**COMPARISON OF EFFECTIVE MODE AREA AND NONLINEAR COEFFICIENT CHARACTERISTICS OF CIRCULAR AND RECTANGULAR PHOTONIC CRYSTAL FIBER WITH HOLLOW-CORE INFILTRATED CARBON DISULFIDE**

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**Abstract:** In this paper, we simulate and compared the effective mode area and the nonlinear coefficient of circular and rectangular lattices photonic crystal fibers (PCFs) structures when infiltrating carbon disulfide (CS2). By changing the lattice constant *Ʌ =* 1.0 µm; 1.5 µm; 1.8 µm, and 2.0 µm with the filling factor *d*1 */Ʌ* from0.3 to 0.8 to change the core diameter *Dc (Dc = 2Ʌ - 1.2d1,* there *d1* isthe first ring diameter*)*, we have selected 02 structures of the circular lattice of fibers #CF1 (*Ʌ* = 1.0 µm, *d1 /Ʌ* = 0.75, *Dc* = 1.1 µm), #CF*2* (*Ʌ* = 1.0 µm, *d1 /Ʌ* = 0.8, *Dc* = 1.04 µm) and 02 structures of the rectangular lattice of fibers # F1(*Ʌ* = 1.0 µm, *d1 /Ʌ* = 0.75, *Dc* = 1.1 µm), and #RF2 ( *Ʌ* = 1.0 µm, *d1 /Ʌ* = 0.8, *Dc* = 1.04 µm). When comparing the effective mode area and nonlinear coefficient of these optimal structures, we found that at the same structural parameters with the same pump wavelength of 1.55 µm, the #CF1 has an effective mode areasmaller by 0.137 µm2 and the nonlinear coefficient is higher by 5170 W -1.km -1than the # RF1; these results correspond to 0.138 µm2and 2820 W -1 .km -1when comparing two fibers #CF2 and #RF2. From this, we show that when CS2 is infiltrated into thecore, we have found the optimal PCF fibers with a small effective mode area and high nonlinear coefficient there the circular lattices are more optimal than the rectangular lattices. The structures we propose are very suitable for the study of supercontinuum generation (SC) in the near-infrared region.

**I. Introduction**

Photonic crystal fiber (PCF) is very popular in the optical field due to its versatility and applications. PCF can be characterized by changing its structural parameters. However, once the specific design of the PCF has been fabricated, it becomes difficult to change its optical properties. To overcome this problem, since 2006, people have been injecting liquid into the fiber core to control the characteristics of PCF [1] and therefore, the applications of PCF have also been further enhanced such as optical amplifiers, chemical and biochemical sensors [2-3], fiber lasers [4] and especially supercontinuum(SC) [5].

As is known, for a PCF fiber to have good SC efficiency, one of the main determining factors is that its core must have a high nonlinear coefficient with a small effective mode area (*Aeff* ). The effective mode area is a very important quantity and is considered a measure of the nonlinearity of the PCF fiber. When the effective mode area is low for high power density, which is essential for nonlinear effects. Besides, the effective mode area has a great influence on the loss inside the PCF fiber such as confinement loss [6]… Therefore, it is necessary to choose a liquid with a high nonlinear refractive index to inject into the PCF fiber core and found the optimal structure with a small effective mode area for application in SC.

To do this, we have carried out an infiltration of Carbon disulfide (CS­2) into the PCF fiber core. In this paper, we choose circular and rectangular lattices PCF with the same silica substrate, inside the fiber, there are 8 circularly arranged stomatal rings with lattice constant values *Ʌ =* 1.0 µm; 1.5 µm; 1.8 µm, and 2.0 µm; where the diameter of the first ring is variable (*Dc =* 2*Ʌ - 1.2d1)* by changing the fill factor of the first ring *d*1 / *Ʌ*  from 0.3 to 0.8. With the help of Lumarical Mode Solutions (LMS) and Matlab, we have simulated numerically and produced the characteristic line shape the effective mode areaand the nonlinear coefficient of two structures. By doing this, we can completely compare the effective mode area and nonlinearity coefficient of circular and rectangular lattices PCF structures, thereby finding the optimal structure for application and SC.

**II. Describe the structure and theory of effective mode area, nonlinear coefficients in crystalline optical fibers**

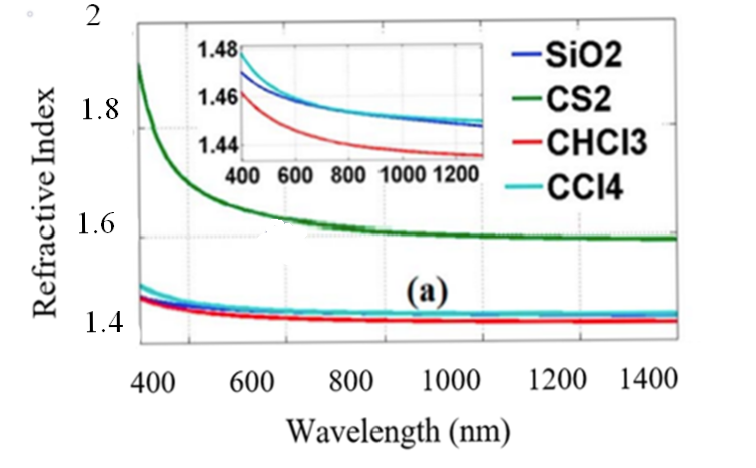
The structure of PCF circular and rectangular lattices is simulated as shown in Figure 1.

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|  |  |
| (a) | (b) |

**Figure 1.** Diagram of modeling the geometrical structure of PCF circular lattice (a), and rectangular lattice (b)

From Figure 1, the two structures that we used for simulation have 8 stomatal rings with lattice constants with values *Ʌ =* 1.0 µm; 1.5 µm; 1.8 µm, and 2.0 µm where the first ring diameter *d1*can be changed by varying the fill factor *d*1/*Ʌ* from 0.3 to 0.8; the central core permeable by CS­2 has a diameter between 0.52 µm and 1.64 µm (*Dc = 2Ʌ - 1.2d1 )*.

CS2 is chosen because the nonlinear coefficient extremely is large and much higher than Carbon tetrachloride (CCl4) or Chloroform (CHCl3). The nonlinear refractive index of CS2 has a value of 320.10-20 m2/W at 1.55 µm and is 100-fold higher than that of silica (SiO2) [7] and thus, SC in the infrared and infrared regions can be induced in hollow-core PCF fibers filled with CS­2 [8-10]. The difference in the nonlinear refractive index of CS2 compared with CCl4 and CHCl3 ­is depicted in Figure 2.



**Figure 2.** The refractive index curves of CS2 versus CCl4 and CHCl3 ­[7]

As mentioned, the nonlinear coefficient of the PCF fiber plays a very important role for SC. The larger the PCF nonlinear coefficient, the higher the super continuous transmission efficiency. The nonlinear coefficient is given by the formula [11]

 (1)

where *Aeff* is the effective mode area given by [11]

 (2)

Thus, choosing CS2 with a large nonlinear refractive index to penetrate the PCF core and choosing a structure with a small effective mode area will be favorable conditions for SC research.

In this paper, we compare effective mode areaand the nonlinear coefficient of two hollow core PCF structures with circular and rectangular lattices permeated CS2 with silica substrates. The object that we aim to conduct the comparison is PCF structures with small the effective mode areaand high the nonlinear coefficient*.*

**III. Results and Discussion**

To compare the effective mode area and the nonlinear coefficient of two hollow core PCF structures permeable CS2, we simulate using LMS software the PCF structures with lattice constant *Ʌ =* 1.0 µm; 1.5 µm; 1.8 µm and 2.0 µm have a firstring diameter that can be changed by varying the fill factor *d*1/*Ʌ* from 0.3 to 0.8 and get the results shown in Figure 3.

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**Figure 3.** Effective mode area graph *Aeff* of PCF circular and rectangular lattices infiltrated CS2 a) *Ʌ =* 1.0 µm ; b) *Ʌ* = 1.5 µm ; c) *Ʌ* = 1.8 µm ; d) *Ʌ* = 2.0 µm .

In general, for two PCF structures circular and rectangular lattices, when at the same lattice constant, the effective mode areawill increase as the wavelength increases and decrease as the fill factor increases. To further clarify the value of *Aeff*, we proceed to calculate the value of effective mode areaat the pump wavelength of 1.55 µm as Table 1.

**Table 1.** Table ofthe effective mode area *Aeff* (µm2) values of circular and rectangular lattices PCF structures permeable to CS2 at pumping wavelength 1.55 µm.

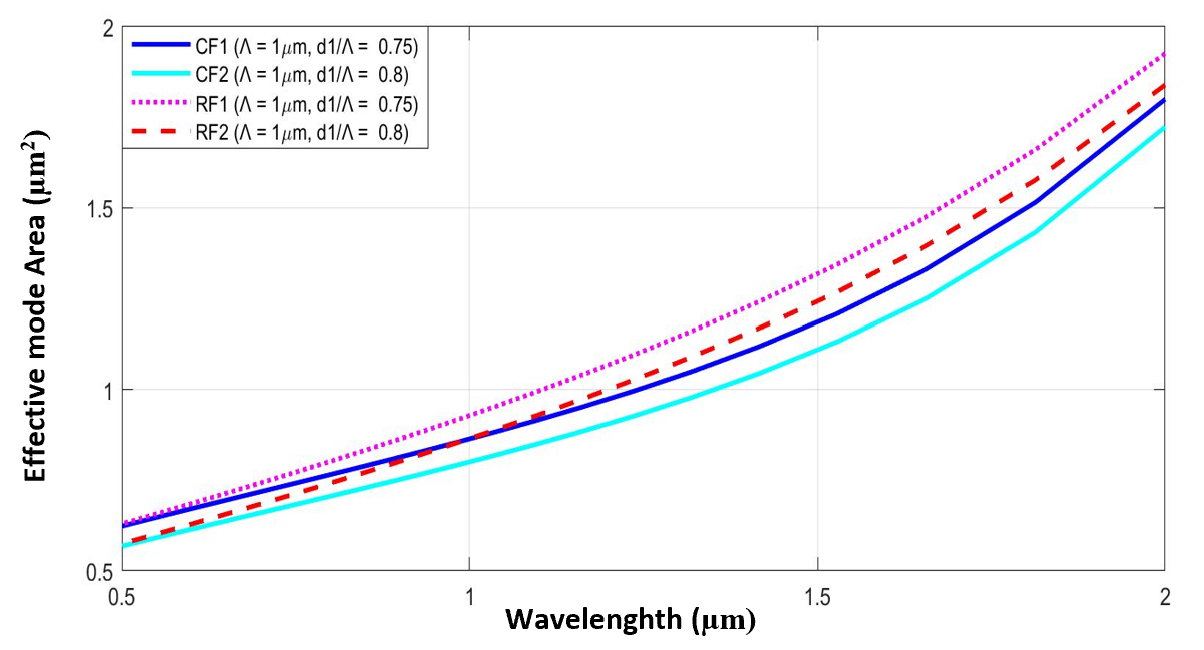
|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *d*1/*Ʌ* | ***Ʌ =* 1.0 µm** | | ***Ʌ =* 1.5 µm** | | ***Ʌ* = 1.8 µm** | | ***Ʌ =* 2.0 µm** | |
| Circle  lattice | Rectangular  lattice | Circle  lattice | Rectangular  lattice | Circle  lattice | Rectangular  lattice | Circle  lattice | Rectangular  lattice |
| 0.3 | 2.115 | 2.313 | 3.704 | 3.834 | 4.897 | 5.03 | 5.795 | 5.936 |
| 0.35 | 2.071 | 2.182 | 3.471 | 3.834 | 4.606 | 4.727 | 5.441 | 5.573 |
| 0.4 | 1.943 | 2.058 | 3.255 | 3.606 | 4.299 | 4.440 | 5.093 | 5.232 |
| 0.45 | 1.821 | 1,941 | 3.047 | 3.189 | 4.023 | 4.167 | 4.763 | 4.905 |
| 0.5 | 1.708 | 1.830 | 2.848 | 2.996 | 3.758 | 3.906 | 4.448 | 4.592 |
| 0.55 | 1.60 | 1.725 | 2.660 | 2.809 | 3.505 | 3,652 | 4.145 | 4.287 |
| 0.6 | 1.498 | 1.628 | 2.480 | 2.634 | 3.262 | 3.415 | 3.853 | 4.001 |
| 0.65 | 1.403 | 1.535 | 2.308 | 2.465 | 3.031 | 3.182 | 3.575 | 3.723 |
| 0.7 | 1.314 | 1.448 | 2.149 | 2.305 | 2.812 | 2.966 | 3.313 | 3.459 |
| 0.75 | 1.23 | 1.367 | 1.993 | 2.152 | 2.602 | 2.756 | 3.059 | 3.207 |
| 0.8 | 1.152 | 1.29 | 1.849 | 2.007 | 2.401 | 2.557 | 2.82 | 2.967 |

From table 1, it can be seen that for circular lattice the minimum effective mode area is 1.152 µm2 and the largest is 5.795 µm2. Meanwhile, this result for rectangular lattice is 1.29 µm2 and 5.936 µm2. Thus, at the same parameters, circular lattice PCF structures at 1.55 µm pump wavelength give the effective mode areasmaller than rectangular lattices. From this result, we choose the optimal 02 fibers about the effective mode area for each lattice structure as shown in Table 2.

**Table 2.** Optimal structures of the effective mode areaof PCF circular and rectangular lattices

|  |  |  |
| --- | --- | --- |
| PCF structure | # | *Aeff* (µm2 ) |
| Circular lattice | **#CF1** :  *Ʌ* = 1.0 µm, *d1 /Ʌ* = 0.75, *Dc*= 1.1 µm | 1.23 |
| **#CF2** : *Ʌ* = 1.0 µm, *d1 /Ʌ* = 0.8, *Dc*= 1.04 µm | 1.152 |
| Rectangular lattice | **#RF1** : *Ʌ*= 1.0 µm, *d1 /Ʌ* = 0.75, *Dc* = 1.1 µm | 1.367 |
| **#RF2** : *Ʌ* = 1.0 µm, *d1 /Ʌ* = 0.8, *Dc*= 1.04 µm | 1.29 |

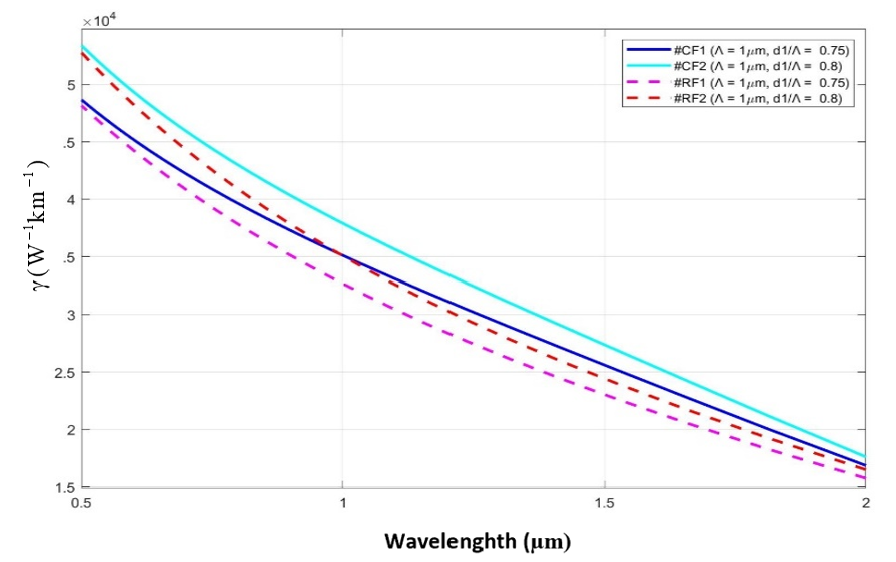
The schematic diagram of the selected optimal structures is depicted in Figure 4:



**Figure 4.** Synthesis of the effective mode area of the PCF structures #CF1, #CF2, #RF1, and #RF2 of the circular and rectangular lattices when permeating CS2.

From Table 2 and Figure 4 it can be seen that, as the wavelength increases, the effective mode area of the PCF constructs #CF1, #CF2, #RF1, and #RF2 also increase, especially rapidly in the wavelength range from 1.5 µm to 2.0 µm. When comparing at the same wavelength of 1.55 µm, at the same parameter *Ʌ =* 1.0 µm, *d*1/*Ʌ =* 0.75*, Dc* = 1.1 µm,the#CF1 structure of the circular lattice has the effective mode area0.137µm2  smallerthan #RF1 fiberof the rectangular lattice; while this difference is in *Ʌ =* 1.0 µm, *d*1/*Ʌ* = 0.8*, Dc* = 1.04 µm of #CF2 and #RF2 is 0.138 µm2.

Next, we compare the nonlinear coefficients of #CF1, #CF2, #RF1,and #RF2 fibersat a pump wavelength of 1.55 µm. The nonlinear coefficients of the optimal structures are depicted as shown in Figure 5.



**Figure 5.** Summaryof the PCF structures #CF1, #CF2, #RF1, and #RF2 of the circular and rectangular lattices when permeating CS2.

From Figure 5, the nonlinear coefficient of the structures #CF1, #CF2, #RF1,and #RF2 of the circular and rectangular lattices underCS2 permeation decrease rapidly with increasing wavelength. When at the same structure parameters, the nonlinear coefficient of #CF1, and #CF2 fibersof the circular lattice are both larger than those of the #RF1 and #RF2 fibersof the rectangular lattice. At the pump wavelength of 1.55 µm, these structures give values  as shown in Table 3:

|  |  |  |
| --- | --- | --- |
| PCF structure | # | (W -1.km -1 ) |
| Circular lattice | #CF1 | 27400 |
| #CF2 | 26370 |
| Rectangular lattice | #RF1 | 22230 |
| #RF2 | 23550 |

**Table 3.** Values the nonlinear coefficient of the structures #CF1, #CF2, #RF1 and #RF2 at pump wavelength 1.55 µm.

Table 3 shows the optimal structures about *Aeff* of the circular and rectangular lattices when permeation CS2 has very high nonlinear coefficients. In which, when at the same structural parameters and the same pump wavelength, it is 1.55 µm then #CF1 fiberis about 5170 W -1.km -1 larger than #RF1 fiber and #CF2 fiber isalso larger by 2820 W -1.km -1compared to fiber #RF2. Thus, the circular lattice structure is more optimal than the rectangular lattice because the effective mode areaissmall and the nonlinear coefficient is high when impregnated with the same liquid as CS2. This is a very favorable condition for super continuous generation research. The results outlined in this paper are also optimal compared with some previous publications, as shown in Table 4.

**Table 4.** The characteristic values of the proposed PCFs in comparison with previous publications.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Photonic crystal fibers | Liquids | *#* | *D*c  (μm) | Pump wavelength  (µm) | *A*eff  (µm2 ) | (W -1 .km -1 ) |
| [12] | CCl4 | #F1 | - | 1.55 | 11.83 | - |
| #F2 | - | 1.55 | 10.58 | - |
| [13] | CHCl3 | #F1 | - | 1.03 | 1.5 | 1290 |
| #F2 | - | 1.03 | 4.48 | 440 |
| [14] | C7 H8 | #I\_0.3 | 3.34 | 1.55 | 7.78 | - |
| #I\_0.35 | 3.23 | 1.55 | 78.9 | - |
| [15] | CS2 | - | - | 1.55 | 1.63 | 7940 |
| This work | CS2 | #CF1 | 1.1 | 1.55 | 1.23 | 27400 |
| #CF2 | 1.04 | 1.55 | 1.152 | 26370 |
| #RF1 | 1.1 | 1.55 | 1.367 | 22230 |
| #RF2 | 1.04 | 1.55 | 1.29 | 23550 |

**IV. Conclusion**

In this paper, with changing lattice constant and fill factor *d*1/ *Ʌ* from 0.3 to 0.8 to change the first ring diameter and core diameter (from 0.52 µm to 1.64 µm), we simulated and obtained structures with the effective mode areaoptimized with nonlinear coefficienthigh composed of fibers #CF1, #CF2, #RF1, and #RF2 of the circular and rectangular lattices when penetrated with CS2. The results show that the permeation of CS2 into the PCF core of the circular and square lattices obtained structures with the effective mode area is small (from 1.152 µm2 to 5.795 µm2 for circular lattice and from 1.29 µm2up to 5.936 µm2­for rectangular lattice at pump wavelength 1.55 µm). Furthermore, the effective mode areaof circular lattice structures is better than rectangular lattices. Specifically, when at the same structural parameters and the same pumping wavelength of 1.55 µm, the effective mode areaof #CF1 fiberisless than 0.137 µm2 and the nonlinear coefficient higher than 5170 W -1.km -1compared to fiber #RF1; these results correspond to 0.138 µm2and 2820 W -1 .km -1when comparing the two fibers #CF2 and #RF2. These are the optimal fibers with the effective mode areasmall and high nonlinear coefficients that are good candidates for the study of super continuous emission in the near-infrared region.

**Acknowledgments**

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 103.03-2020.03.

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