Understanding Optical Coupling in Collapsed Hollow-Core Optical Fiber

by

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Abstract

Frequency references based on saturated absorption spectroscopy that are stable, portable, and accurate can be constructed using photonic bandgap (PBG) fibers filled with acetylene.[1][2][3][4][5][6] A method for sealing acetylene inside the PBG fiber with minimal contamination involves collapsing the core of the PBG fiber, which causes high loss in the final splice. We investigate the light coming out of the PBG fiber and methods for coupling it back into fiber. Results show that the light exiting the fiber does not have a Gaussian shape and can be coupled back into fiber using a two-lens set-up, with 26% being the highest coupling achieved.

Introduction and Background

Stable, accurate, and portable frequency references are greatly needed in remote sensing, meteorology, telecommunications, and many other applications.[1] It has been established that saturated absorption spectroscopy can be used for these references and that photonic bandgap fibers (PBG) are an ideal building material for frequency references based on acetylene spectroscopy.[2][3][4][5][6] Hollow core PBG fibers can trap gases, such as acetylene, and have long interaction lengths, which require lower acetylene pressures.[3][7] However, sealing the gas inside the fibers often holds challenges.

A fiber cell consists of solid core single-mode fiber being spliced to both ends of a hollow core PBG fiber. Constructing a fiber cell usually requires one end of the PBG to be exposed to the air.[8][9][10][11][12] Due to the low acetylene pressures needed for the spectroscopy, it is vital that as little contamination as possible is introduced to the PBG fiber while a cell is being constructed. Exposing the PBG end to the air allows contaminants to rush into the cell and makes useful measurements impossible.[8][10][11] One alternative method involves sealing the open end of the PBG, collapsing the core near that end, and cleaving in the collapsed section. This allows the final splice to be completed without ever exposing the core to the air. Unfortunately, this final splice has a splice loss of at least 10 dB due to the collapsed portion of the core.[8][10][11] Such a high splice loss can make saturated absorption spectroscopy difficult. Prior to this, no one has investigated where the light is going and whether or not it can be re-coupled into the fiber using other methods. In this paper, we examine where the light is going as it exits the collapsed PBG and how to collect that light in a usable manner.

Materials and Methods

Six meters of 20 μm hollow core PBG fiber purchased from Crystal Fiber was used for this experiment. It was spliced to 125 μm SMF using a Vytran filament splicer. The core was also collapsed using the same splicer. No acetylene was trapped inside the hollow core during this experiment.

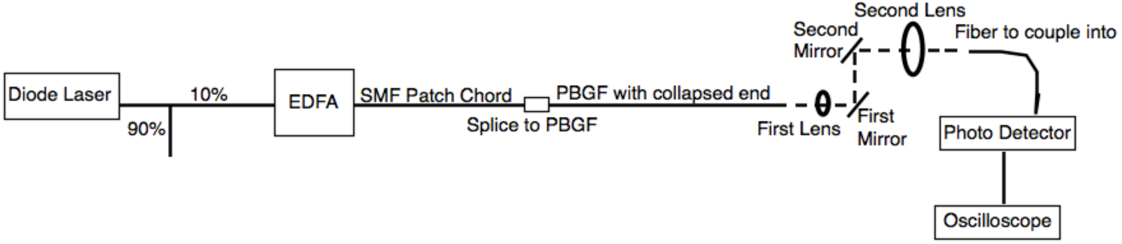
The light was first characterized by taking a knife-edge measurement of the light coming out of the collapsed portion of the fiber and of light coming out of a normal SMF fiber. This was done by running light from a 1531 nm tunable diode laser through the collapsed PBG fiber and focusing the light, using a 2 inch diameter f =30 mm lens, onto a power meter. A vertical razor blade on a one-axis stage was slowly moved across the beam profile, and the power at each step was recorded. A fitting function in Origin, derived from the fact that light from an SMF should follow a Gaussian shape, was used to fit a line to the data. The data from the SMF curve was then compared to the data from the collapsed PBG curve.

An IR card placed after the collapsed portion of the fiber when the laser was sending light through the fiber was also used to visualize the beam. The beam profile was seen as a serious of concentric bright rings for the PBG fiber and as a single bright dot for the SMF fiber.

Three free-space set-ups were tested; each set-up involved one or two lenses, and one of the set-ups involved an off-axis parabolic mirror. All of the set-ups used the tunable diode laser and amplified the signal using an erbium doped fiber amplifier (EDFA). The signal was split 90/10 out of the laser with 10 going to the EDFA to be amplified and the rest being used during set-up installation. The light from the EDFA was then sent through the collapsed PBG fiber. At this point, each set-up is unique.

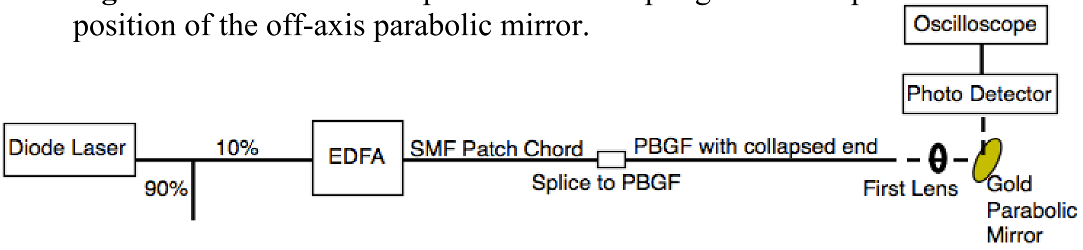
The first set-up has two lenses and two mirrors after the PBG fiber (as seen in Fig. 1). The first lens is an f=8.00 mm, 12.18 mm diameter, large NA, aspheric lens, and the second lens is an f=40 mm, 1 inch diameter, achromatic lens. The light is measured before the second lens and after being coupled into fibers placed after the second lens.

Figure 1: The first set-up used to test coupling from collapsed PBGF.



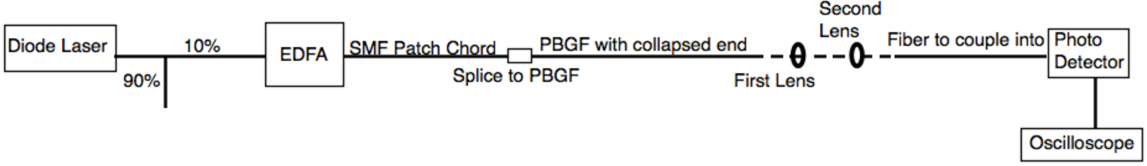
The second set-up has a f=25 mm, ½ inch diameter, doublet lens followed by a gold ½ inch diameter off-axis parabolic mirror with a reflected focal length of 15.0 mm (see Fig. 2). The light is measured after the mirror.

Figure 2: The second set-up used to test coupling from collapsed PBGF. Note the position of the off-axis parabolic mirror.



The third set-up has f=25 mm, 1 inch diameter, singlet lens followed by an f=75 mm, 1 inch diameter, spherical lens (see Fig. 3). The light is measured before the second lens and after being coupled into fibers placed after the second lens.

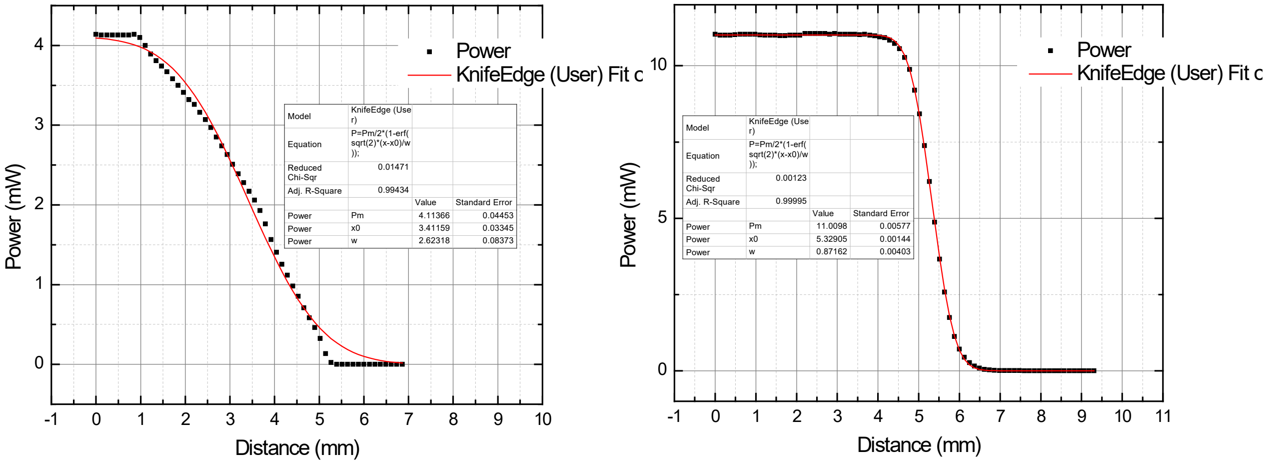
Figure 3: The third set-up used to test coupling from collapsed PBGF. Notice the straight alignment of the lenses.



The light in all three set-ups is measured using a large area photo detector, and the data is read off of a digital oscilloscope. In set-ups one and three, light is coupled into three different fibers: a 62.5 µm core multi-mode fiber (MMF) patch chord, two meters of 400 µm core MMF bare fiber, and two meters of 62.5 µm core MMF bare fiber. All fibers, mirrors, and lenses were purchased from Thor Labs.

Results

The knife-edge measurement of the SMF resulted in a curve that fit almost perfectly with the fitting function; the fit line is directly on top of all of the data points. The knife-edge measurement of the collapsed core PBG, however, resulted in a curve that did not match the fitting function well. Where the SMF plot had curves, the PBG plot had sharp bends. This is a good indication that the beam profiles are quite different (see Fig. 4 below). Differentiating the knife-edge curve shows us the shape of the curve. The SMF curve fit a Gaussian beam, whereas the PBG curve looked much flatter (see Fig. 5 below).



Model	KnifeEdge (User)		
Equation	P=Pm/2*(1-erf(sqrt(2)*(x-x0)/w));		
Reduced Chi-Sqr	0.01471		
Adj. R-Square	0.99434		
		Value	Standard Error
Power	Pm	4.11366	0.04453
Power	x0	3.41159	0.03345
Power	w	2.62318	0.08373

Model	KnifeEdge (User)		
Equation	P=Pm/2*(1-erf(sqrt(2)*(x-x0)/w));		
Reduced Chi-Sqr	0.00123		
Adj. R-Square	0.99995		
		Value	Standard Error
Power	Pm	11.0098	0.00577
Power	x0	5.32905	0.00144
Power	w	0.87162	0.00403

Figure 4: The results from the knife-edge measurement when the razor blade was 0.8 cm from the fiber end. The PBG results are on the left, and the SMF results are on the right. Notice how well the SMF results (in black) match the fitting function (in red).

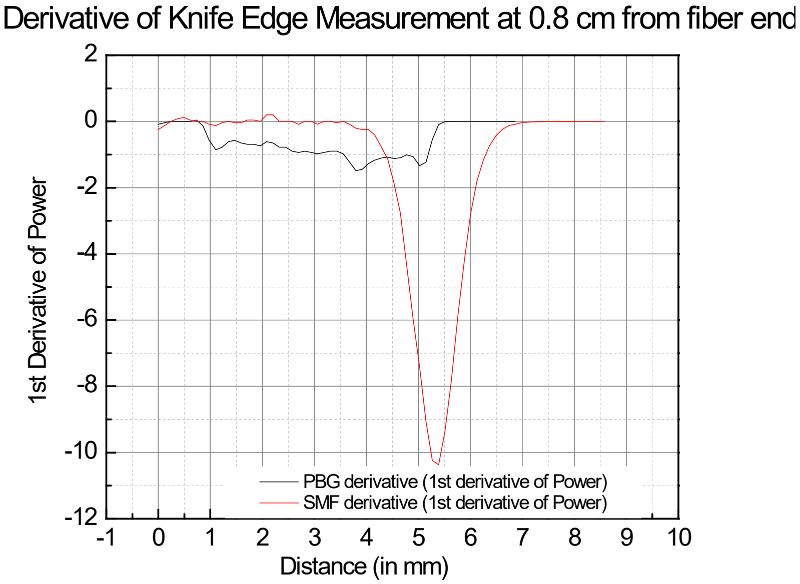


Figure 5: The results from differentiating the knife-edge measurement when the razor blade was 0.8 cm from the fiber end. Notice the SMF results (in red) follow a Gaussian beam shape, whereas the PBG results (in black) are almost a flattop function.

The results for all three set-ups are summarized in Table 1 below. This data shows that the third set-up had the highest power reading and the best coupling. These power readings can be compared with the 12.7 mW that is coming out of the collapsed fiber end.

Table 1:

Set-up number	Where the light was measured	Power of the light at that position (in mW)
1	Free space before the second lens	0.659
1	After coupling into 400 um MMF	0.251
1	After coupling into 62.5 um MMF	0.0206
1	After coupling into MMF patch chord	0.251
2	Free space after parabolic mirror	1.17
3	Free space after second lens	4.64
3	After coupling into 400 um MMF	4.03
3	After coupling into 62.5 um MMF	1.63
3	After coupling into MMF patch chord	1.09

While not all of the light is being collected in set-up 3, more light is coupled in that set-up than in the other two. So, more investigation was done to see if this coupling could be increased. Three different lenses were placed in the position of lens 2, and the power after the lens and after coupling into 62.5 um MMF fiber was measured. The three different lenses were all 1 inch in diameter with focal lengths of 30 mm, 40 mm, and 45 mm. The results are summarized in Tables 2 and 3 below.

Table 2: Power measurements after lens 2

Lens used in lens 2 position	Power reading (in mW)
f=30 mm	7.50
f=40 mm	8.84
f=45 mm	9.64

Table 3: Power measurements after light is coupled into 62.5 um MMF

Lens used in lens 2 position	Power reading (in mW)
f=30 mm	1.65
f=40 mm	3.37
f=45 mm	0.809

These results show that the most power can be found after lens 2 when lens 2 has a focal point of 45 mm. However, this light is difficult to collect. The highest coupling occurs when lens 2 has a focal point of 40 mm. It is likely that the f=45 mm light is difficult to couple due to the beam size and/or angle of incidence in the MMF fiber.

Discussion/Conclusion

Our results showed us that the beam profile of collapsed core PBG fiber looks very different from SMF beam profiles. It does not fit a Gaussian curve. From our IR card visualization, it is clear that the light is coming out of the collapsed core in rings. These rings are most likely part of why it is hard to couple into SMF.

Our other investigation shows that the light can be coupled back into fiber using a variety of free-space set-ups. The best results were achieved using one large achromatic lens and one large spherical lens in a straight line. When a lens with a focal length of f=25 mm is combined with a lens with focal length of f=40 mm, the greatest coupling is achieved (26% coupling). While these results are an improvement from previous coupling attempts, they still show quite a bit of loss. Further investigations should investigate methods for making this system all-fiber. One possible method could use a Fresnel lens small enough to be spliced to the collapsed part of the PBG fiber.

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