Baghdad Science Journal **Vol.7(1)2010**

Low Loss in a Gas Filled Hollow Core Photonic crystal fiber

Hanan J. Taher*

Date of acceptance 28 / 2 / 2010

Abstract

The work in this paper focuses on the experimental confirming of the losses in photonic crystal fibers (PCF) on the transmission of Q-switched Nd:YAG laser. First HC-PCF was evacuated to 0.1 mbar then the microstructure fiber (PCF) was filled with He gas & N_2 gas. Second the input power and output power of Q-switched Nd:YAG laser was measured in hollow core photonic bandgap fiber (HCPCF). In this work loss was calculated in the hollow core photonic crystal fiber (HCPCF) filled with air then N2, and He gases respectively. It has bean observed that the minimum loss obtained in case of filling (HC-PCF) with He gas and its equal to 15.070 dB/km at operating wavelength (1040-1090) nm.

Key word:Photonic crystal, microstructure fabrication,optical fibers

Introduction

Photonic Bandgap Fibers (PBGF) are optical waveguides in which a micro-structured cladding provides a one- or two-dimensional photonic bandgap that confines light to the fiber core[1, 2, 3]. Unlike conventional all-solid fibers, that guide light by total internal reflection require a cladding material with an index lower than that of the core, PBGF can be designed to guide light in an empty or gas-filled hollow core. Since as much as 99% of the optical power in these fibers can travel in air and not in the glass, they do not suffer from the same limitations to loss as conventional fibers and can exhibit radically reduced optical non-linearity, making them promising candidates for future ultra-low loss transmission fibers. Rapid progress has been made since air-guiding fibers were first demonstrated in 19991[4, 5]; however, the reduction of loss remains a key issue. We report here a silica hollow core PBGF with a minimum attenuation of 15.070 dB/km, significantly reducing the remaining gap in loss between conventional fibers and PBGFs.

Photonic crystal fibers

There are different types of fibers. The fiber name mostly depends on the constitutes, guiding construction and recently on the physical principle of operation like the photonic crystal fiber. Except the photonic crystal fibers all the other fibers are called conventional optical fiber. Due to the unique features of the photonic crystal fibers (PCF) make them very attractive for many applications.

Photonic crystal fibers can be classified into categories, depending on the nature of the core as shown in Fig. (1). Microstructure fibers (MFs) Fig. (1*a)* possess a solid core made of materials such as silica or non-silica glasses where as photonic bandgap

* Institute of Laser for Postgraduate Studies, University of Baghdad

fibers (PBFs) Fig. (*1b)* exhibit a hollow core or a core made of a

dielectric whose refractive index is lower than that of silica [6].

The guiding mechanism of the Microstructure fibers (MFs) relies on a modified total internal reflection. Both types (solid core and hollow core) are currently used widely in many applications like the transportation of high laser energy [7] and in the supercontinuum generation [8]. The breakthrough in the applications of these fibers may be in the applications of the hollow core PCFs may be in the transmission of CO_2 laser beam which could not be transported by any other conventional optical fiber [9].

In the present work, we will deal mainly with the photonic bandgap fiber which has a hollow core and study the losses of different gas fillings inside the hollow core on the guiding properties of this fiber.

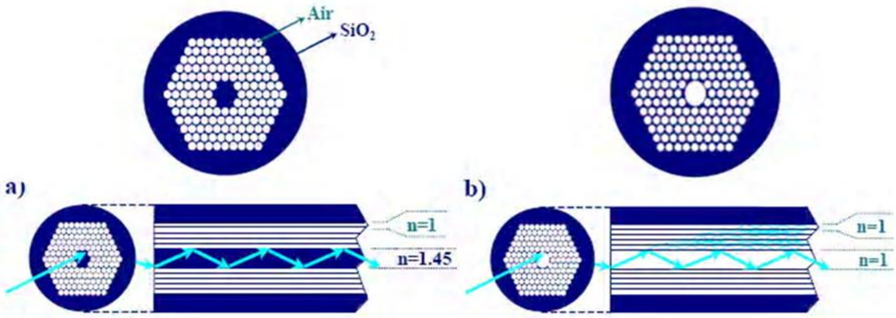

Figure (1): A schematic comparison between a band gap guiding fiber and an index-guiding PCF with a PC cladding comprising a triangular array of holes a) Guidance principle in an MF. b) Guidance principle in a PBF.

1-2 The hollow core PCF

In these experiments, the HC-PCF investigated was a 70 mm length of 19-cell defect fiber, where the cell defect number refers to the number of capillaries removed from the perform center to form the HC. The 19-cell fiber had a core diameter of approximately 14.7 μm surrounded by a seven layer photonic bandgap structure with approximately a 2.9-μm pitch. The air-filling fraction in the holey region was > 90%. The fiber is 1064 nm photonic band gap fiber from BlazePhotonics having bandwidth (loss < 100 dB/km): 1040-1090 nm and loss at operating wavelength is 60 dB/km [10], and having the following characteristics:

Table (1): HC-PCF specification

Center operating wavelength	**1060 nm**
Core diameter Core formed by removing 19 hexagonal unit cells of the cladding	14.7 µm
Pitch (distance between cladding hole centers)	2.85-2.90 µm
cladding hole diameter	2.53-2.55 µm
Air Filling Fraction in the holey region Excluding core and outermost ring of holes	> 90%
Diameter of holey region	50 µm
Diameter of silica cladding	123 µm
Coating diameter	220 µm
Numerical aperture	0.12
Width of the transmission band	>50 nm
Attenuation at operating wavelength	< 0.1 dB/m

Due to non availability of standard commercial cleaving and stripping tools for this type of fiber and the impossibility to polish the end faces of a PGB fiber, a lot of effort was needed to cleave this fiber. All the cleaved samples were examined under an optical microscope. Mechanical steps have been taken to perform the cleaving. The fiber end was immersed in ethanol, after 10-15 minutes the coating was melted. The melted coatings at the ends are taking away by fingers. Using a scalpel to scratch the fiber and then broke it by hands. The remaining ethanol in the hollow core and cladding holes was evaporated after few minutes. This technique is subjected to trial and error so it needs skilled hands to do it perfectly. The hollow core PCF cannot be cut by the scalpel or any other instrument directly to prevent the expected distortion of the PCF face and the pollution of the inner structure by the small fragments of the PCF material.

The HC-PCF was tested along the fiber length under the optical microscope. Figure (2) shows the middle part of the PCF.

Figure (2): the middle part of the HC-PCF under optical microscope

The two ends of the PCF were tested under the optical microscope. The end parts of the PCF are shown in Figure (3).

Figure (3): Both sides of the HC-PCF under optical microsco

The cross section of the hollow fiber was tested under the microscope as shown in Figure (4), To be sure that no damage occurred for both side of the HC-PCF:

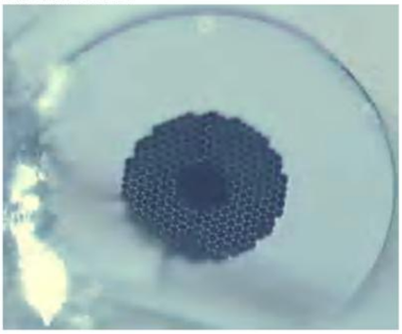

Figure (4): the cross section of the HC-PCF

2. The experimental set up used to fill the HC-PCF with gas

The fiber that has been used to perform the experiments is a 19 cell HCPCF from Blazephotonic originally exhibited a bandgap centered at 1060 nm. The fiber length, interhole distance (pitch) and the core diameter are 70 mm, 2.58 μm and 14.7 μm respectively. The filling was performed by a specially designed cell and vacuum chamber. Vacuum camber has been designed and made from stainless steel it has length 21.7 cm and inner diameter 10 cm. It has front and rear openings (windows), sealed with glass to allow laser transportation. There are three valves in the design; one is for reducing the pressure inside the chamber to 0.1 mbar. Moreover, the other valves are for pumping gas inside the chamber and lead through. The lead through valve was designed to control a piece of metal; there is a groove in the middle of the metal where the fiber lay on it which is called a fiber holder and it has length 6 cm. It is used to adjust the hollow core photonic crystal fiber with the laser by micrometer in the lead through to get the best coupling between the hollow core photonic crystal fiber and the laser. Two lenses with the same focal length equals 7.5 mm are fixed on the endings of the fiber holder which is variable to get the best coupling between hollow core photonic crystal fiber and the Q-switch Nd-YAG laser. Figure (5) shows the photographs of the vacuum chamber [11].

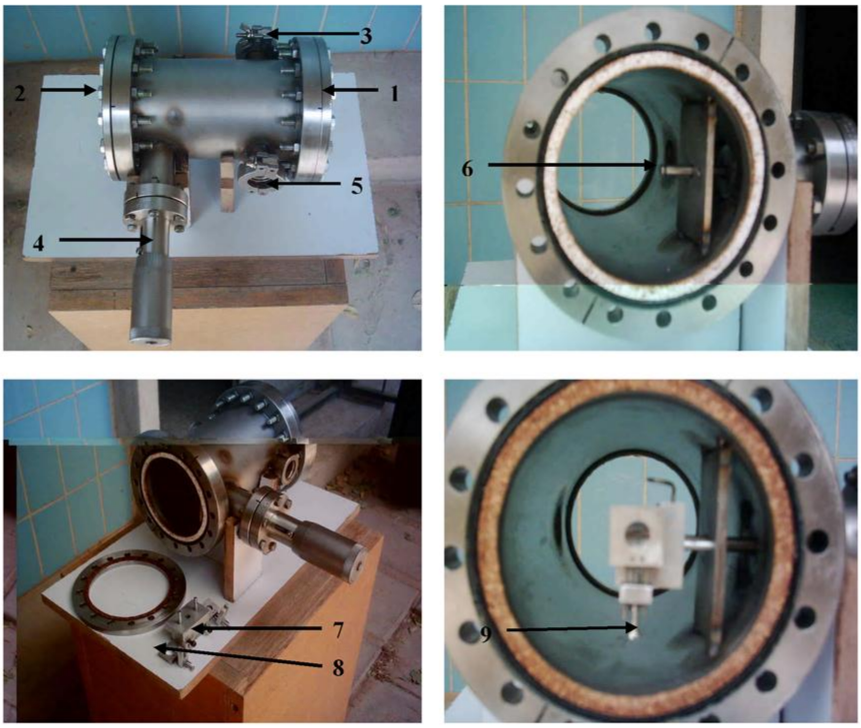

Figure (5) Photographs of vacuum chamber .

1-Front window 2- Rear window . 3- Value of reducing pressure inside the chambar 4- Lead through which adjust the PCF in the x direction. 5- Value for pumping gas inside the chamber. 6-Metal from lead through which hold the fiber holder.7- PCF holder. 8-Lens f=7.5mm. 9- Metal is used to adjust the two lesses in y direction to get the best coupling between PCF and the laser

The HC-PCF ends were mounted into a specially designed cell and the core, figure (6) shows the experimental set up.

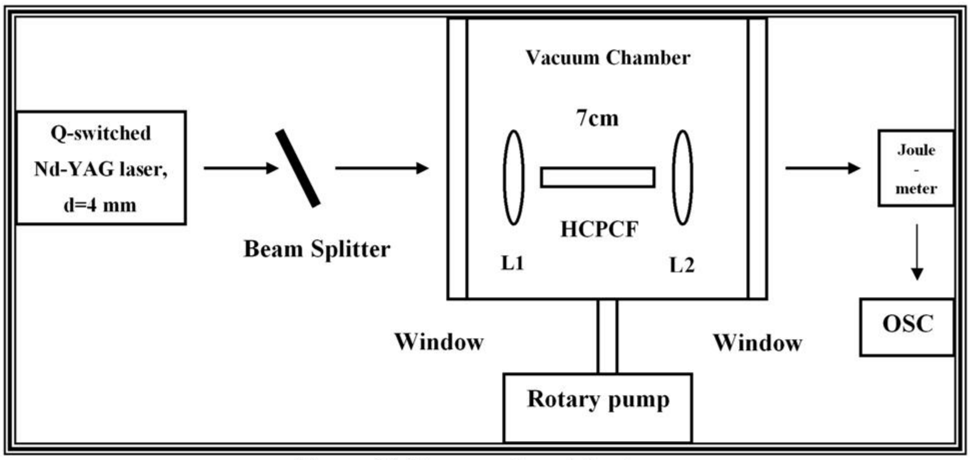

Figure (6) The experimental set up.

The maximum output pulse energy of the constructed Q-switched Nd:YAG laser was measured, and its value was 30 mJ as maximum energy and with pulse duration of 10 ns. The power of the laser represents the crucial parameters for transmission through any fiber. This depends on the energy as well as the pulse duration. The power of the constructed Q-switched Nd:YAG laser comes out to be **3 MW** (three Mega Watt). A joule-meter of high absorption rate type genetic model ED100 was used as energy detector to detect and measure the energies of input and output signal to hollow core photonic crystal fiber. A joule-meter model ED100 is a payro-electric detector. Its conversion ratio was 10.3 V/J.

3. Experimental procedure and results

We have studied near-field patterns over the photonic bandgap wavelength range. A short length (70mm) of HC-PCF has been used. The same piece of the fiber was used to carry out all the experiments to eliminate any possible spectral changes that would be due to structural differences between different fiber samples of varying index contrast. Three different wavelengths from Nd:YAG (1.06μm), He-Ne (0.632 μm) and a green laser (0.532 μm) were coupled to the input end of the HCPCf. The coupled measured efficiency was more than 90%. It is clear as the HC-PCF is designed for 1.06 μm , the only 1.06 μm was almost confined with the PCF core.

Photonic crystal fiber losses can be classified into attenuation, dispersion, bending and coupling. Typical fiber loss is measured in units of decibels per kilometer (dB/Km) using the relation

$$\alpha_{dB} = -(10/L) \log (P_T/P_0)$$

Where (α_{dB}) is the fiber loss in decibels, (L) is the fiber length, (P_0) is the power launched into the fiber, and (P_T) is the power transmitted through the fiber [12].

The hollow-core photonic crystal fiber has a hollow core containing air under atmospheric pressure, so the coupled energy should be less than the optical breakdown threshold of the air which is 0.625×10^{12} W/cm^2 [13] and the coupled energy should be less than the optical breakdown threshold of the glass which is 2×10^{11} W/cm^2 [14, 15] . Hence, the maximum permissible coupled energy or power density is limited according to the optical breakdown threshold of air and glass. The transmission of the Q-switched Nd:YAG laser via HCPCF under atmospheric pressure and the losses via HCPCF is shown in table (2) .

Table (2)

i/p energy μ J	o/p energy μ J	i/p Power Watt	o/p Power Watt	i/p Power density W/cm^2	o/p Power density W/cm^2	Losses dB/km
200	190	20×10^3	19×10^3	0.452×10^{11}	0.430×10^{11}	31.82
400	380	40×10^3	38×10^3	0.905×10^{11}	0.860×10^{11}	31.82
600	570	60×10^3	57×10^3	1.358×10^{11}	1.290×10^{11}	31.82
800	760	80×10^3	76×10^3	1.811×10^{11}	1.721×10^{11}	31.82
890	–	89×10^3	–	2×10^{11}	–	–

To increase the optical breakdown threshold and the transmission efficiency and to decrease the losses, the hollow-core photonic crystal fiber (HCPCF) was evacuated to 0.1 mbar. This was done by putting the fiber and the fiber holder inside a sealed vacuum chamber as shown in figure (6).

The output energy from the Q-switched Nd-YAG laser was decreased from 30 mJ to 5 mJ by using the beam splitter to be propagated via hollow core photonic crystal fiber under vacuum pressure 0.1 mbar. By increasing the input power of the laser coupled through the fiber to about 1.31×10^6 W corresponding to 13.1 mJ of energy and corresponding to the power density (intensity) 2.9×10^{12} W/cm^2, we observed damage on the tip of the fiber because the above value of power density is equal to the optical damage of fused silica under 0.1 mbar vacuum pressure equals 2.9×10^{12} W/cm^2 which is forming the wall of the air core of the PBG fiber represents the limit for the maximum permissible energy propagation as shown in table (3).

Table (3)

i/p energy mJ	o/p energy mJ	i/p Power Watt	o/p Power Watt	i/p Power density W/cm^2	o/p Power density W/cm^2	Losses dB/km
5	4.8	0.5×10^6	0.48×10^6	1.132×10^{12}	1.086×10^{12}	25.32
7.5	7.2	0.75×10^6	0.72×10^6	1.698×10^{12}	1.630×10^{12}	25.32
10	9.6	1×10^6	0.9×10^6	2.264×10^{12}	2.173×10^{12}	25.32
12.5	12.00	1.25×10^6	1.2×10^6	2.830×10^{12}	2.717×10^{12}	25.32
13.1	–	1.31×10^6	–	2.966×10^{12}	–	–

To increase the optical breakdown threshold and the transmission efficiency and to decrease the losses via HCPCF, the hollow-core photonic crystal fiber was evacuated to 0.1 mbar then the N_2 gas was pumped inside the vacuum chamber with different pressure. This was done by putting the fiber and the fiber holder inside a sealed vacuum chamber as shown in fig (6).

The output energy from the Q-switched Nd:YAG laser was decreased from 30 mJ by using the beam splitter to 200 μJ to propagate via HCPCF under 0.1 mbar vacuum pressure and N_2 gas pressure. We observed the behavior of transmission of Q-switch Nd:YAG laser via HCPCF in this case it is similar to that of propagation and losses of laser via HCPCF in air under atmospheric pressure is equal to 31.82 dB/km as shown in table (2).

To increase the optical breakdown threshold and the transmission efficiency and decreases the losses via HCPCF, the hollow-core photonic crystal fiber was evacuated to 0.1 mbar then the **He** gas was pumped inside the vacuum chamber with different pressure. This was done by putting the fiber and the fiber holder inside a sealed vacuum chamber under vacuum pressure 0.1 mbar and pumping He gas as shown in fig. (6).

The output energy from the Q-switched Nd-YAG laser was decreased by using the beam splitter until reach 1 mJ to propagate via hollow core photonic crystal fiber under vacuum pressure 0.1 mbar and pumping He gas inside vacuum chamber, then the output energy of Q-switched Nd-YAG laser was increased until reach the value 18.5 mJ as shown in the table (4) the hollow core photonic crystal fiber was burn. In this case we find the loss via HCPCF have a minimum value and is equal to (15.070 dB/km).

Table (4)

i/p energy mJ	o/p energy mJ	i/p Power Watt	o/p Power Watt	i/p Power density W/cm ^{2}	o/p Power density W/cm ^{2}	Losses dB/km
5	4.88	0.5×10^6	0.488×10^6	1.132×10^{12}	1.105×10^{12}	15.070
10	9.76	1×10^6	0.976×10^6	2.264×10^{12}	2.210×10^{12}	15.070
15	14.64	1.5×10^6	1.464×10^6	3.396×10^{12}	3.315×10^{12}	15.070
17.5	17.08	1.75×10^6	1.708×10^6	3.962×10^{12}	3.867×10^{12}	15.070
18.5	–	1.81×10^6	–	4.189×10^{12}	–	–

4. Conclusions:

Filling the core and the cladding of HC-PCF with another material instead of air seems a promising technique for finding a new transmission medium for different laser types from UV to IR region of the spectrum with out a need to redesign and fabricate a new fiber. The hollow core photonic crystal fiber was filled with N_2 gas and He gas. [The obtained results show in case of pumping He gas inside HCPCF and the vacuum chamber is better so we fined the losses via HCPCF is 15.070 dB/km]. The minimum value of loss via HCPCF is 15.070 dB/km in case of pumping He gas in the vacuum chamber compared to the maximum value of loss 31.82 dB/km of air under atmospheric pressure.

References:

[1] Photonic crystals", *Physics Web*, pp. (1-9), 2000.

[2] J. Ouellette, ""Seeing the future in photonic crystals", *The Industrial Physics*, pp. (14-17), 2002.

[3] P. St. J. Russell, J. C. Knight, T. A. Birks, B. J. Mangan and W. J. Wadsworth, "Photonic crystal fibers", *Report*, Optoelectronics Group, Department of Physics, University of Bath, U. K.

[4] P. St. J. Russell, J. C. Knight, T. A. Birks, B. J. Mangan and W. J. Wadsworth, "Photonic crystal fibers", *Report*, Optoelectronics Group, Department of Physics, University of Bath, U. K.

[5] P. St. J. Russell, J. C. Knight, T. A. Barks and P. J. Roberts, "Photonic crystal fibers", *Report*, Photonics and Photonic Materials Group, Department of Physics, University of Bath, U. K., 2005.

[6] G.Genty, "Supercontinuum generation in microstructured fibers and novel optical measurement techniques," Ph.D. thesis, Helsinki University of Technology Department of Electrical and Communications Engineering, March 2004.

[7] P. St. J. Russell, "Photonic crystal fibers", *Science*, Vol. 299, pp. (358-362), 2003.

[8] W. J. Wadsworth, N. Joly, J. C. Knight, T. A. Birks, F. Biancalana, P. St. J. Russell, "Supercontinuum and four-wave mixing with Q-switched pulses in endlessly single-mode photonic crystal fibers," Optics Express 12, 299-309,2004.

[9] G. J. Pearce, J. M. Pottage, D. M. Bird, P. J. Roberts, J. C. Knight and P. St.J. Russell, "Hollow-core PCF for guidance in the mid to far infra-red," Optics Express 13, 9637-9646,2005.

[10] "Hollow core photonic bandgap fiber", www.blazphotonics.com .

[11] H. J. Taher, "Study of Laser Propagation via Photonic Crystal Fiber", Ph.D. Theses, 2007.

[12] G. Keiser, "Optical fiber communications", 3rd Edition, *Mc Graw Hill, Boston*, 2001.

[13] G. Humbert, J. C. Knight, G. Bouwmans, P. St. J. Russell, D. P. Williams, P. J. Roberts and B. J. Mangan, "Hollow core photonic crystal fiber for beam delivery", *Opt. Express*, Vol. 12, No. 8, pp. (1477-1484), 2004.

[14] A. Schiavi, D. H. Campbell, O. Willi, "Nonlinear absorption of ultra-intense laser pulses in glass", *Central Laser Facility, Annual Report*, (1999/2000).

[15] A. H. Al-Janabi and E. Wintner, "High power laser transmission through photonic band gap fibers", *Laser Phys. Lett.*, Vol. 2, No. 3, pp. (137-140), 2005.

خسائر قليلة في الليف البلوري الفوتوني ذي قلب المجوف المملوء بالغاز

حنان جعفر طاهر*

*معهد الليزر للدراسات العليا/جامعة بغداد

الخلاصة

يركز العمل على أثبات وبطريقة عملية الخسائر في الأليف البلورية الفوتونية لنقل ليزر الندميوم-ياك ذو عامل النوعية Q.أولاً الليف البلوري الفوتوني ذي القلب المجوف يفرغ من الهواء الى 0.1 ملي بار ثم يملئ بغاز الهليوم وبعدها بغاز النايتروجين الليف الصغير التركيب (PCF). ثانياً تم قياس القدرة الداخلة والقدرة الخارجة لليزر الندميوم-ياك ذو عامل النوعية Q خلال الليف البلوري الفوتوني ذي القلب المجوف, في هذا العمل الخسائر حسبت في الليف البلوري الفوتوني ذي القلب المجوف(HCPCF) المملؤ بالهواء وبعدها بغاز الهليوم ثم بغاز النايتروجين تم ملاحظة أقل خسائر مستحصلة في حالة مليء الليف البلوري الفوتوني ذي القلب المجوف بغاز الهليوم وتساوي 15.070 dB/km عند الطول الموجي (1040-1090) نانومتر.