Title: FIBER LASER CONSTRUCTION AND THEORY INCLUDING FIBER BRAGG GRATINGS Photonic Crystal Fibers (PCFs) and applications of gas filled PCFs

Author(s): Sutton, Jacob O.

Intended for: ECE:475 Paper

Issued: 2017-03-08

FIBER LASER CONSTRUCTION AND THEORY INCLUDING FIBER BRAGG GRATINGS Photonic Crystal Fibers (PCFs) and applications of gas filled PCFs

Jacob Sutton
ECE: 475

FIBER LASER CONSTRUCTION AND THEORY INCLUDING FIBER BRAGG GRATINGS
Photonic Crystal Fibers (PCFs) and applications of gas filled PCFs

1 Abstract

The principles used in fiber lasers have been around for a while but it is only within the past few years that fiber lasers have become commercially available and used in high power laser applications. This paper will focus on the basic design principles of fiber lasers, including fiber Bragg gratings, principles of operation, and forms of non-linear effects. It will describe the type and associated doping of the fiber used and difficult designs used to guide energy from the pump to the active medium. Topics covered include fiber laser design, fiber Bragg gratings, materials used, differences in quantum energy loss, thermo-optical effects, stimulated Raman scattering, Brillouin scattering, photonic crystal fibers and applications of gas filled Photonic Crystal Fibers (PCFs). Thanks to fiber lasers, the energy required to produce high power lasers has greatly dropped and as such we can now produce kW power using a standard 120V 15A circuit. High power laser applications are always requiring more power. The fiber laser can now deliver the greater power that these applications demand. Future applications requiring more power than can be combined using standard materials or configurations will need to be developed to overcome the high energy density and high non-linear optical scattering effects present during high power operations.

2 Introduction

Ken Hill first observed the critical element needed to produce a fiber laser in 1978 during experiments using a germania doped silica fiber. What was seen was approximately a 4% back reflection of visible light. It was thought this was due to a change in the index of refraction at the end of the fiber, but without the ability to reproduce the experiment the concept was tabled. Later Ulf Osterberg and Walter Margulis found that infrared radiation could condition or change the index of refraction in a Germania doped silica fiber after a long exposure. This led to the development of the key concept of fiber Bragg gratings, the creation of a periodic changing in the refractive index in a small length of a fiber. This would enable a user to select a grating based on the chosen wavelength and amount of light reflected. The fiber Bragg grating is the key concept used in the creation of the fiber laser.

3 Background

The first fundamental principle guiding the fiber laser is that light, when going from a more dense to a less dense material, will have 100% reflection if the less dense material is struck at an angle greater than the critical angle as depicted in Figure 1. This is governed by Equation 1 where n1 is the index of refraction of material 1, n2 is the index of refraction of material 2, and θ_c is the critical angle. This principle allows light to travel down the fiber with little loss of power.

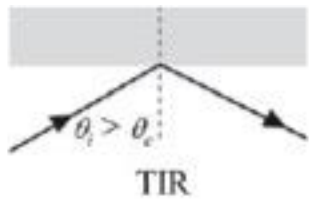


Figure 1

$$Sin\theta_c = \frac{n_1}{n_2} \qquad \text{Equation 1}$$

The second principle is that a fiber radius can define how many modes will propagate down a fiber. A simple method used for gauging how many modes will travel down a fiber is a characteristic parameter called the V number. If V ends up being below 2.405 then the fiber will only support one mode. Equation 2, where the fiber radius, a, is included, is used to determine V.

$$V_{cutoff} = \frac{2\pi a}{\lambda_c}(n_1^2 - n_2^2)^{1/2} \qquad \text{Equation 2}$$

The third principle is the fiber Bragg grating. When light strikes a periodically changing index of refraction over a length, a specific frequency is reflected back and the rest of the wavelengths are free to pass through. The longer the length of the grating the more reflection you will have. This can be seen in action in Figure 2 and is described by Equations 3 through 5. Where q is an integer, $\overline{n}$ is the average refractive index experienced by the propagation mode, Λ is the periodicity of the grating, λ_b is the Bragg wavelength or wavelength that will be reflected, Δn is the index contrast, λ is the operating wavelength, κ is the characteristic Fiber Bragg grating parameter, L is the Bragg grating length, R is the reflectance. Equation 6 or 7, where if κL is greater than 1 it is strong and if less than 1 it is weak will tell us the bandwidth of the Bragg reflected light.

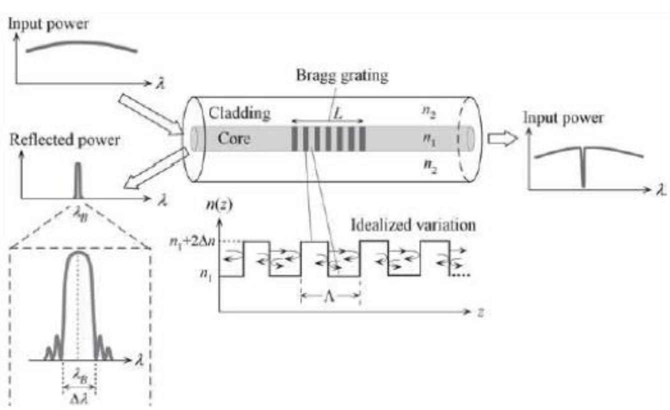


Figure 2

$$q\lambda_B = 2\overline{n}\Lambda \qquad \text{Equation 3}$$

$$R = tanh^2(\kappa L) \qquad \text{Equation 4}$$

$$\kappa = \pi\left(\frac{\Delta n}{\lambda}\right) \qquad \text{Equation 5}$$

$$\Delta\lambda_{weak} = \frac{\lambda_B^2}{\bar{n}L} \qquad \text{Equation 6}$$

$$\Delta\lambda_{weak} = \frac{4\kappa\lambda_B^2}{\pi\bar{n}} \qquad \text{Equation 7}$$

The fourth principle is an optical resonator. Optical resonators are present in fiber lasers when two Bragg gratings are placed a distance apart in a fiber and light is pumped into the created cavity. As seen in Figure 3 and described by Equation 8, only specific modes will be allowed to amplify at a specific wavelength when the Bragg gratings are a specific distance apart. In this equation m is the mode number, an integer, L is the length, and λ is the wavelength in the material.

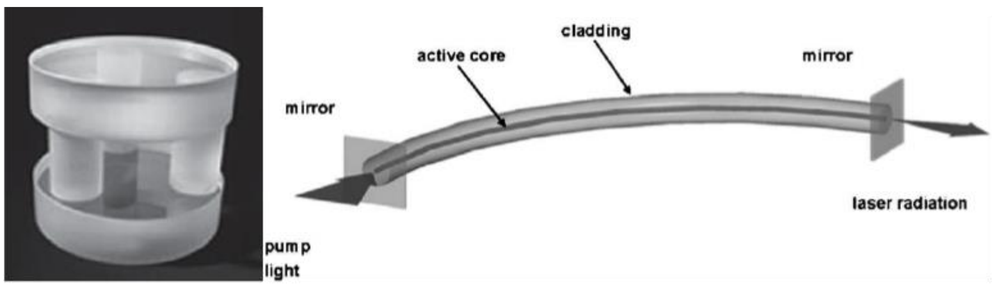


Figure 3

$$m\left(\frac{\lambda}{2n}\right) = L \;\; m = 1,2,3, \ldots. \qquad \text{Equation 8}$$

The fifth principle is scattering effects. Both Raman and Brillouin scattering are third order non-linear effects that start to accrue in fibers at different power levels. They are due to the large product of intensity and interaction length inside the fiber core. The scattering is laser radiation transferring a part of its energy to the glass. In Roman scattering the energy is transferred to vibrational modes and in Brillouin scattering is transferred to acoustical modes. If the threshold level of either is reached it could cause the core to have portions that are not getting excited therefore parts of the core would not contribute to the spontaneous emission process, as is the case with Ramon scattering, or turn the glass into little shards destroying the fiber, as is the case with Brillouin scattering. Brillouin scattering has the lower threshold level making it the more important limiting factor as can be seen in Figure 4. The threshold values for both effects are determined by Equations 9 and 10 where P_{srs} is the threshold value for Ramon scattering, P_{sbs} is the threshold value for Brillouin scattering, A_{eff} is the effective mode area of the guided fiber mode, g_R is the peak Raman gain coefficient (g_R=1x10^-13 m/W in fused silica at pump wavelength 1µm), L_{eff} is the effective fiber length, g_B is the peak Brillouin gain coefficient (g_B =5x10^-11 m/W) which is almost independent of the pump wavelength.

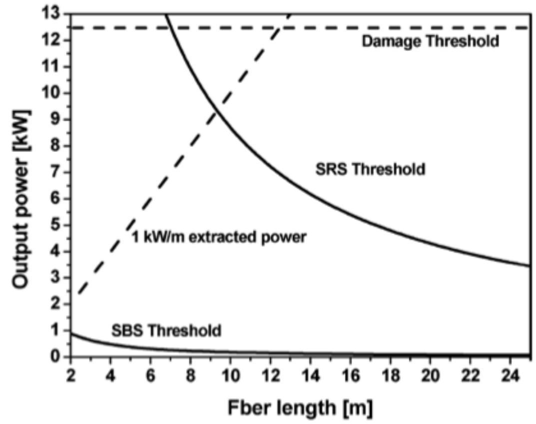


Figure 4

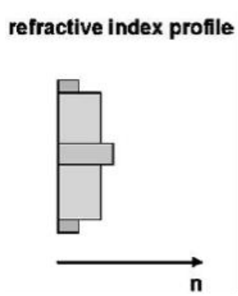
$$P_{th}^{SBS} \cong \frac{21A_{eff}}{g_B L_{eff}} \quad \text{Equation 9}$$

$$P_{th}^{SRS} \cong \frac{16A_{eff}}{g_R L_{eff}} \quad \text{Equation 10}$$

The principles above try to step through the fundamental concepts used in a fiber laser as you would use them for building a fiber laser. It starts out with how light propagates down a fiber, how you can select different modes based off fiber diameters, what a mirror in a fiber is, how to create an optical cavity in a fiber, and what the two primary scattering effects or limiting principles for a fiber laser are.

4 Technology

The basic outline of a fiber laser can be seen in Figures 5 and 6 below. It consists of a core or active medium, usually doped with a rare earth element like ytterbium (Yb), surrounded by the inner cladding which has a lower index of refraction and a diameter that is large in comparison to the core diameter, followed by the outer cladding. Inside the fiber are two Bragg gratings that act as an optical cavity that is used to amplify the emissions of the core material. Light is then end or side pumped into the fiber inner cladding.



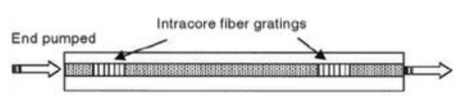


Figure 5

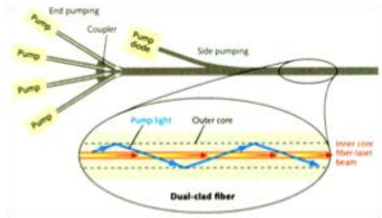


Figure 6

To make a fiber laser, first the glass core is doped with a very small percentage of phosphate and large percentage of Ytterbium. The phosphate is used so that the Ytterbium doesn't cluster. Clustering causes ion-ion interactions that reduce the excitation state lifetimes. Other material combinations can be used to avoid clustering. Next a thick cladding layer that has a lower index of refraction than the core is applied. Then a thinner cladding layer is applied. Using an infrared laser, sections of the fiber can be conditioned to create the Bragg gratings needed on both sides of the core for a wavelength specified in the design. Finally a diode or other source can be end or side pumped into the cladding of the fiber. Turn on the light source and you will have a fiber laser.

While the designs above are simplistic, they can also be much more complicated. One of the major factors to consider is that the gain in a medium is calculated by the product of pump light intensity and interaction length with the laser radiation in the gain medium. This suggests that we need to get as much pump light to interact with as much of the core as we can. To increase gain people have come up with index changes, like that shown in Figure 7, to perform on the inner cladding to try and push as much of the pump energy into the core as they can. Other ways of aiming the pump light into the core and increasing gain include changing the shape of the inner cladding to hexagonal, D-, or rectangular shape. Research has not been clear as to which design is more efficient, but the designs add a level of complexity to the calculations. Generally speaking people have also chosen to end pump their fibers instead of side pumping them because it is more efficient to end pump and results in a greater gain. Other configurations, like the composite cavity laser in Figure 8, which includes another lower reflective Bragg grating at the input end, enhance the center mode giving more discrimination between modes as seen in Figure 9. Another design, shown in Figure 10, adds to that by including polarization filters or chirped gratings. Chirp is defined as a time varying wavelength or frequency. The polarization filters are added to help prevent spatial hole burning or the loss of specific frequencies in the output spectrum. The chirped grating can be used to un-chirp beams since ytterbium naturally tends to chirp beams. Another design thought is that you could build in multiple Bragg gratings or cavities to excite even more modes in the core thus increasing power output. You could also go the other way and eliminate modes through their evanescent waves by bending the fiber. You could also go to single mode or multimode just by changing the diameter of your core. Not that it’s always true, but just about everything you can do on an optical table with solid-state lasers can be done on a fiber laser.

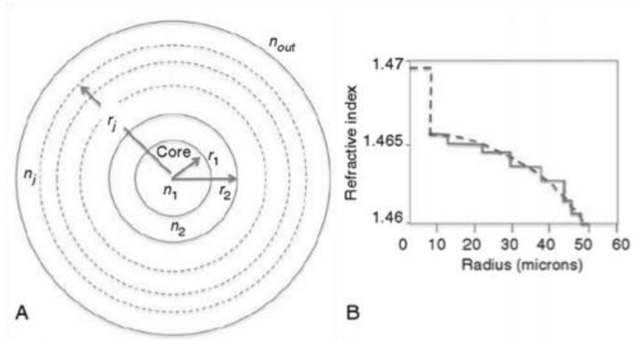


Figure 8

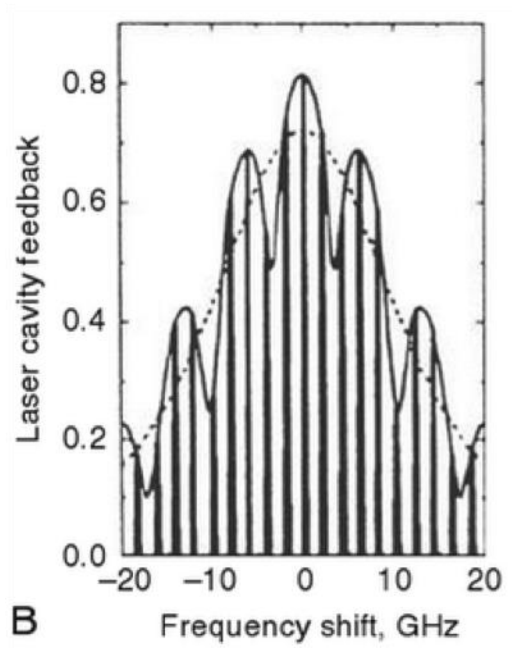


Figure 9

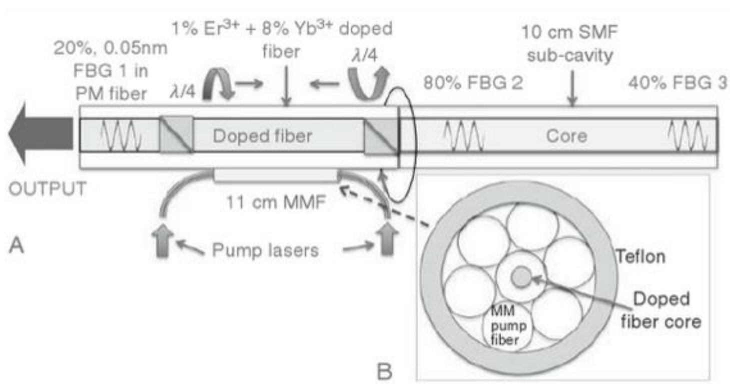


Figure 10

All the designs above have some inherent advantages over their cousin the solid-state laser. First of all, a solid-state laser medium suffers from a large amount of thermo-optical problems; meaning that as the temperature of the rod increases the shape of the rod starts to change or thermal lensing starts to occur. Simply put, as you change the power your beam quality and focus position will change. Fiber lasers are known for having excellent thermo-optical properties due to the fact that they have a large surface area along the fiber to dissipate heat. Since fiber lasers don't suffer from the first order thermo-optical effects they are most limited by the smaller third order effects above. Another advantage of ytterbium in fiber lasers is that it only has a quantum defect (lost energy) of 9% vs. neodymium pumped lasers with a quantum defect of 25%. Due to the fact that the fiber laser is completely in fiber it is much more efficient to move the power from element to element. With solid-state lasers you will need to worry about optical losses on mirrors and in lenses, damage thresholds moving from element to element, and losses due to a mismatch of the laser to the fibers numerical aperture and coupling efficiency if you wanted to launch the beam into a fiber.

5 Application

Fiber lasers have had their largest impact on the welding and automotive industry as well as the military, Figure 11, but have also had some impact on our ability to perform long distance measurements as well as other applications that require high power single mode lasers. In welding people are always asking for more and more power with higher beam quality. The higher power means that they can make deeper cuts and welds and the higher beam quality means that they can do it with less power. The fiber laser has already borne fruit in the automotive industry where fiber lasers are being used to cut and weld high strength steel to lighten weight and improve strength. Fiber lasers, like solid-state lasers, can do the cutting and welding but using less space, less energy, and less power; not to mention that the laser is already in a fiber and ready to be placed on a robot to position the weld head. People today are choosing fiber lasers over solid-state because of the reasons above and because they require virtually no maintenance or other upkeep.

Figure 11

6 State-of-the-art

In recent years, fiber laser manufacturers have stepped up to the challenge of industry and the military by producing single mode lasers up to 10 kW and multi-mode lasers up to 50 kW. In the past history of lasers the military was able to accomplish these powers using a chemical laser so large it had to be mounted inside a Boeing 747. Today, using fiber lasers, this same amount of power can be generated by using a fiber laser the size of two refrigerators. This kind of power has revived one of the coolest military programs, previously called Star Wars, where they use lasers to shoot down incoming planes or missiles. Today the program has a different name but the mission is basically the same.

While fiber laser have overcome many of the first order limitations seen in solid state lasers, they will start to face their own limitations as seen in figure 4 above as manufactures starting to reach the damage threshold of silica glass caused by dielectric breakdown and have problems overcoming Raman and Brillouin scattering. To keep up with the demand for more power manufactures will need to incorporated/adapt new features into their design. A feature not yet adapted into the design of commercial fiber lasers is PCFs / Photonic Band Gap (PBGs) which have been in existence since early 1996. PCFs are fibers with a periodic transverse microstructure that operate by trapping light in by means of a two-dimensional (2-D) PBG. Light is guided down the PCF by three distinct guidance mechanisms: 1) a modified form of total internal reflection (TIR) 2) PBG and 3) a leaky mechanism based on a low density of photonic states in the cladding. The most widely accepted way of producing these fibers is by stacking 1 mm outer diameter and 0.3 to 0.9 mm inner diameter tubes in a configuration shown in figure 12. The inner to outer diameter ratio is the primary determinant in the fibers final diameter to pitch value. For a hollow core design, a number of tubes are removed from the center meaning that position B should be in the center of Figure 12. Next a wire is placed around the stack to hold the tubes and an outer glass sleeve is placed over the stack. Finally the stack is placed under pressure or vacuum and the fiber is drawn. The drawing process itself produces highly reproducible distortions due to the viscous flow, surface tension, and pressure applied.

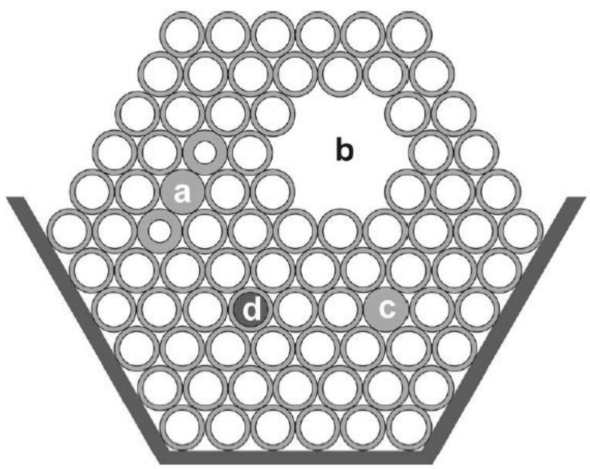


Figure 12

The highly reproducible distortion is seen in a form of ripples frozen into place causing surface roughness which in turn causes scattering losses when modes traveling near the surface of the inner diameter make contact with the ripples. Some different designs of PBGs include large mode area, dispersion controlled, hollow core, birefringent, multi-core, and solid core. My primary focus will be on the hollow core design as seen in Figure 13.

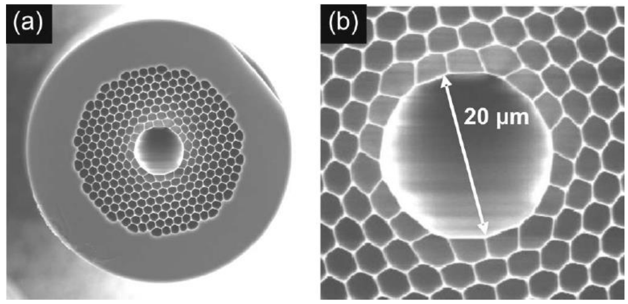


Figure 13

Figure 14 specifies design parameters for creating a PCF based on a desired frequency needing to pass through it. β is the axial wave vector component that can be solved for using Maxwell's Equations. In section 1 light is able to travel in all directions and all materials, in section 2 light is limited from traveling in air, in section 3 from air and Photonic crystal and in section 4 cut off completely due to TIR or the PBG. The full 2-D PBGs exist in the black finger-shaped regions.

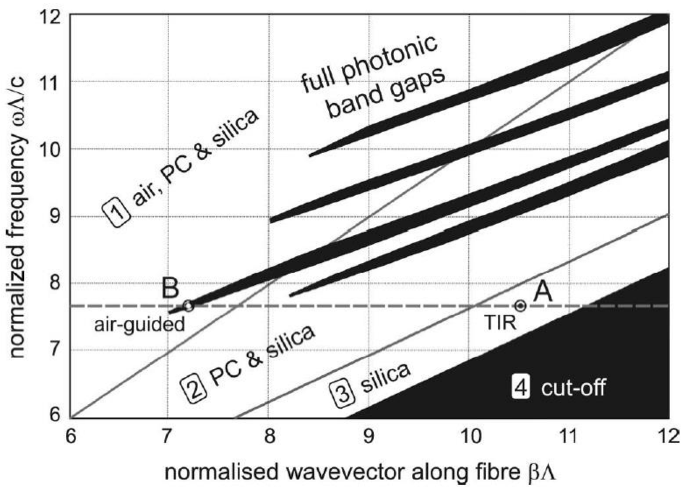


Figure 14

PCF losses are primarily determined by the fraction of light in glass and the roughness at the glass-air interface. If we think of the transition from a solid-core design to a hollow-core design the percentage of light in air or gas can range from 100% to 1%. The lowest loss reported for a solid-core design was in Japan at 0.28 dB/km. In a hollow-core design the lowest reported loss has been 1 dB/km but the calculated lowest loss is .2dB/km making it the most likely to have the largest benefit for fiber lasers. If only 1% of the power traveling in the fiber is incident on the glass we can reach much higher beam powers before we start to approach the damage threshold of the silica glass. That power can also travel much further before being attenuated to the same levels seen in traditional fiber if we could achieve the 1% loss.

Figure 15

An advantage of hollow core PCFs is that the hole can be filled with a gas creating a gas laser. One of the drawbacks of hollow core PCFs, as can be seen in Figure 15, is that they have the lowest loss at a specific center frequency, so 1 reported restricted bandgap. This makes carrying a pump wavelength that is drastically different than the primary to stimulate an active medium further down the line without incurring a large amount of loss to the pump wavelength very difficult. Researchers are currently looking into Kagome hollow core PCFs that they believe will have the ability to guide light in two wavelengths without a large amount of loss to either wavelength. Their guiding principle is to try and balance the Kagome dispersion with the gas dispersion. Their suggested configurations can be seen in Figure 16, where A and B represent their hexagonal design, and C and D represent their square design.

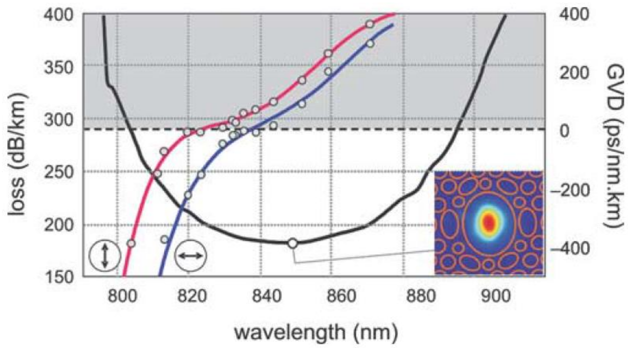


Figure 15

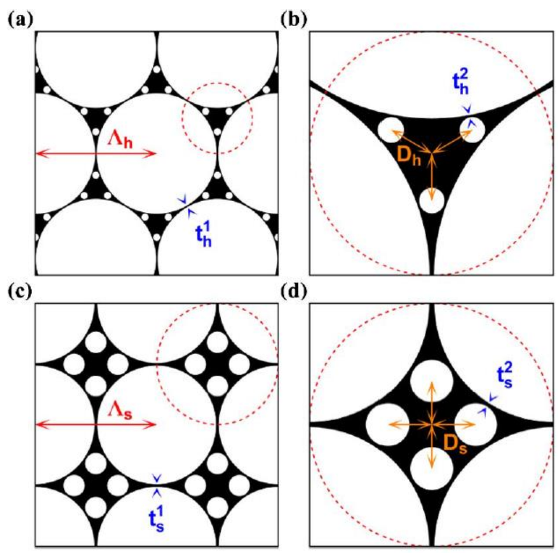


Figure 16

After performing a numerical analysis where they used $r\frac{1}{h} = .0495\Lambda_h$, $r\frac{2}{h} = .0345\Lambda_h$ where Λ_h is the hexagonal large air hole pitch for the hexagonal and $r\frac{1}{s} = .49\Lambda_s$, $r\frac{2}{s} = .0884\Lambda_s$ where Λ_s is the square large air holes pitch they were able to obtain in Figure 16.

Figure 16

In Figure 17 the blue indicates the square and the black indicates the hexagonal designs. Graph A in Figure 17 represents the fundamental mode where B represents the higher order bandgaps demonstrating that the hollow core PCF can now support two wavelengths within the same fiber.

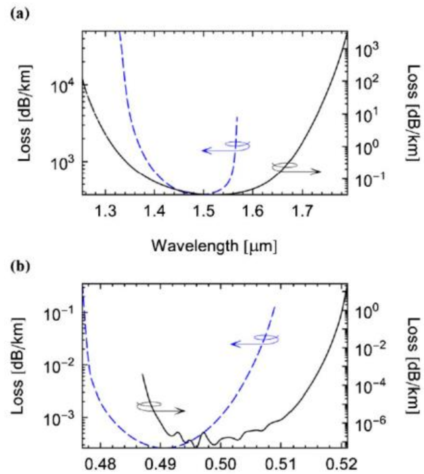


Figure 17

More and more research these days are going into the characteristics of these hollow core gas filled PCFs. One area of interest is in the modeling of the ionization and Raman effects near and away from the zero dispersion wavelength. The photon ionization blue shift occurs when the pulse intensity exceeds that ionization threshold and the Raman induced redshift takes place along the whole propagation with a rate that has an approximately linear dependence on the pulse intensity. What has been found is that around 1.75 μJ, photoionization blueshift starts to take place due to plasma formation. Then as the input pulse energy increases the induced blueshift starts to compensate and take over the red shift. It was also found that by changing the cavity pressure and input current the center frequency could be changed allowing the laser to have a tunable frequency of around 400 nm.

7 Future

While the fiber laser described above is a well-developed technology and PCFs have been around for a long time, the future of fiber lasers lies in our ability to marry the two technologies and overcome the limitations set by the damage threshold of silicon and scattering effects. That being said, I don't think design improvements to the fiber laser are going to make much of an impact in the next century. What I am interested in seeing is how people will use fiber lasers in both high and low power configurations. The fiber laser and fiber amplifiers have come to the point of being well-developed technologies and now we should see what kind of cool toys we can develop using them. If we were to gain a greater understanding of the materials used or were able to overcome the third order scattering effects maybe we could shrink fiber lasers down to a smaller more manageable size where they could be put on jet fighters instead of being mounted on the sides of large boats.

Another interesting thought is fusion. Inertial Confinement fusion uses a laser to attempt to initiate fusion by heating and compressing a fuel target that is typically comprised of deuterium and tritium. To do this we would need a laser with an energy output of around 1 MJ, having a pulse width around 1-10 ns, an efficiency around 5%, a pulse repetition rate around 10 Hz, and a short wavelength to increase coupling efficiency. Using today's technology we could be able to use a Titanium sapphire laser to pump an array of Argon filled Kagome hollow core PCF to create a deep UV ultrafast pulse. We could then possibly combine the outputs from the array into a single output launched into a hollow core PCF that is able withstand MW of power due to the power traveling mostly in air.

In the future we could be able to continue the fiber laser design by switching out the doped fiber with a gas filled fiber then switching out the standard fiber with a hollow core PCF. If the conversion to the fiber laser can be accomplished we could be able to receive the low wavelength, high energy short duration pulses needed for fusion. The laser would produce MW power either pulsed or continuous wave without Q-switching or any other kind of work arounds. Adding to this is that as the wavelength of light falls the optical fields in a PCF are better able to distinguish between the glass regions and the air.

The future of fiber lasers in my opinion is bright, with MW of power for welding, astronomy, military, and fusion.

8 Conclusion

I have explained the basic design of a fiber laser, the principles and equations that govern the operation, the main limiting factors, the advantages of fiber lasers over solid state-lasers, how fiber lasers are being used today, Photonic crystal fibers, gas filled photonic crystal fibers, current applications of photonic crystal fiber and what I believe to be the future of fiber lasers when the concepts of current fiber lasers meet the concept current photonic crystal fiber.

References

1) Kashyap, Raman. Fiber Bragg Gratings. : Elsevier Science, 2009. ProQuest Ebook Central. Web. 11 March 2016.

2) Mathieu Gagné and Raman Kashyap, "Random fiber Bragg grating Raman fiber laser," Opt. Lett. 39, 2755-2758 (2014)

3) L. Dong and W. F. Liu, "Thermal decay of fiber Bragg gratings of positive and negative index changes formed at 193 nm in a boron-codoped germanosilicate fiber," Appl. Opt. 36, 8222-8226 (1997)

4) Graham D. Marshall, Robert J. Williams, Nemanja Jovanovic, M. J. Steel, and Michael J. Withford, "Point-by-point written fiber-Bragg gratings and their application in complex grating designs," Opt. Express 18, 19844-19859 (2010)

5) Mathieu Gagné, Sébastien Loranger, Jerome Lapointe, and Raman Kashyap, "Fabrication of high quality, ultra-long fiber Bragg gratings: up to 2 million periods in phase," Opt. Express 22, 387-398 (2014)

6) R. Paschotta, article on 'fiber Bragg gratings' in the Encyclopedia of Laser Physics and Technology, accessed on 2016-03-11

7) Hecht, Jeff. 2012. Fiber lasers: The state of the art. *Laser Focus World* 48, (4) (04): 57-60, http://search.proquest.com/docview/1031289648?accountid=27865 (accessed March 21, 2016).

8) Limpert, J. ; Roser, F. ; Klingebiel, S. ; Schreiber, T. ; Wirth, C. ; Peschel, T. ; Eberhardt, R. ; Tiinnermann, A.

9) IEEE Journal of Selected Topics in Quantum Electronics, May-june 2007, Vol.13(3), pp.537-545 [Peer Reviewed Journal]

10) Kasap, S. O. *Optoelectronics and Photonics: Principles and Practices*. 2nd ed. Vol. 1. Upper Saddle River, NJ: Prentice Hall, 2001. Print.

11) J. Russel, article on 'photonic-crystal fibers' in the *Journal of Lightwave Technology*, 24. edition December 2006

12) Mohammed F. Saleh and Fabio Biancalana, "Tunable frequency-up/down conversion in gas-filled hollow-core photonic crystal fibers," Opt. Lett. 40, 4218-4221 (2015)

13) Z. Montz and A. A. Ishaaya, "Dual-bandgap hollow-core photonic crystal fibers for third harmonic generation," Opt. Lett. 40, 56-59 (2015)