Bulletin of Pure and Applied Science
Physics, Vol.41D No.1,
January-June 2022 P.8-13
Original Research Article

Print version ISSN 0970 6569
Online version ISSN 2320 3218
DOI: 10.5958/2320-3218.2022.00002.1
Available online at www.bpasjournals.com

Performance of Silica Single Mode Hollow-core Optical Fibers in Optical Communications

Upendra Kumar Yadav

Author's Affiliations:
Upendra Kumar Yadav
Research Scholar, University Department of Physics, J.P. University, Chapra, Bihar 841301, India.
E-mail: upendraddp1986@gmail.com

Corresponding author:
Upendra Kumar Yadav
Research Scholar, University Department of Physics, J.P. University, Chapra, Bihar 841301, India.
E-mail: upendraddp1986@gmail.com

Received on 26.08.2021
Revised on 28.12.2022
Accepted on 05.01.2022

ABSTRACT We have studied the performance of silica single mode hollow-core optical fibers in optical communication. Silica single mode optical fibers form the core of high capacity telecommunication network. Hollow-core optical fibers have an air filled core surrounded with micro structured glass cladding allowing high level of light confinement. Light guiding mechanism of Bragg, photonic band gap and antiresonant fibers were considered. Nested antiresonant nodeless fibers and conjoined fibers are the two most promising antiresonant fiber designs for achieving ultra-low attenuation. Mode field adaptation using graded index multimode fiber; we have achieved record low insertions loss and also suppressed higher order modes. Deposition of anti-reflective coating allowed reducing unwanted back reflections. We have developed an approach for a hollow-core optical fiber of single mode interconnection based on a modified fiber array technology which solved the problem of back reflections by applying optical coating. Fundamental mode coupling was achieved by using mode theory adapters in the form of graded index multimode fibers.

KEYWORDS Single mode, Hollow-Core Fiber, Optical Communication, Microstructured, Cladding, Photonic Band Gap, Antiresonant, Attenuation, Mode Field, Fiber Array, Optical Coating.

How to cite this article: Yadav UK. (2022). Performance of Silica Single Mode Hollow-core Optical Fibers in Optical Communications. *Bulletin of Pure and Applied Sciences- Physics,* 41D (1), 8-13.

INTRODUCTION

GAO et al. [1] presented that fusion splicing is method which is used for permanent, low-loss interconnection of solid core optical fibers. This method was applied to the hollow-core fibers of single mode fibers interconnection, but does not address back reflections angled-splicing of hollow-core fibers was proposed but it was proved to be quite lossy [2-3]. In telecommunications hollow-core fibers are new process for the attenuation of standard single mode fibers [4]. An 11Km long hollow-core fiber has been drawn by Chen et al. [5] while predictions of more than 100 KM long hollow-core fiber drawing were presented by Jasion et al. [6] for effective use hollow-core fibers in conventional fiber optic-systems, it is essential to connect hollow-core fibers to solid core optical fibers in most cases of single mode fibers. Three main challenges existed for such an hollow-core fiber-single mode fiber interconnection (i) the air silica boundary causing unwanted back reflections (ii) state of the art low loss hollow-core fibers have a significantly larger mode field diameter compared to single mode fibers and (iii) hollow-core fibers with large mode field diameter are inherently multi modal, therefore higher order mode excitation must be suppressed to ensure only fundamental mode coupling.

Komanec et al. [7] developed an approach for a hollow-core fiber-single mode fiber interactions based on a modified fiber array technology which solved the issue with back reflections by applying optical coating, optical coating cannot be used in fusion splicing because of high temperatures. Fundamental mode coupling was achieved by using mode field adapters in the form of graded index multimode fibers. Wave guidance in a hollow-core has been existed which was shown by Thomson [8] and Lord Rayleigh [9] and presented the possibility of metallic waveguides.

Marcatili and Schmelter [10] proposed a hollow-core metal coated dielectric wave-guide for short range transmission of millimeter waves. Hidaka et al. [11] formed a hollow-core metal-coated fibers which were designed for the 10.63μm band to guide light from CO_2 lasers. These hollow-core fibers were made of pb-oxide glass and exhibited attenuation of 7.7 dB/m. Silica-glass based hollow-core fiber was presented by Nagano et al. [12] for CO_2 laser delivery with attenuation below 7.7 dB/m. Saito et al. [13] studied on hollow-core fibers appeared that were based on the silica-air design. Hollow-core fibers in the vicinity of 10μm were used to measure gas concentration where hollow-core fiber with a 1.5 mm inner core diameter of 1m length acted as a gas cell to analyse NH_3 content.

Sirkis et al. [14] presented an interferometric hallow core fiber based fiber where the hollow-core fiber was formed by a glass capillary with a 70μm inner diameter and length of 137μm.

Renna et al. [15] used simple glass capillary hollow-core fiber to transport atoms by optical forces. The main limitation originated from glass capillary attenuation proving the need for better light guidance.

Pennetta et al. [16] studied hollow-core photonic band gap fiber led to numerous application areas hollow-core fiber were afterwards advantageously used as gas sensing, gas filled lasers [17], fiber optic gyroscopes, high speed data transmission and many more [18].

Wheeler et al. [19] studied the attenuation of negative curvature Kagome hollow-core fiber was significantly higher than that of photonic band gap fiber, the band width was superior to that of photonic band gap fiber.

GAo et al. [20] presented conjoined tube fiber with minimal loss of 2dB/Km at 1512 nm was demonstrated.

METHOD

We have developed an approach for a hollow-core fiber combination with single mode fiber interconnection based on a modified fiber array technology which solved the back-reflections by applying optical coatings. The fundamental mode coupler was achieved by using mode field adapters in the form of graded index fibers. Hallow core fiber samples to current state of the art hollow-core nested antiresonant node less fibers with only 0.28dB/Km attenuation at 1550 nm were considered. Then we have considered the main hollow-core fiber guidance mechanisms from Bragg fibers. Photonic band gap fibers were followed to antiresonant fibers summarizing hollow-core fiber key properties. We have compared photonic band gap fibers and antiresonant fibers. The fusion splicing results were compared with modified fiber array technology. Advantages of interconnection technique were taken with regard to hollow-core fiber applications. An Omniguide fiber was presented with high refractive index glass and a low refractive index polymer microstructure. Omniguide fibers exhibited less than 1dB/m attenuation at 10.6μm while it was possible to get tens of meters of Omniguide fibers in a single draw. Then we have considered primarily placed on Bragg fibers from pure silica where rings were held together by glass struts. Photonic crystal fibers allowed freedom in photonic crystal parameters tailoring such as the chromatic dispersion curve, zero dispersion wave length single mode cut off wavelength, mode field diameter which was modified by changing the design of the photonic fiber microstructure. Endlessly single mode photonic crystal fiber appeared, group velocity dispersion management became possible and super continuum generation was demonstrated using photonic crystal fibers with zero dispersion wavelengths at 800nm producing broadband radiation from visible to near infrared region. Optical networks the most important parameters are fiber attenuation in 1550 nm band and fiber transmission band width. The design of the photonic band gap fiber eventually limited the progress in achieving low attenuation and broadband performance the achieved band width was only 70 terahertz and an alternative hollow-core design was obtained. This was due to the negligible optical field overlap with the glass leading to low surface scattering losses.

RESULTS AND DISCUSSION

Fig (1) shows the negative curvature shape of first ring around the antiresonant fiber core which led to a decrease of fiber attenuation down to hundreds of dB/Km with a band width of 1000nm. The attenuation of this negative curvature Kagome hollow-core fiber was significantly higher than that of photonic band gap fiber, the band width was better to that of the photonic band gap fiber. Efforts on exploiting the negative curvature simultaneously reduced the microstructure complexity. These antiresonant fibers do not require a periodic lattice and works just on the principle of antiresonance. Among the lattice variants the tubular antiresonant fiber provided the simplest design and the best performance. The lowest current attenuation of a single ring tubular antiresonant fiber was found 7.7dB/Km at 750 nm. The obtained results were impressive in comparison to conventional single mode fibers. The potential of antiresonant fibers when including additional resonator inside of each existing tubes forming so called nested antiresonant fibers when including additional resonator inside of each existing tubes forming so called nested antiresonant node less fibers. The nested antiresonant nodeless fibers surpassed the attenuation of other hollow-core fibers types and eventually that of single mode fibers. This is due to the negligible optical field overlap with glass leading to low surface scattering losses. Antiresonant fibers suffered from significantly higher confinement losses and were addressed by the proposed nested antiresonant nodeless fiber designing by including more antiresonant elements. Fig (2) shows and advanced negative curvature fiber with non touching capillaries. These fibers eliminate the remaining glass nodes which are not in antiresonance. Antiresonance prohibits the aircore mode from overlapping with glass material. This leaded to low surface scattering and low material induced attenuation which is required for low propagation to achieve competitive losses to standard single mode fibers greater coupling suppression between the air core mode and the cladding modes are required. Graph (1) Shows a simplified formation of the photonic band gap as the photonic band gap fiber. The guided modes are expressed by the dispersion equation using the normalized frequency ν and rod radius *r* as

$$\nu = \frac{2\pi r}{\lambda}\left(n_1^2 - n_0^2\right)$$

Then it has set the air line as

$$w^2 = \left(\beta^2 - k_0^2\right) r^2 = 0$$

where β is the propagation constant in the direction of propagation and k_0 is the wave number in air. No modes can propagate above air line as they are in anti resonance with the rod modes and also they cannot propagate in the cladding. Graph (1) (a) shows that below the air line is continuum of plane wave like air modes. Graph (1) (b) shows that when rods are arranged in a symmetric or periodic fashion to form a single ring around the central rod, the dispersion equation changes and conditions broaden around the particular mode cut offs. The rod modes became expanded that they overlapped with the other rod modes and a spatial superposition occurred. Periodic forbidden bands appeared below the air line as shown in graph (1) (b). Graph (2) (a) shows the measured interference pattern of the fundamental mode LP_{01} with higher order modes for a 10-m long photonic band gap fiber. From this interference pattern using Fourier transform relative amplitude of the propagation modes were calculated. Higher order mode propagation is shown in the graph (2) (b) and have found suppression of greater than 30dB for higher order modes. The field adapters based on graded index multimode fiber were used to match quality. The interference of higher order mode amplitude were found for various levels. Using arc discharge that heated the two fiber ends presented together to form a permanent robust, repeatable and low loss splice, because creating a permanent interconnection of two optical fibers is fusing splice. The appearance of Hollow-core fibers, modified splicing technique found emerged on maintaining the delicate microstructure, which were easily collapsed when it was over heated. Among hollow-core fibers the antiresonant fibers provided a homogeneous and low defect structure with substantial migration of high order modes became the most suitable choice to form gas cells. Advantage of silica hollow-core fibers for gas sensing is their transparency. We have found that using fiber array interconnection technology back reflections were suppressed. We have increased the reflection and allowed multipath propagation on hollow-core fiber attenuation and coating reflectivity. The fundamental mode excitation reduced the noise of the sensing system. The results were compared with previous results and were found in good agreement.

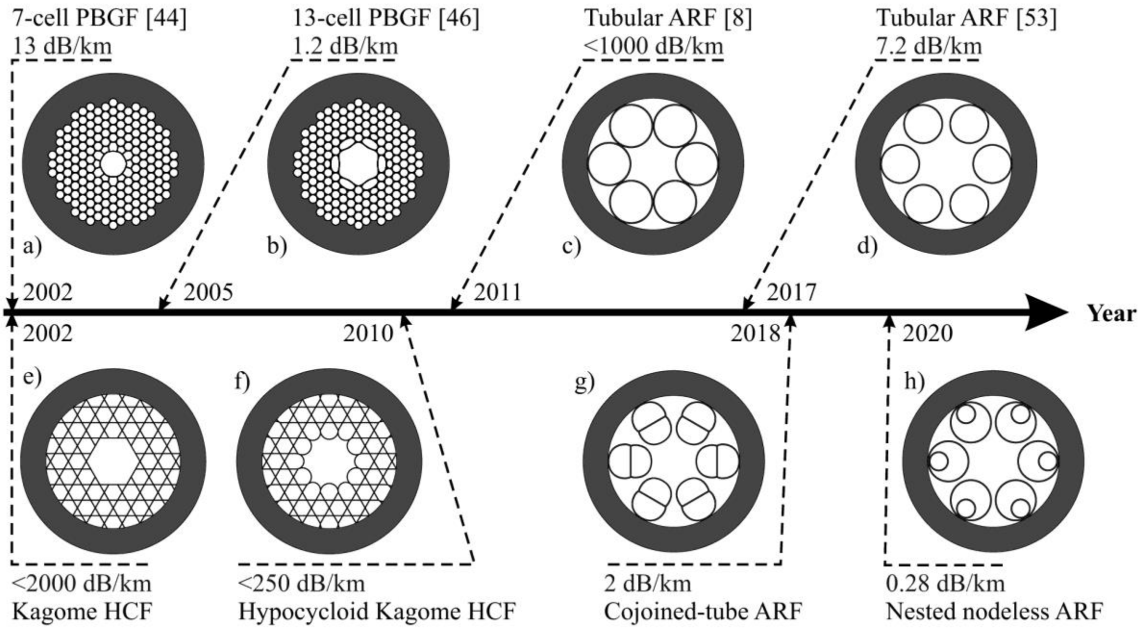


Figure 1: Timeline of the hollow-core optical fiber evolution including both fiber design and attenuation milestones, values are given for the wavelength of 1550nm.

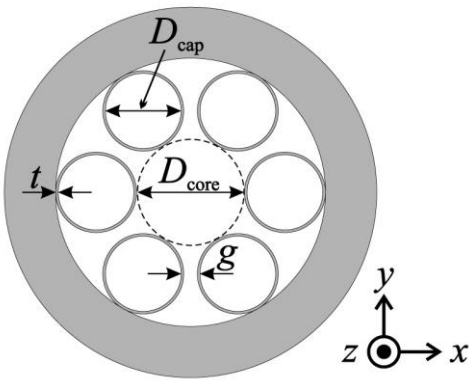
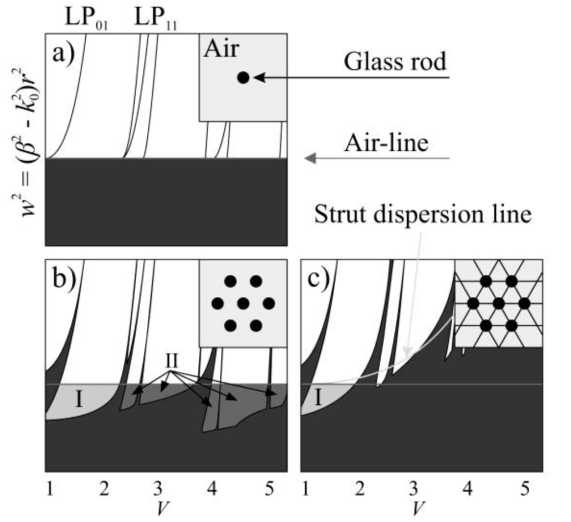
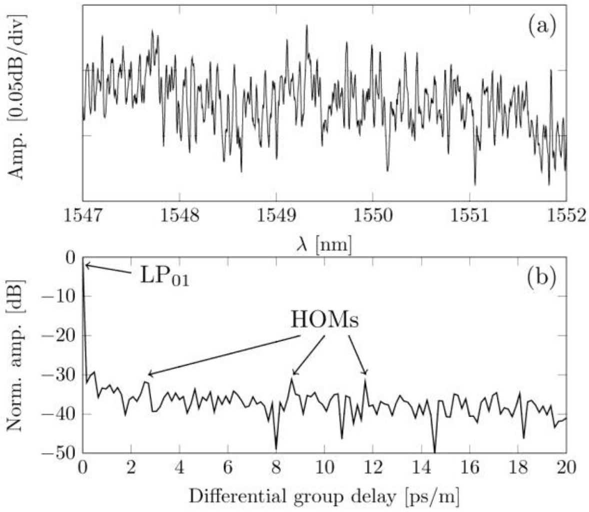


Figure 2: Tubular fiber structure with non-touching glass capillaries.



Graph 1: Formation of air guiding photonic band gap.



Graph 2: Higher-order mode interference pattern in a 10-m-long photonic band gap fiber.

CONCLUSION

We have studied the performance of silica single mode hollow-core optical fibers in optical communications. Light guiding mechanisms were presented and performances of hollow-core fibers were obtained. The interconnection techniques to standard optical fibers were compared with respect to possible hollow-core fiber applications. Fusion splicing results were presented with and alternative interconnection solution based on a modified fiber array technique newly developed by us. Cutting edge hollow-core fiber applications have advantages hollow-core fiber interconnection mode field adaptation using graded index multimode fiber. We have achieved record of low insertion loss and also suppressed higher order modes. Deposition of anti-reflective coating allowed us to reduce unwanted back reflections. To achieve sub -1dB insertion losses, the move to bridge fibers acting as model field adapters was necessary. Showing the potential of bridge fibers formed by thermally expanded core fibers, the splice loss of only 0.73 dB was found for an single mode fiber-expanded core-photonic band gap fiber interconnection. The obtained results were compared with previously obtained results and were found in good agreement.

REFERENCES

[1] GAO. S, Wang. Y, Jian. C et al, (2014), IEEE Photonics Technology Letters, 26, 21, 2134.

[2] Couny. F, Benabid. F, Light. P. S., (2007), IEEE Photonic Technology Letters, 19, 13, 1020.

[3] Miller. G. A, Cranch. G. A, (2016), 28, 4, 414.

[4] Jasion. G. T, Bradley. T. D, Harrington. K et al, (2020), In Fiber communication conference and exhibition post deadline papers. San Diego (U.S.A) p.1-3, DOI 10.1364/OFC 2020 Th 4B4.

[5] Chen. Y, Liu. Z, Sandoghchi. S. R. etal, (2016), Journal of Light wave Technology, 34, 1, 104-113, DOI: 10.1109/JLT.2015.2476461.

[6] Jaison. G. T., Poletti. F, Shrimpton et al, (2015), In Optical fiber communication conference and exhibition, Los Angeles (USA), p. 1-3, DOI:10.1364/ OFC 2015.

[7] Komanec. M, Suslov. D, Zvanovec. S, etal, (2019), IEEE Photonic Technology Letters, 31, 10, 723-726, DOI: 10.1109/LPT 2019.

[8] Thomson. J. J., (1893), Maxwell's Treatise on Electricity and Magnetism, ISBN: 978.1332470754.

[9] Lord Rayleigh F.R.S. XVIII, (1897), The London Edinburg and Pulin Philosophical Magzine and Journal of Science Vol -43, no. -261, p- 125-132, DOI: 10.1080/1478644970862069.

[10] Marcatili. E.A, J. Sch. Meltzer, R. A. (1964), The bell system Technical Journal, 43, 4, 1783-1809, DOI: 10.1002/ j. 1538-7305, 1964.tb04108.X.

[11] Hidaka. T, Morikawa. T, Shimada. J, (1981), Journal of Applied Physics, 52, 7, 4467-4471, DOI: 10.1063/1.3293739.

[12] Nagano. N, Saibo. M, Muyagi. M et al, (1991), Applied Optics, 30, 9, 1074-1079, DOI: 10.1364/A0.30.001074.

[13] Saito. Y, Kanaya. T, Nomura. A.A. et al, (1993), Optics Letters, 18, 24, 2150-2152, DOI: 10.1364/06.18.002150.

[14] Sirkis. J. S, Brennan. D. D, Putman. M. A. et al, (1993), Optics Letters, 18, 22, 1973-1975, DOI: 10.1364/0L.18.001973.

[15] Renn. M. J, Montgomery. D, Vdovin. O et al, (1995), Physical Review Letters, 75, 18, 3253-3256, DOI: 10.1103/ Phys. Rev. Lett. 75. 3253.

[16] Pennetta. R, XIE. S, Lenanhan. F, et al, (2017), Physical Review Applied, 8, 1, p-1-6, DOI: 10.1103/ Phys. Rev. Applied. 8.014014.

[17] Dadashzadih. N, Thirugnana Sambadam, M. P., Weerasinghe. H. W. K. etal, (2017), Optics Express, 25, 12, 13351-13358, DOI: 10.1364/OE.25.013351.

[18] Klimczak. M, Dobrakowski D., Ghosh. A. N. et al, (2019), Optics Letters, 44, 17, 4395-4398, DOI: 10.1364/QL.44.004395.

[19] Wheeler. N, Bradley. T, Hayes. J. et al, (2016), In Speciality Optical Fibers Meeting at the Advanced Photonics Congress. Vancouver (Canada), p-1, DOI: 10.1364/Sof.2016.Som 3f2.

[20] GAO. S. F., Wang. Y. Y, Ding. W et al, (2018), Nature Communications, 9, no-1, p – 1-6, DOI: 10.1109/IPC con.2016.781157.

****