

# Analysis of Dual Core Hexagonal PCF Based Polarization Beam Splitter

M. R. Khatun<sup>1</sup> M. S. Islam<sup>1</sup> A.N.M. Bazlur Rashid<sup>2\*</sup>

1. Institute of Information and Communication Technology, Bangladesh University of Engineering and Technology, Dhaka - 1000, Bangladesh
2. Department of Computer Science and Engineering, Comilla University, Comilla - 3503, Bangladesh

\* E-mail of the corresponding author: [bazlur.cse@cou.ac.bd](mailto:bazlur.cse@cou.ac.bd)

## Abstract

In this research work an analysis has been carried out on symmetric dual core hexagonal PCF-based polarization beam splitter by using finite element method (FEM). The splitter designs are carried out with hexagonal PCFs with simple symmetric design by varying only air holes diameter. The results of numerical calculation show that coupling lengths are higher for polarization splitters with larger air hole diameters and with the increase of operating wavelength coupling length decreases. Furthermore it is possible to obtain an 8.4 mm-long polarization beam splitter with high extinction ratio (250dB). This study will be very helpful to design and manufacture simple PCF based splitters with better performance.

**Keywords:** photonic crystal fiber (PCF), finite element method (FEM), polarization beam splitter, birefringence, extinction ratio, coupling length

## 1. Introduction

Optical fiber communication system as well as optical devices is a subject of growing interest due to its extremely attractive features. Moreover, the rapid pace of advances in technology has surpassed the most optimistic predictions, creating additional advantages [1]. This has led researchers to put more effort on improving the various characteristics of different optical fibers by continuous study and research. Photonic crystal fibers (PCFs) are micro-structured optical fiber, which are constructed by single material with multiple air holes periodically arranged around the core [2]. Microstructured fibers guide light due to modified total internal reflection. Unlike conventional fibers, PCFs can be made entirely from a single material, typically undoped silica. The holes act to lower the effective refractive index in the cladding region and so that light is confined to the solid core, which has a relatively higher index. In a PCF, the number of holes and their sizes, shapes, orientations and placements can provide degrees of freedom and hence unique properties, which are not available in conventional optical fibers [3-4]. The strong wavelength dependency of the effective refractive index and the inherently large design flexibility of the PCFs allow for a whole new range of novel properties. Such properties include endlessly single-mode fibers, extremely nonlinear fibers and fibers with anomalous dispersion in the visible wavelength region [5-6]. They could serve as a fiber host for developing a wide range of fiber devices for high power fiber laser, second harmonic generation, polarization beam splitter, super continuum generation, radiation detection, etc. PCFs may be divided into two categories [7]: high index guiding fibers and low index guiding fibers. Similar to conventional fibers, high index guiding fibers (solid core) are guiding light in a solid core by the modified total internal reflection (M-TIR) principle. The total internal reflection is caused by the lower effective index in the microstructured air-filled region. PCFs are of great interest for optical communication and for new optical devices.

Polarization beam splitters (PBSs) are a special kind of coupler. They can split incoming light from a single fiber into two orthogonally polarized beams [8]. The key features of good polarization beam splitter is high extinction ratio, highly modular and flexible design, wide bandwidth, bi-directional, broadband

performance and mode independent behavior in multimode fiber applications [9]. The most popular applications of polarization beam splitter are EDFA amplifier, Raman amplifier combiner, polarization mode dispersion compensation, polarization extinction ratio measurements, fiber optic sensors, coherent communication systems and quantum cryptography, return loss measurement *etc.*

The PCF-based polarization splitter can achieve good extinction ratios and coupling lengths in contrast with conventional dual-core fiber or waveguide-based polarization splitters [10-11]. Highly birefringent dual-core PCF can be used as polarization splitter. The high birefringence gives rise to very small coupling length and adequate difference in the coupling lengths for the two orthogonal polarizations [12-13]. Several research works have been done to find out the performance of dual-core PCF based PBS. Wen *et al.* (2008) proposed three-core PBSs based on resonant tunneling. In this paper they have found PBS with the coupling length 1.039 mm and the extinction ratio is -36.98 dB at wavelength 1550 nm. A novel broadband PBS based on asymmetric dual core square-lattice PCFs has been designed by Ming *et al.* in [15]. The numerical results demonstrate that a device length of 5.9 mm show extinction ratio -20dB with bandwidth 101. Jung *et al.* proposed a new PCF based splitter with 0.33 mm-long and extinction ratio of 23 dB [16]. In [7] numerical simulations demonstrate that it is possible to obtain a 4.72 mm-long PBS, with splitting ratio better than -20 dB and bandwidth is about 190 nm.

However, almost all of the splitters employed two or three highly birefringent cores formed by a combination of large and small air holes, which may be more likely to cause deformation and collapse of the air holes. Currently, designing the splitters with a simple air-hole pattern, high extinction ratio, short coupling length and wide bandwidth is a key issue to make them practical. It will be more feasible to design simplified PCF-based polarization splitter that shows good polarization splitter behavior and possesses easy fabrication process. So that we have analyzed here the properties of very simple designed dual core hexagonal PCF-based polarization splitters which show very high extinction ratio and short coupling length.

## 2. Analysis and Design

The effective indices of the two orthogonal modes have been calculated with a finite element method (FEM) [6]. FEM is a numerical method for solving a differential or integral equation. In FEM the intricate cross section of a PCF can be represented by using many triangles of different shapes and sizes. The total result is found by integrating all adjacent triangles result. The effective index  $n_{eff}$  is a number quantifying the phase delay per unit length in a waveguide, relative to the phase delay in vacuum. The modal effective indexes are solved from Maxwell's equations and given by  $n_{eff} = \beta/k_0$  where  $\beta$  is the propagation constant,  $k_0 = 2\pi/\lambda$  is the free-space wave number. First, the effective index  $n_{eff}$  of the fundamental mode of the PCF is computed as a function of wavelength [2].

There are four nearly degenerate supermodes in normal dual-core optical fibers. According to the theory of mode coupling, the coupling of a dual-core fiber can be described by use of the even and odd supermodes which formed by modes of the individual cores and have symmetric and antisymmetric field distribution, respectively. In dual-core PCFs the coupling length is defined as [17].

$$L_i = \frac{\pi}{\beta_e^i - \beta_o^i} = \frac{\lambda}{2(n_e^i - n_o^i)}, \quad i = x, y \quad (1)$$

Where  $\beta_e^i$  and  $\beta_o^i$  are the propagation constants of  $i$ -polarized even and odd supermodes,  $n_e^i$  and  $n_o^i$  are the effective refractive indices of  $i$ -polarized even and odd supermodes, respectively.

If we assume that input power  $P_O = P_{Ox} + P_{Oy}$  is launched into one input port of the device, the output power  $P$  at the through port with device length  $L$  is then given by [18].

$$P = P_x + P_y = P_{Ox} \cos^2 C_x L + P_{Oy} \cos^2 C_y L \quad (2)$$

where the coupling coefficients for  $x$ - and  $y$ - polarized light  $C_x$  and  $C_y$  are derived as

$$C_x = (\beta_e^x - \beta_o^x)/2, \quad C_y = (\beta_e^y - \beta_o^y)/2 \quad (3)$$

respectively.  $\beta_e^i$  and  $\beta_o^i$  are the propagation constants of even and odd modes, respectively and  $i$  is a polarization state index ( $i = x$  and  $y$ ).

Normally the performance of the polarization splitter can be described by using the splitting ratio or extinction ratio (ER). It is defined as [17].

$$ER = 10 \lg \frac{P_{x\text{-polarized}}}{P_{y\text{-polarized}}} \quad (4)$$

where  $P_{x\text{-polarized}}$  is the output power for y-polarized mode and  $P_{y\text{-polarized}}$  is the output power for x-polarized mode.

Hexagonal PCFs cladding region is designed by arranging air holes in hexagonal lattice. Here polarization beam splitters have been designed with symmetric solid dual core hexagonal PCFs. In this case the design parameters:  $R$  is cross sectional radius,  $d$  is the air hole diameter  $\Lambda$  is pitch (distance between two air holes) and  $Nr$  is the number of air hole rings. We have considered splitters are made by only single material ( $\text{SiO}_2$ ), where refractive index  $n_s=1.45$  and all air holes are circular shaped with same diameter. The total area of air in the splitter cross section changes with the change of air holes diameter. We have designed the dual core hexagonal PCFs with different amount of air area by varying air holes diameter (0.8  $\mu\text{m}$ , 1.0  $\mu\text{m}$ , 1.2  $\mu\text{m}$ , 1.4  $\mu\text{m}$  and 1.6  $\mu\text{m}$ ), where other design parameters  $\Lambda$  and  $Nr$  have been considered constant. Figure 1 shows the cross-section of dual core hexagonal PCF, where  $R=12 \mu\text{m}$ ,  $\Lambda=2.5 \mu\text{m}$ ,  $d=1.2 \mu\text{m}$  and  $Nr=4$ .

### 3. Results and Discussion

Job-shop production refers to a manufacturing environment that produces goods in small batches according to customer specifications. We have carried out the experiment by using COMSOL Multiphysics modeling and simulation tool, where electromagnetic module has been used to carry out the optical mode analysis of the PCFs. The experiment has been carried out on very simple hexagonal air hole arrangement dual core PCF based splitter. We have got the modal effective index as the output of optical analysis. The modal solution approach in COMSOL is based on the FEM, where the intricate cross section of a PCF can be represented by using many triangles of different shapes and sizes. The total result is found by integrating all adjacent triangles result. According to normal mode coupled theory four lowest order modes are found as modal solution. Figure 2 shows transverse magnetic field vector distributions of dual core hexagonal PCF, where  $R=12 \mu\text{m}$ ,  $d=1.2 \mu\text{m}$  and  $\Lambda=2.5 \mu\text{m}$ . Here Figure 2(a) symmetric (even) and Figure 2(b) anti-symmetric (odd) show modes of  $x$ -polarized state and the Figure 2(c) symmetric (even) and Figure 2(d) anti-symmetric (odd) shows modes of  $y$ -polarized state. Again Figure 3 shows 2 dimensional and 3D dimensional views of the power flow time average  $z$  component through both cores.

Effective refractive index is a number quantifying the phase delay per unit length in a waveguide. Figure 4 shows that effective index decreases with the increase of air hole diameter, where  $R$ ,  $\Lambda$  and  $Nr$  have been considered unchanged. It also shows that  $x$ -polarized effective index is higher than  $x$ -polarized for lower air hole diameter but they remain almost same with higher air hole diameter. Difference between  $x$ -polarized and  $y$ -polarized effective index (birefringence) is higher for the PBSs with smaller air hole diameter. In order to analysis the performance of the designed polarization beam splitter, we have investigated the coupling characteristics also. Coupling lengths for  $x$ -polarized and  $y$ -polarized as a function of air hole diameter is shown in Figure 5. This figure describes that coupling length of both polarized light increases with the increase of PCF air hole diameter. It is found that the  $x$ - and  $y$ -polarized light have different coupling lengths. Here it is also found that differences between  $x$ -polarized and  $y$ -polarized coupling length is higher for the PBSs with larger air hole diameter. The results indicates that PBS with  $d=1$  show  $L_x=0.6$  mm and  $L_y=0.7$  mm, PBS with  $d/\Lambda=1.2$  show  $L_x=1$  mm and  $L_y=1.2$  mm and PBS with  $d/\Lambda=1.4$  show  $L_x=1.9$  mm and  $L_y=2.3$  mm.

The normalized power which transfers along the fiber length is illustrated in Figure 6(a), (b), (c) and (d) with the air holes diameter  $d=1.0 \mu\text{m}$ ,  $d=1.2 \mu\text{m}$ ,  $d=1.4 \mu\text{m}$  and  $d=1.6 \mu\text{m}$  respectively. The figures display

the normalized output power of two polarization states as a function of fiber length, where other fixed parameters  $R=12\ \mu\text{m}$ ,  $\lambda=1.55\ \mu\text{m}$  and  $\Lambda=2.5\ \mu\text{m}$ . The dashed vertical lines indicate the splitter length. Again it can be seen that the normalized power of  $y$ -polarized light has the maximum value while the normalized power of  $x$ -polarized light has the minimum value at the propagation length of 8.3 mm, 8.4 mm, 11.8 mm and 21 mm from the Figure 4(a), (b), (c) and (d) respectively. Now it is clear to understand that at this length two polarizations are separated from each other and the length of the polarization splitter is realized as 8.3 mm, 8.4 mm, 11.8 mm and 21 mm for the PBS with  $d=1.0\ \mu\text{m}$ ,  $d=1.2\ \mu\text{m}$ ,  $d=1.4\ \mu\text{m}$  and  $d=1.6\ \mu\text{m}$  respectively.

The extinction ratio, defined as the power ratio between the undesired and desired polarization states in each output core. The performance of the polarization splitter can be described by using the extinction ratio. By numerical calculation we have found that PBS with  $d=1.2\ \mu\text{m}$  shows comparatively higher extinction ratio 188.8 dB, where operating wavelength  $\lambda=1.55\ \mu\text{m}$ . The variation of extinction ratio with the change of wavelength is shown in Figure 7. It depicts that extinction ratio is very high in a large wavelength range 1.3-1.7  $\mu\text{m}$  and it shows highest extinction ratio 205 dB with operating wavelength 1.6  $\mu\text{m}$ .

#### 4. Conclusion

In this paper, we have investigated a very simple designed dual-core hexagonal PCF-based splitter. Here we observed the properties of splitter by varying the air holes diameter only. From the simulation results it has been found that coupling length increases with the increase of air hole diameter. It is also observed that difference of coupling lengths for the  $x$ - and  $y$ -polarized light is significant for the PBSs with larger air hole diameter. The results show that high extinction ratio 205 dB can be achieved with 8.4 mm splitter. Furthermore it operates in a large wavelength range with high extinction ratio.

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**M. R. Khatun** was born in 1983 at Chuadanga, Bangladesh. She received the B.Sc. degree in Computer Science and Engineering from Khulna University of Engineering and Technology (KUET), Khulna, Bangladesh in 2005 and M.Sc. in Information and Communication Technology from Bangladesh University of Engineering and Technology, Dhaka, Bangladesh in 2012. She is working as a Lecturer in the Department of Computer Science and Engineering of International Islamic University Chittagong (IIUC). Her current research interests include optical fiber, photonic crystal fiber, wireless network and cognitive network. E-mail: [rokeya2kcse@gmail.com](mailto:rokeya2kcse@gmail.com)

**M. S. Islam** received the B.Sc. degree in Electrical and Electronic Engineering from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh in 1989, M.Sc. in Computer Science and Engineering from Shanghai University, China in 1997 and Ph. D from BUET in 2008. He has published many research papers in national and international journals and conferences. Currently, he has been serving as a Professor in the Institute of Information and Communication Technology of BUET. His research interest includes DWDM transmission system, dispersion, nonlinearity and wireless communication. E-mail: [mdsaifulislam@iict.buet.ac.bd](mailto:mdsaifulislam@iict.buet.ac.bd)

**A.N.M. Bazlur Rashid** was born in 1984 at Rangpur, Bangladesh. He received the B.Sc. Engg. degree in Computer Science and Engineering from Rajshahi University of Engineering and Technology, Rajshahi, Bangladesh in 2005 and M.Sc. Engg. degree in Information and Communication Technology from Bangladesh University of Engineering and Technology, Dhaka, Bangladesh in 2010. He has several years of professional experience in the field of database having Oracle professional certification in database administration. Currently, he has been serving as a Lecturer in the Department of Computer Science and Engineering of Comilla University, Comilla, Bangladesh. His major field of study includes query processing, query optimization, materialized view, database and information system, data warehousing, data mining and optical communication. E-mail: [bazlur.rashid@yahoo.com](mailto:bazlur.rashid@yahoo.com)

**Appendix**

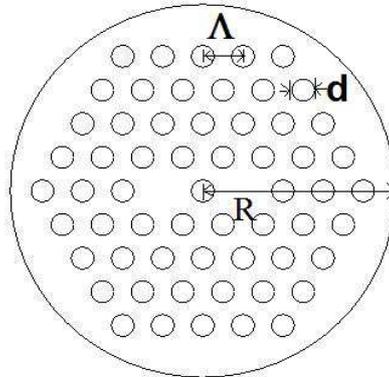


Figure 1. Cross Sections of Dual Core Hexagonal PCF, where  $R=12 \mu\text{m}$ ,  $d=1.2 \mu\text{m}$ ,  $\Lambda=2.5 \mu\text{m}$  and  $N_r=4$

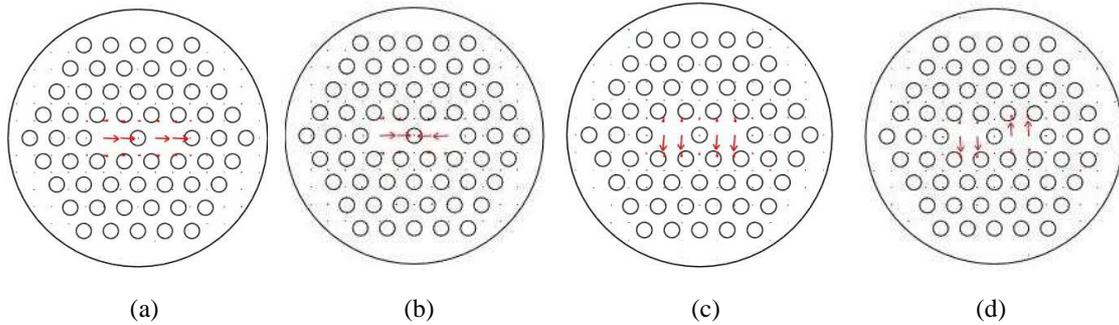


Figure 2. The Transverse Magnetic-Field Vector Distributions of (a) Even, (b) Odd Modes for  $x$ -Polarized and (c) Even, (d) Odd Modes for  $y$ -Polarized States

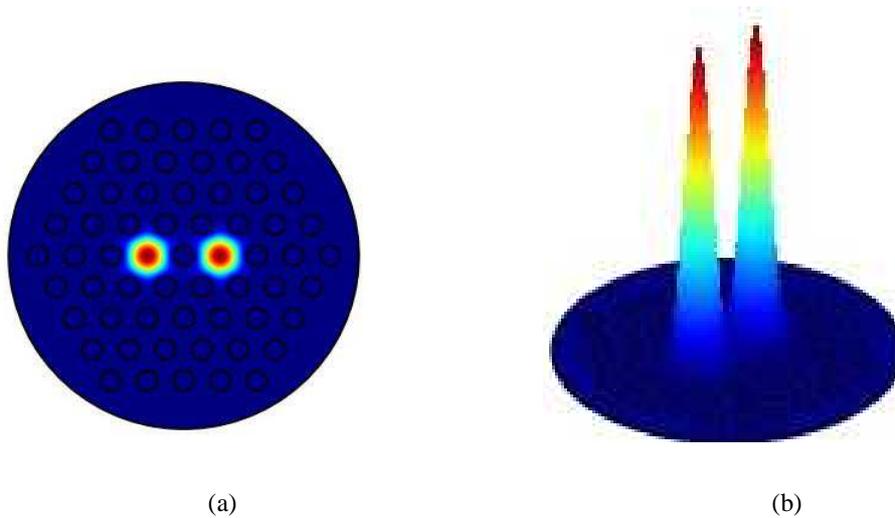


Figure 3. Surface Power Flow Time Average  $z$  Component for Dual Core Hexagonal PCF, (a) 2-Dimensional View (b) 3-Dimensional View

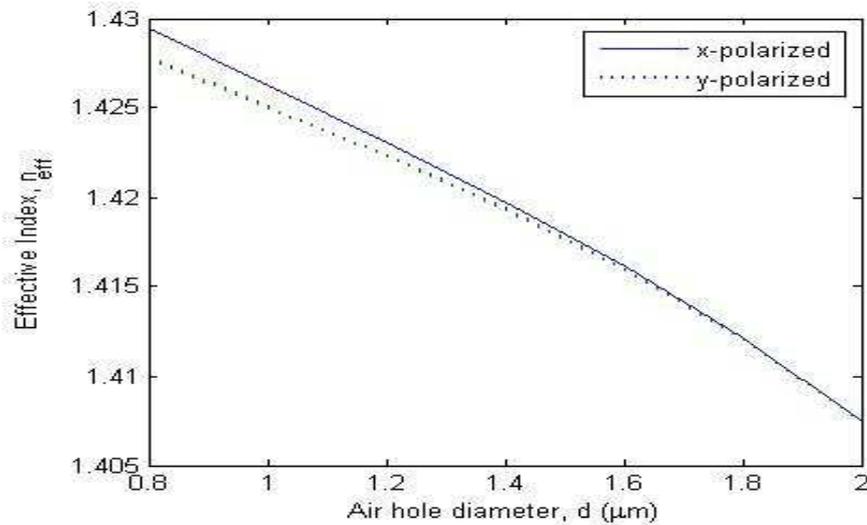


Figure 4. Effective Index for *x*-Polarized and *y*-Polarized Light as a Function of Air Hole Diameter, where  $R=12\ \mu\text{m}$ ,  $N_r=4$ ,  $\lambda=1.55\ \mu\text{m}$  and  $\Lambda=2.5\ \mu\text{m}$

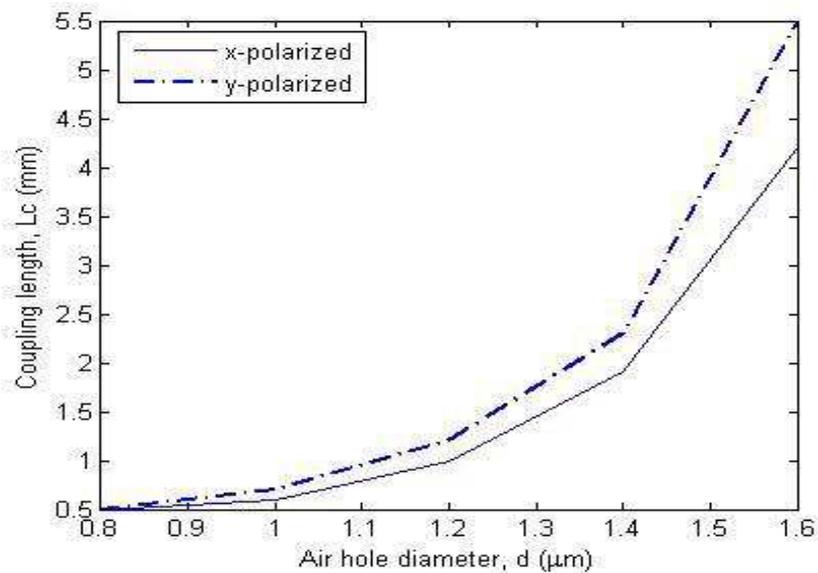
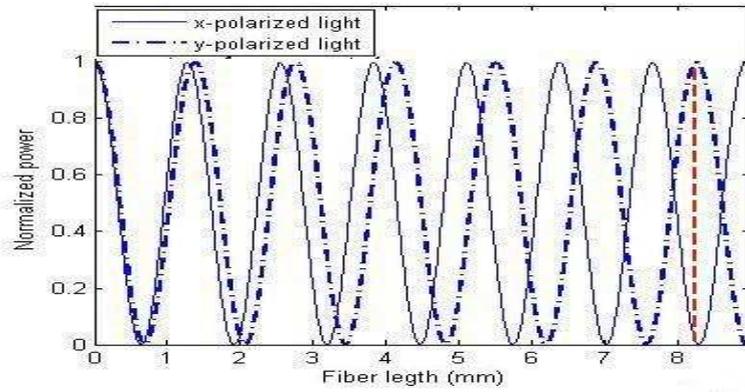
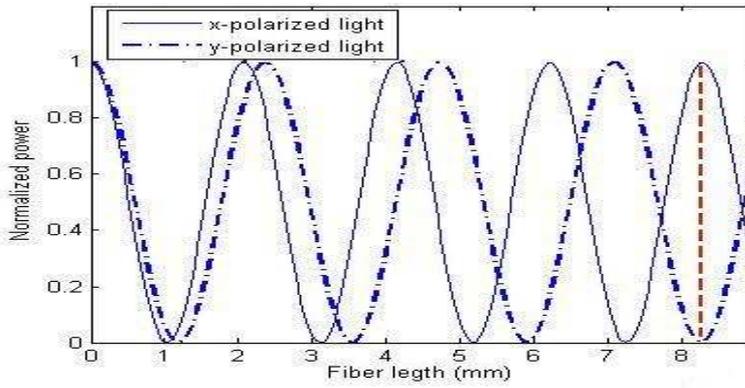


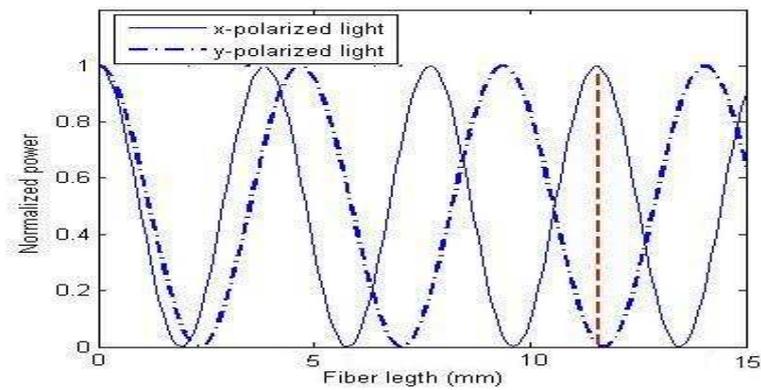
Figure 5. The *x*-Polarized and *y*-Polarized Coupling Lengths as a Function of Air Hole Diameter, where  $R=12\ \mu\text{m}$ ,  $N_r=4$ ,  $\lambda=1.55\ \mu\text{m}$  and  $\Lambda=2.5\ \mu\text{m}$



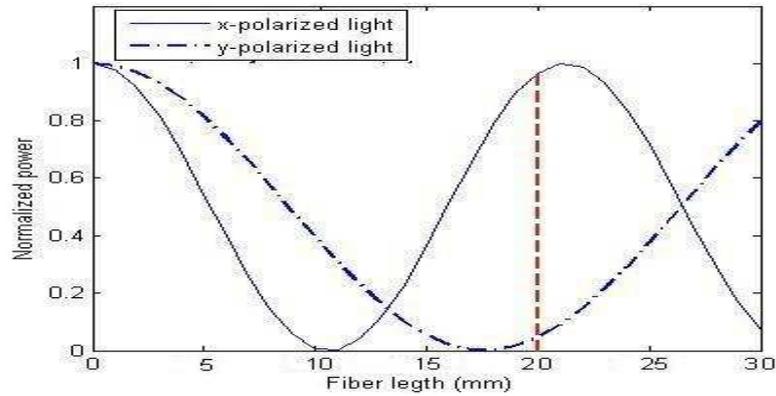
(a)



(b)



(c)



(d)

Figure 6. Normalized Output Power of Two Polarization States (*x*-Polarized and *y*-Polarized) versus Fiber Length at through Port for the Splitter with Air Hole Diameter (a)  $d=1.0\ \mu\text{m}$ , (b)  $d=1.2\ \mu\text{m}$ , (c)  $d=1.4\ \mu\text{m}$  and (d)  $d=1.6\ \mu\text{m}$ , where  $R=12\ \mu\text{m}$ ,  $N_r=4$ ,  $d=1.2\ \mu\text{m}$ ,  $\Lambda=2.5\ \mu\text{m}$ . The re colored dashed vertical line indicates the splitter length of the polarization splitter

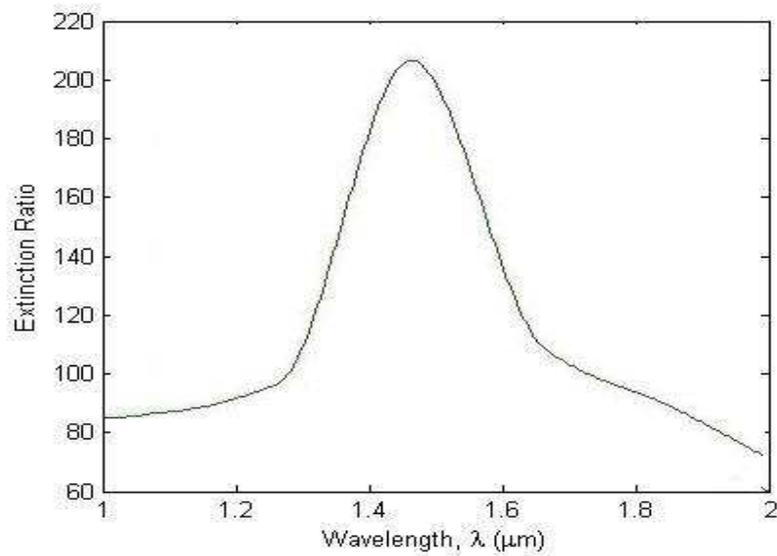


Figure 7. Extinction Ratio as a Function Air Hole Diameter, where  $R=12\ \mu\text{m}$ ,  $N_r=4$ ,  $d=1.2\ \mu\text{m}$ ,  $\Lambda=2.5\ \mu\text{m}$  and Splitter Length 8.4 mm

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