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RESEARCH ARTICLE

# Nearly zero-dispersion, low confinement loss, and small effective mode area index-guiding PCF at 1.55 μm wavelength

**Saeed OLYAEE** (✉), **Fahimeh TAGHIPOUR**, **Mahdieh IZADPANAH**

Nano-photonics and Optoelectronics Research Laboratory (NORLab), Faculty of Electrical and Computer Engineering, Shahid RajaeeTeacher Training University (SRTTU), Lavizan 16788-15811, Iran



**Abstract** In this paper, a new simple structure of index-guiding photonic crystal fiber (PCF) is designed and presented. In this PCF, dispersion, confinement loss, and effective mode area characteristics are investigated in the second communication window (1.55 μm). Since 1.55 μm wavelength is widely used in optical communication systems, we try to optimize the PCF characteristics in this wavelength by designing an index-guiding PCF and three versions of optimized PCF. The results show that the dispersion is obtained very close to zero around $4.6\times10^{-4}$ ps/(nm·km). Also, the confinement loss is $2.303\times10^{-6}$ dB/km and effective mode area is as small as 2.6 μm$^2$.

**Keywords** dispersion, effective area, confinement loss, index-guiding, photonic crystal fiber (PCF)

## 1 Introduction

Nowadays, single mode fibers are widely used as transmission media in wavelength division multiplexing systems. In these fibers, dispersion and confinement loss depend on the wavelength. Because optical fibers show minimum loss at 1.55 μm, this wavelength is very applicable to transfer information. In standard optical fibers, loss is around 0.1 dB/km and dispersion equals 16 ps/(nm·km) in 1.55 μm wavelength.

Recently, a new type of microstructure fibers having zero dispersion value in a wide range of wavelengths is presented. These fibers are called photonic crystal fibers (PCFs) and have unique characteristics. PCFs can be composed of silicon glass with arrays of air-holes channels running along its length [1]. Created defect in the center of this array plays the role of the core. In this paper, an index-guiding fiber is presented that its core refractive index is more than cladding refractive index. So, the light propagates based on the total internal reflection (TIR) effect in the fiber.

In conventional PCFs, 20 rings of same air-holes are used to achieve acceptable loss. This leads to increase in the fiber diameter. Newly, scientists are focused on PCFs with multi-structures to control the characteristics better. PCF with three-fold symmetric hybrid core can achieve zero dispersion as well as low confinement loss. In this PCF, dispersion and confinement loss are respectively around −2 ps/(nm·km) and less than 7.9 dB/km [2]. The later designs [2–13] have shown better results by using various techniques such as: PCFs with elliptical air holes [3], PCF structure with gradually increasing the diameter of the hole from inner ring to the outer [4], filling air holes with different liquids selectively [5], and PCFs with double cladding [6], although the fabrication processes are difficult in these plans.

In this paper, first a primary PCF is designed to achieve desirable characteristics for using in the optical communication systems in 1.55 μm wavelength. Then, three modified structures are designed and simulated. The most important advantage of this fiber is its simple structure containing only two air holes to control dispersion, confinement loss, and effective mode area. These PCFs are analyzed with finite-difference time-domain (FDTD) method and the perfectly matched layer (PML) boundary conditions.

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E-mail: s_olyaee@srttu.edu

## 2 Design and simulation of the index-guiding PCFs

### 2.1 Primary design

To design a PCF with appropriate confinement loss and dispersion characteristics in 1.55 μm wavelength, a simple structure is presented. As shown in Fig. 1, this structure has the same circular air-holes. This PCF consists of 6 air-holes rings ($N_r = 6$) with the diameter $d$ and lattice constant $\Lambda$. The air-hole diameter is supposed smaller than lattice constant, because as the rate $d/\Lambda$ decreases, dispersion becomes less.

First, the diameter of the air-holes is considered 0.9 μm, then $d$ is changed so that in the dispersion curve, closest point to the zero obtain. This is the optimum value of air-holes diameter. Figure 2 shows the dispersion curve for different air holes at wavelength range from 1.25 to 1.7 μm. As expected, the dispersion curve shifts above as air-hole diameter increases. In Fig. 3 dispersion curve is depicted around the 1.55 μm wavelength. So, the exact value of dispersion can be determined. As can be seen, for $d = 0.9154$ μm the dispersion is zero.

Figure 4 illustrates the confinemnt loss curve of PCF for different air-hole diameter values. The effect of air-hole diameter variations on the confinement loss has an opposite behavior in comparison of dispersion curve. That means, as diameters of the air-holes increase, dispersion decreases and better results can be achieved. In Fig. 5, the confinement loss is shown around the 1.55 μm wavelength. For a PCF with 0.9154 μm air-hole diameter, the confinement loss is $3.53 \times 10^{-2}$ dB/km.

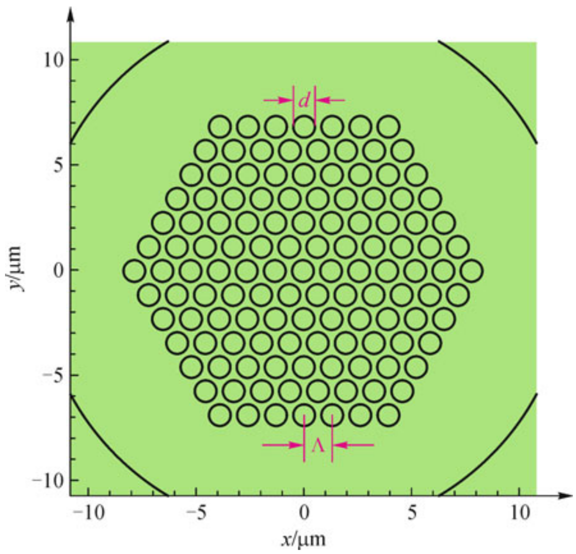


**Fig. 1** Primary structure of PCF with air hole diameter $d$, lattice constant $\Lambda$, and 6 air-hole rings

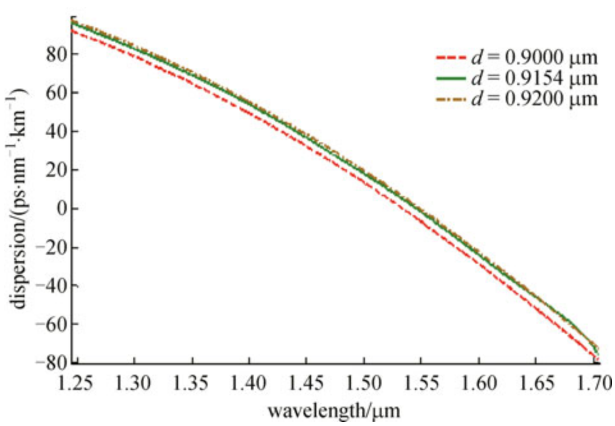


**Fig. 2** Dispersion curve of primary PCF for different hole diameters and $\Lambda = 1.3$ μm

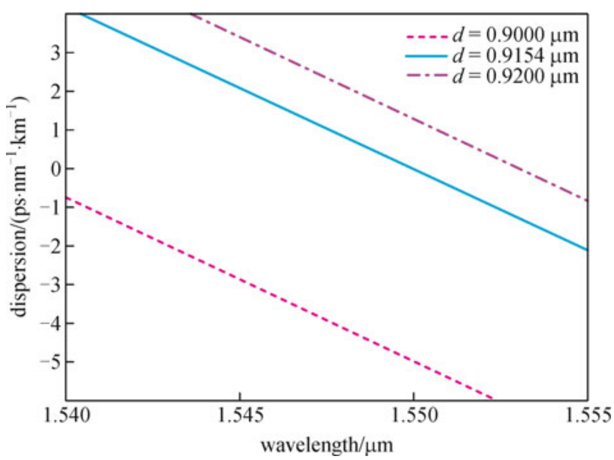


**Fig. 3** Dispersion of the primary PCF for different hole diameters and $\Lambda = 1.3$ μm and for wavelengths around 1.55 μm

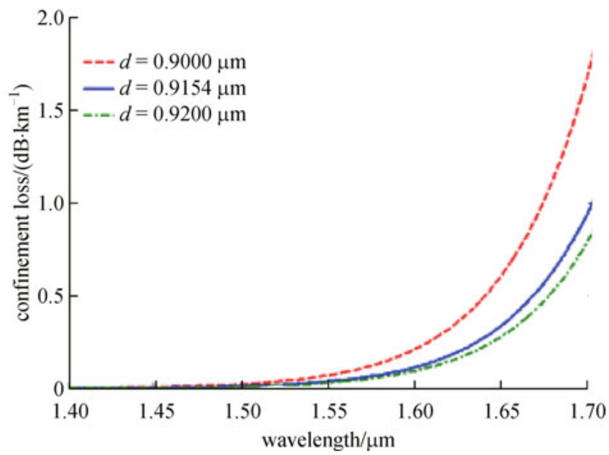


**Fig. 4** Confinement loss curves in primary PCF for different air-holes and $\Lambda = 1.3$ μm

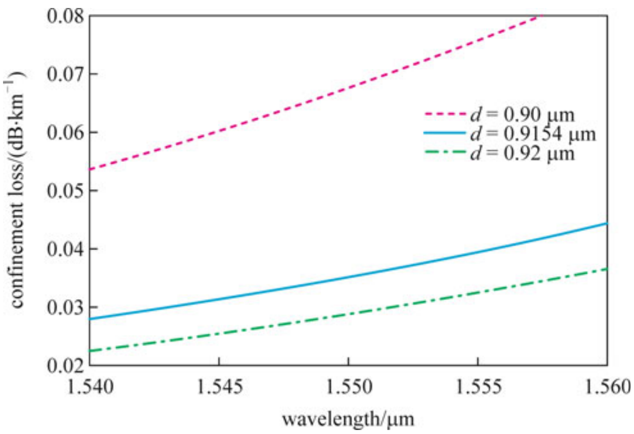


**Fig. 5** Confinement loss curves in primary PCF for different air-holes and $\Lambda = 1.3\ \mu m$ around the 1.55 μm wavelength

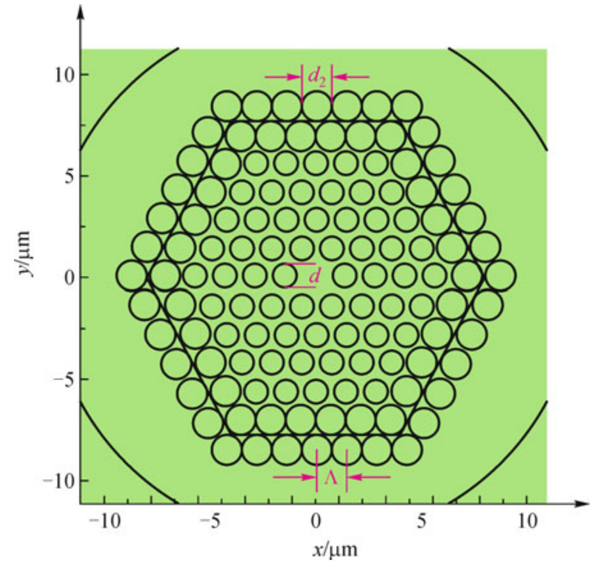


**Fig. 6** $PCF_1$ structure with $\Lambda = 1.3\ \mu m$ (diameter of air-holes in four inner rings is $d = 0.90836\ \mu m$ and the diameter of the air-holes in two last rings is $d_2 = 1.2\ \mu m$)

## 2.2 Zero-dispersion PCF ($PCF_1$)

Although with the simple structure of Fig. 1, dispersion becomes zero in 1.55 μm wavelengths, but the confinement loss characteristic is not minimized. So, a modification should be applied in three steps to get better result. As follows, $PCF_1$, $PCF_2$, and $PCF_3$ are designed to getting better characteristics.

Figure 6 shows $PCF_1$ structure that its cladding has two layers and two air-hole diameters. The diameter of air-holes in four inner rings is $d = 0.90836\ \mu m$ and the diameter of the air-holes in two last rings is $d_2 = 1.2\ \mu m$. Figure 7(a) shows confinement loss of $PCF_1$ in a wide wavelength range. This curve is enlarged around the 1.55 μm wavelength in Fig. 7(b). As shown in Fig. 7(b), when the diameter of outer air-holes increases, confinement loss decreases significantly; so that confinement loss decreases from $3.53 \times 10^{-2}$ to $4.643 \times 10^{-5}$ dB/km in 1.55 μm wavelength.

## 2.3 Zero-dispersion and low confinement loss PCF ($PCF_2$)

It should be noticed that increasing the diameter of air-holes especially in the last ring and consequently augmenting air filling fraction in the cladding of solid core PCFs led to optimize confinement loss characteristic. So, in the next design step, the diameter of air-holes in the three outer rings is increased, thus, $PCF_2$ forms as shown in Fig. 8(a). The electric field in the core of $PCF_2$ is illustrated in Fig. 8(b). As shown in Fig. 8, the light is well trapped at

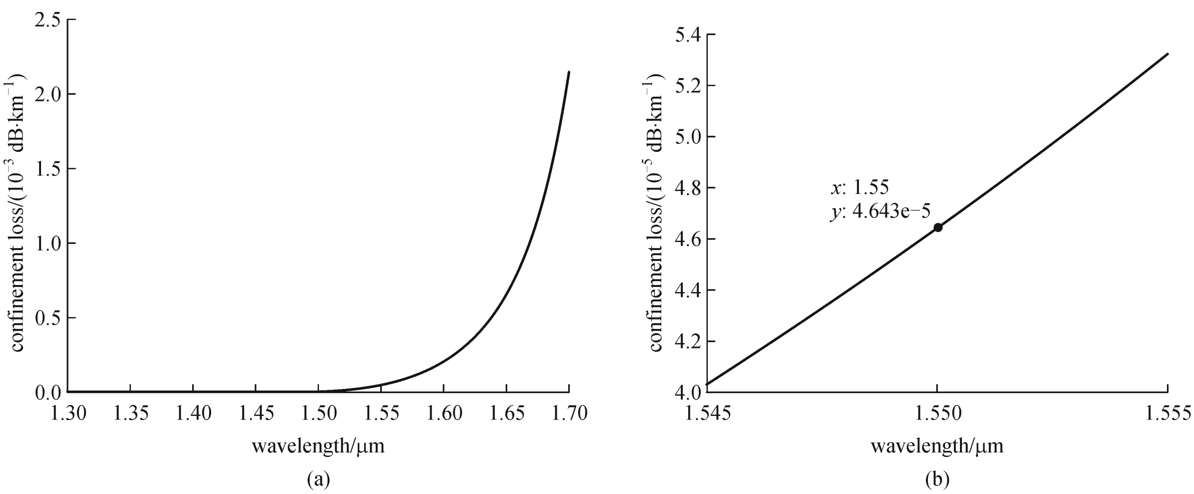


**Fig. 7** Confinement loss curve in $PCF_1$ (a) in a wide wavelength range and (b) around 1.55 μm wavelength

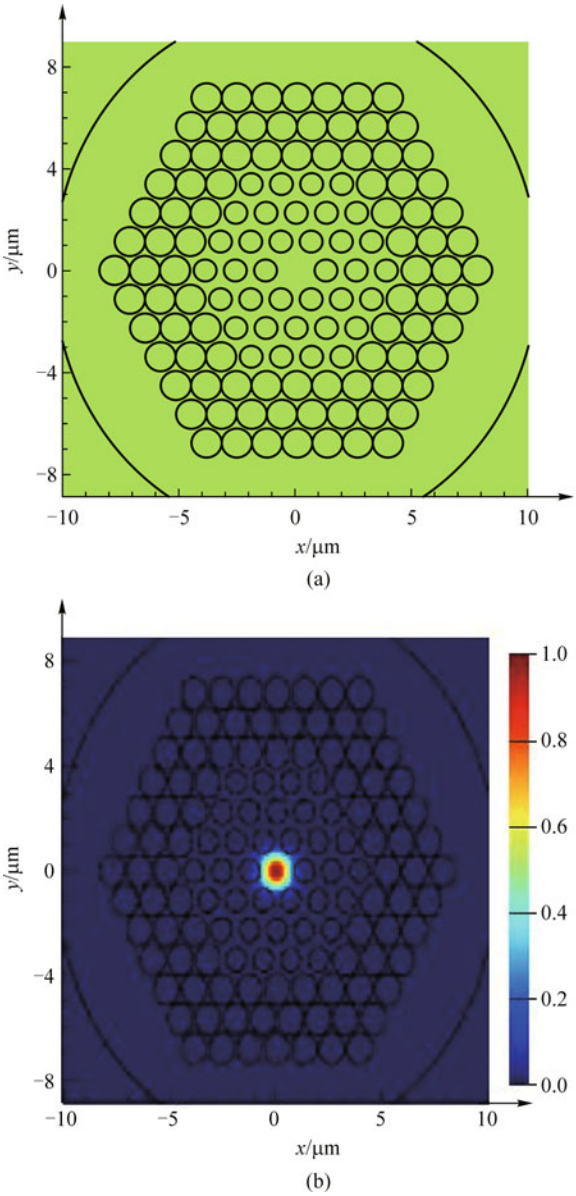


**Fig. 8** (a) $PCF_2$ structure with $\Lambda$ = 1.3 μm, $d$ = 0.90836 μm (diameter of air-holes in three inner rings) and $d_2$ = 1.2 μm (diameter of air holes in the last three rings) and (b) mode field distribution in the core of $PCF_2$

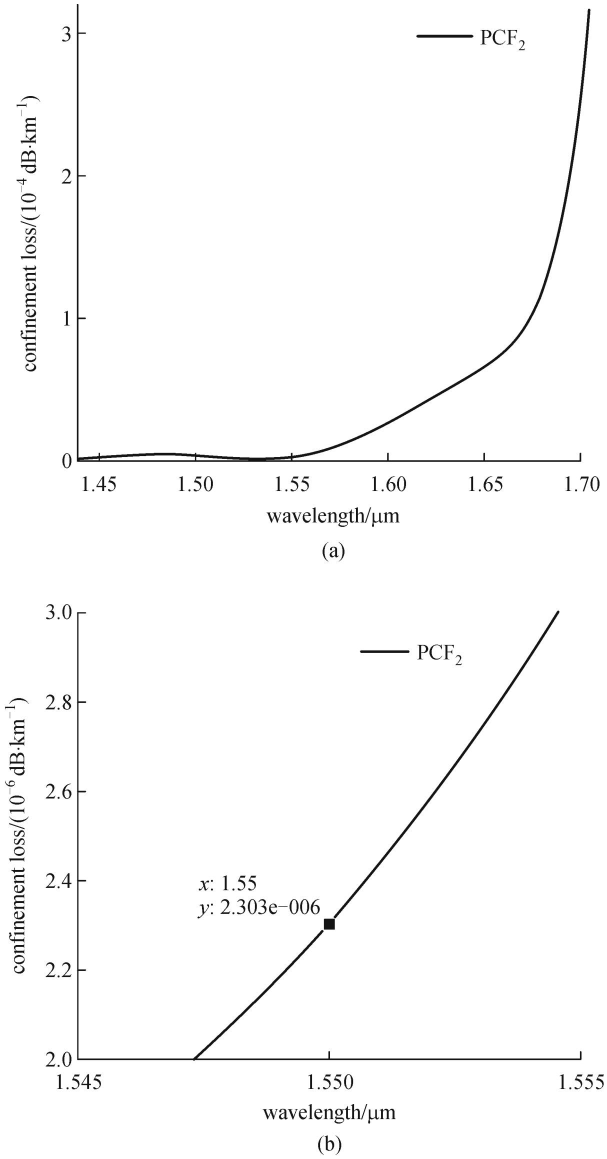


**Fig. 9** Confinement loss in $PCF_2$ (a) in a wide wavelength range and (b) around 1.55 μm wavelength

the center of $PCF_2$ and the mode effective area of 2.6 μm$^2$ is achieved at 1.55 μm.

Figure 9(a) illustrates the $PCF_2$ confinement loss in a wide wavelength range and Fig. 9(b) shows this curve around 1.55 μm wavelengths. As observed in Fig. 9(b), confinement loss in $PCF_2$ is less than $PCF_1$ structure and its value is $2.303\times10^{-6}$ dB/km.

## 2.4 Zero-dispersion and high confinement loss PCF ($PCF_3$)

In PCF design, as the number of air-hole rings decreases, the fiber diameter also reduces and its fabrication process becomes more easily. Thus, the last air-hole ring is omitted so that PCF3 can be created with five air-hole rings. The PCF3 structure is shown in Fig. 10 with lattice constant $\Lambda$ = 1.3 μm and five air hole rings.

Figure 11 shows the confinement loss of $PCF_3$ in a broad wavelength range. According to Fig. 11(b), the confinement loss increases very much and reaches $3.7\times10^{-3}$ dB/km. Consequently, despite of the high impact of the air-holes rings on the confinement loss, $PCF_3$ structure is not the desirable design.

In Fig. 12, dispersion curve for $PCF_1$, $PCF_2$, and $PCF_3$ structures are presented. The best result can be obtained from $PCF_2$ structure that its dispersion is $-4.6\times10^{-4}$

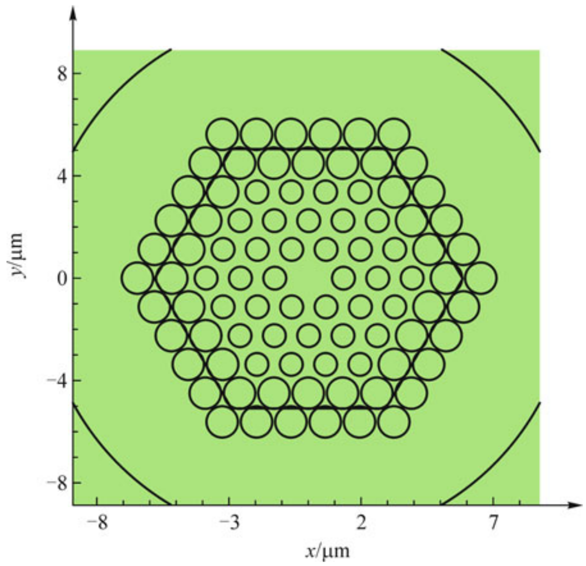


**Fig. 10** $PCF_3$ structure with $\Lambda$ = 1.3 μm and five air hole rings. The diameter of air-holes in the three inner rings is $d$ = 0.90836 μm and the diameter of air holes in the two last rings is $d_2$ = 1.2 μm

ps/(nm·km) in 1.55 μm wavelengths. According to Fig. 8 (b), the light is trapped well in the center of $PCF_2$ and an effective mode area about 2.6 μm$^2$ appears in 1.55 μm wavelength. Because of the small mode field distribution, the maximum optical power is in the center of the fiber core. In addition, a PCF having small effective area is useful for nonlinear optic applications. So, coupling the proposed PCF to the guiding index fiber is so appropriate ($PCF_2$). Generally, $PCF_2$ is more useful in optical telecommunication systems because it has approximately zero dispersion, low confinement loss, and small effective area.

## 3 Conclusions

In this paper, dispersion, confinement loss, and effective area characteristics of four designed PCFs are studied in 1.55 μm wavelength. In order to achieve low dispersion and low confinement loss in this wavelength, the proposed PCF has been designed with small inner air-holes rings and big outer air-holes rings. Since 1.55 μm is one of the optimum wavelengths, it can be tried to design a PCF with optimum characteristics. In this wavelength, dispersion and confinement loss have been achieved as $4.6\times10^{-4}$ ps/(nm·km) and $2.303\times10^{-6}$ dB/km, respectively. This PCF can be linked to standard grated index optical fibers. Since the PCF has almost zero dispersion, low confinement loss, and small effective area, it is also very applicable in optical telecommunication systems. Specially, because of small effective area, this PCF can be well connected to the fiber optics with low connection loss and can be also used in nonlinear optic applications.

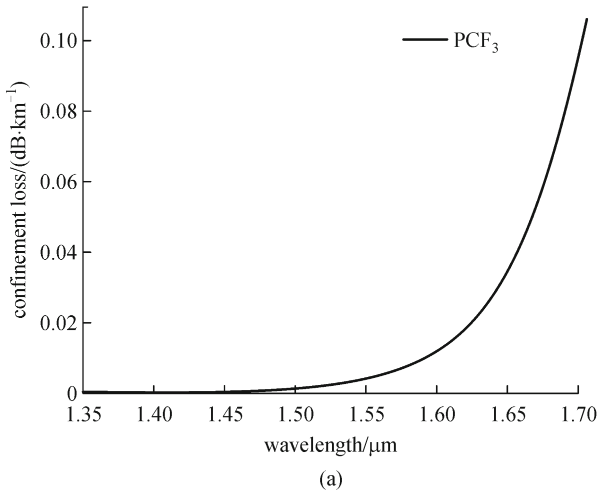


**Fig. 11** Confinement loss in $PCF_3$ (a) in a broad wavelength range and (b) around 1.55 μm wavelength

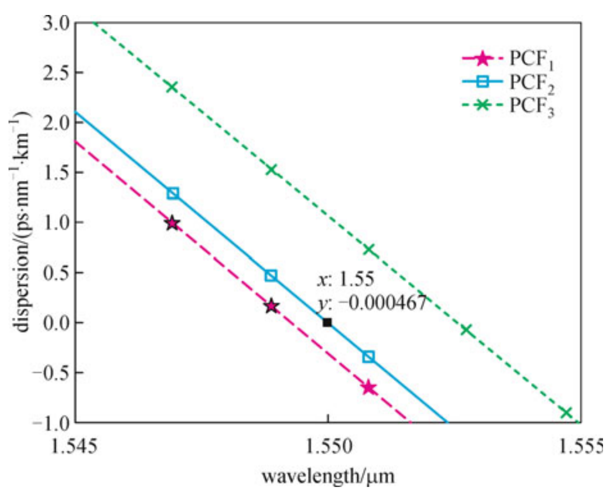


**Fig. 12** Comparison between dispersion curves of $PCF_1$, $PCF_2$, and $PCF_3$ structures around 1.55 μm wavelength

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