avoid it on the ground. Even produced in microgravity, ZBLAN crystallizes if not cooled fast enough. (Peyghambarian, 2010)

One solution to both of the problems is microspheres, because they are only about 200μm in diameter and offer high surface area to volume ratio, they equilibrate very quickly, thus giving the opportunity for fast temperature changes.
ZBLAN has poor chemical durability, which leads to degradation of fiber strength, mostly by moisture. The durability can be significantly improved by coating with various metals or highly stable oxides and fluorides. (Peyghambarian, 2010)

3.4 Summary

ZBLAN fibers are very valuable for telecommunications, medical and manufacturing technologies. The widely used silica fibres have a number of limitations such as narrow optical window and the small band of wavelengths. ZBLAN, because of its broad transmission window, low optical dispersion, low refractive index, ease of machining and polishing stimulated a tremendous interest as an alternative fibre to silica in long-haul optical communication. (Serena Eley, 2002)

4 Attenuation Principles

Attenuation is the total loss of the light signal after it propagating fibers, thus it can be measured by the amounts of light lost between input and output. For the telecommunication, attenuation is an important consideration in the design of an optical communication system, since it plays a major role in determining the maximum transmission distance between a transmitter and a receiver. The fiber attenuation coefficient can be expressed as

$$\alpha(dB/km) = \frac{10}{z(km)}\log(\frac{P(z)}{P(0)}),$$

where P(z) means the output light power and P(0) means the input light power at the original point.

The basic attenuation mechanism in a fiber are absorption, scattering and radiative losses of the optical energy, resulting the wavelength-dependent property of the attenuation. More commonly, the absorption is caused by three different mechanisms, which are absorption by atomic defects, extrinsic absorption and intrinsic absorption. The atomic defects are imperfections in the atomic structure of the fiber material, such as missing molecules, high-density clusters or oxygen defects. All those atomic defects can rise absorption, which is however negligible compared with intrinsic and extrinsic effects. Another loss mechanism, extrinsic absorption is because the loss by impurity atoms in the glass material, which is also referred as impurity absorption effects. Considering the fiber or communication material, it is impossible for them to be purity. The presence of minute quantity of metallic ions and the OH- ions from the water dissolved in the glass can cause the extrinsic loss. The following table shows us the loss of some impurity ions.

Impurity Ion	Loss due to 1ppm of impurity (dB/km)	Absorption Peak Wavelength (um)
Fe^{2+}	0.68	1.1
Fe^{2+}	0.15	0.4
Cu^{2+}	1.1	0.85
Cr^{3+}	1.6	0.625
V^{4+}	2.7	0.725
OH^{-}	1.0	0.95
OH^{-}	2.0	1.24
OH^{-}	4.0	1.38

Table 2: The loss due to kinds of impurity ions in the fiber materials

From the above table, it shows that OH- loss can happen at three different wavelengths and the metallic ions absorption spectrum falls in the relatively shorter wavelength region when comparing to the 2000nm. For the intrinsic absorption, it is associated with basic fiber materials, resulting that this absorption can only be overcome by changing the materials, which leads to broad research in the low loss materials corresponding to different spectrum regions. This absorption mechanism is due to the interaction of the propagating light with the electrons in the valance band and excites them to higher energy levels. Because of different materials have their own band gaps; this absorption differs from different materials.

According to the attenuation mechanism, silicon has become the most potential and most commonly used material for fibers. As shown form the above table, the OH- attenuation is high at the shorter wavelength. In addition, according to the Urbach's rule, the total intrinsic loss for silicon is inversely proportional to the wavelength, which there will be a large loss during the short wavelength. Considering all the loss and put them together, people find three low attenuation windows for the silicon, which is showed in the

Figure 1. Those three windows refer to 800-900nm, 1270-1370nm, and 1400-1500nm, which are the operating wavelength for the telecommunication. The lowest attenuation will happen at the wavelength 1550nm, thus it is the most common operating wavelength for our modern telecommunication. By applying modern fabrication and optimization, the lowest loss for the silicon is 0.2dB/km.

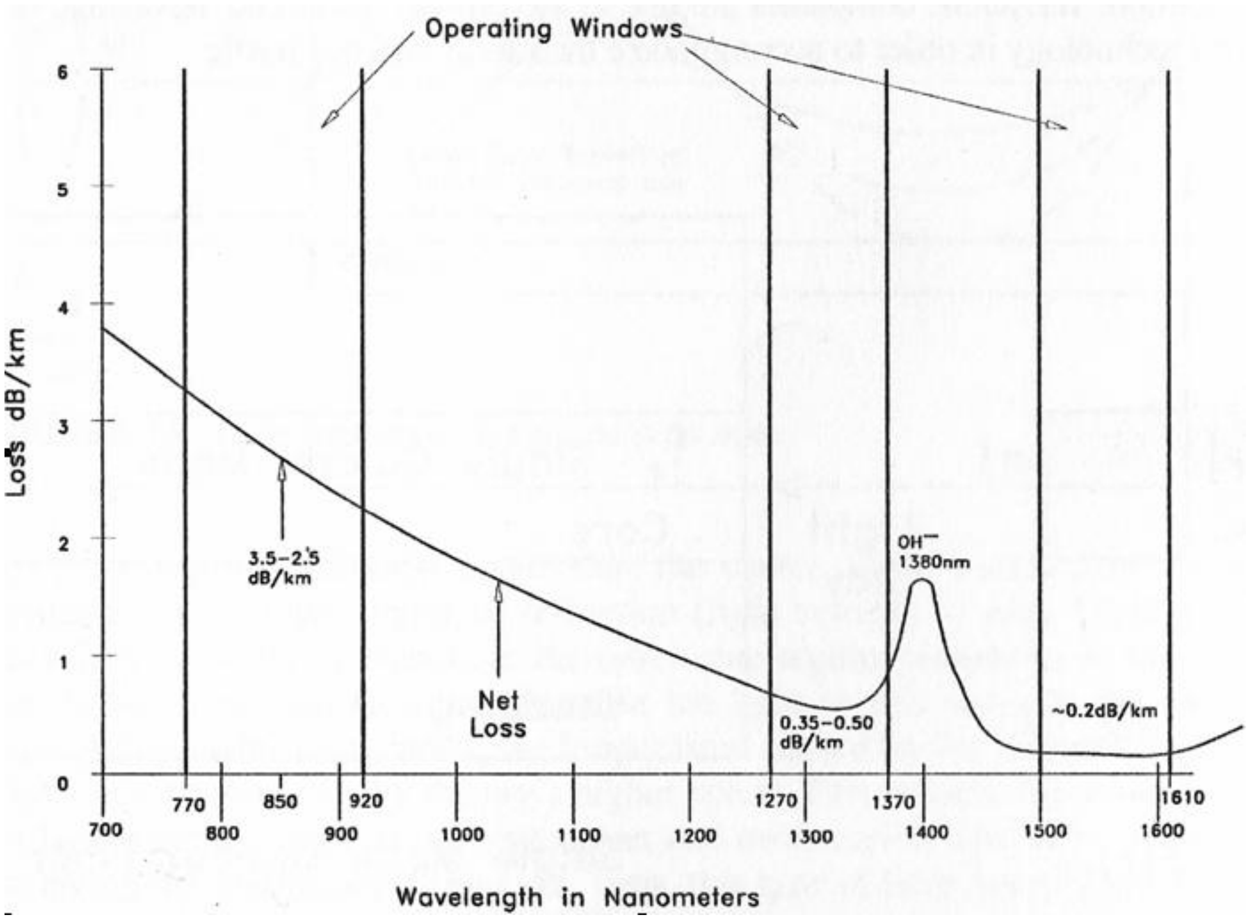


Figure 5: The total attenuation for silicon

Compared to the silicon based fiber, a new kind of material has been develpoed for many years in order to find a lower attenuation at the specific wavelengh. ZBLAN ($ZrF_4 - BaF_2 - LaF_3 - AlF_3 - NaF$), considered as the most stable heavy metal fluoride glass and the excellent host for rare-erath ions, has been exstensively used for efficient and compact ultraviolet fibers due to its low intrinsic loss, wide transparency window, and small photon energy. Because the flouride ion is singly charged, bond strengths are lower in ZBLAN glass than that in the silicon glass. The weaker bonding leads to greater infrinred transparency and higher reactivity. That means that the operationg windows fo the ZBLAN fibers will be red shifted from the silicon operating windows to ultraviote region. As mentioned before, the total intrinsic attentuation is inversly proportional to the wavelength, resulting a very low loss for ZBLAN at the long wavlenght region. The loss is showed in the Figure 2.

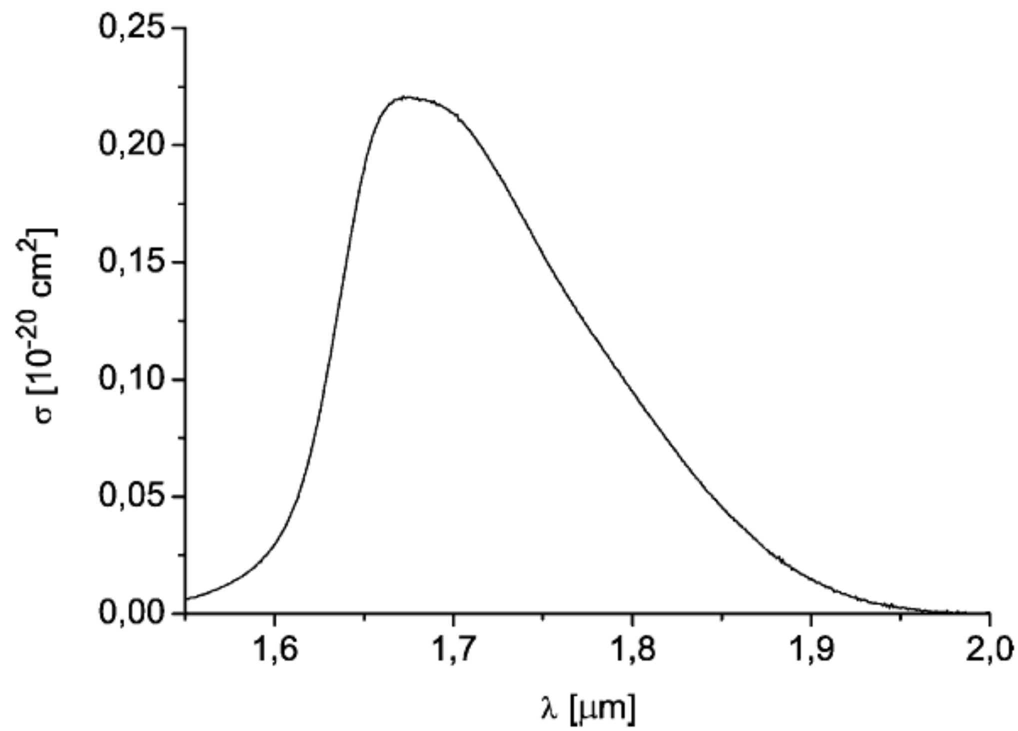


Figure 6: The attenuation for ZBLAN

The above figure also shows that ZBLAN has a very broaden operating windows for the long wavelength, which is more useful for telecommunication. The minimum loss coefficient for ZBLAN glass is predicted as low as 0.01dB/km at 2500nm.

However, another attentuation mechanism is raised form the extrinsic scattering, which is related to the rare earth elements. Because the ZBLAN glass is doped with many rare earth elements, the high impurities may cause serious extrinsic absorption, leading to large attenuation. Another reason for ZBLAN used not commercially is that amorphous ZBLAN is very difficult to produce. Small wrong controls during the fabrication process may also lead to the extra loss or attenuation.

5 Conclusions

The outcome of this project provides an overview of the capabilities of optical fiber and ZBLAN. It was determined that silica optical fiber's applications were best limited to transmitting lower light wavelengths ranging from 800 nm to 1600 nm. Above 1600 nm, the transmission of light in optical fiber currently cannot be done because of the high attenuation. However, a relatively new material by the name of ZBLAN is capable of transmitting light in the ultra-long wavelengths ranging from 300 nm to 7000 nm. Manufacturing of ZBLAN has produced one critical setback since the fabrication produces crystallites when gravity is present. Currently research of new optical transmission materials has yet to come up with a viable solution to higher wavelength light transmission, although sometime in the future a material may be created which can feasibly transmit ultra-long wavelengths.

Bibliography

Aijun Jin, Z. W. (2011). *Experimental Measurement and Numerical Calculation of Dispersion of ZBLAN.* Changsha, P. R. China.: National University of Defense Technology.

Alwayn, V. (2004, April 23). *Fiber-Optic Technologies*. Retrieved March 12, 2012, from Cisco: http://www.ciscopress.com/articles/article.asp?p=170740&seqNum=2

Chenan Xia, Z. X. (2009). *10.5 W Time-Averaged Power Mid-IR Supercontinuum Generation Extending Beyond 4 μm With Direct Pulse Pattern Modulation.* IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 15, NO. 2, MARCH/APRIL 2009.

Fur, J.-B., Thomine, & Le, L. (2003, January 1). Optical Fibre Transmission.

Gerd Keiser, Optical Fiber Communication, third edition (McGraw-Hill Higher Education, U.S.A., 2000), pp. 92-103.

Marc Eichhorn, IEEE, 41, 1574, 2005.

Massa, N. (2000). Fiber Optic Telecommunication. Springfield, Massachusetts, United States

Peyghambarian, X. Z. (2010). *High-Power ZBLAN Glass Fiber Lasers: Review and Prospect.* Tucson, USA: Hindawi Publishing Corporation Advances in OptoElectronics.

Serena Eley, D. E. (2002). *Optical Properties of ZBLAN Microspheres Produced in Microgravity.* Pasadena, California: California Institute of Technology.

Sheng Wang, X. L. (2006). *Near-Infrared Electrochromic and Electroluminescent Polymers.* Beijing National Laboratory for Molecular Sciences.

Xiushan Zhu and N. Peyghambarian, Advances in OptoElectronis, 2010, 23, (2010).