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Study of the Structure of Photonic Crystal Fiber with High Negative Dispersion Coefficient

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Outline

- Introduction
- The theoretical basis of optical transfer in photonic crystal fiber
- The design, modeling, analysis, and calculation
- Conclusions

Introduction

- **Doctor Charles Gao predicted 2 000 000 telephones , 20dB/km, in 1964.**
- **WDM**
- **DWDM**

Wave-Length Division Multiplexing 波分复用（衰减，色散）

negative dispersion coefficient was -59000ps/(nm·km)

Huttunen A. Optimization of dual-core and microstructure fiber geometries for dispersion compensation and large mode area [J]. Optics Express. 2005, 13(2): 627-635

The theoretical basis of optical transfer in photonic crystal fiber

- **Galerkin finite element method**
- **magnetic field component**

$$\nabla \times [\frac{1}{\varepsilon_r} \nabla \times \boldsymbol{H}] - k_0^2 \boldsymbol{H} = 0 \qquad H(x,y,z,t) = [H_x, H_y, H_z]^T (x,y) \exp[i(\omega t - \beta z)]$$

$$\nabla \times \boldsymbol{H} = 0$$

The vector wave equation

$$\begin{bmatrix} \frac{\partial}{\partial y}[\frac{1}{n_{zz}^2}(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y})] \\ -\frac{\partial}{\partial x}[\frac{1}{n_{zz}^2}(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y})] \end{bmatrix} - \begin{bmatrix} \frac{1}{n_{yy}^2}\frac{\partial}{\partial_x}(\frac{\partial H_x}{\partial x} + \frac{\partial H_y}{\partial y}) \\ \frac{1}{n_{xx}^2}\frac{\partial}{\partial_y}(\frac{\partial H_x}{\partial x} + \frac{\partial H_y}{\partial y}) \end{bmatrix} + k_0^2 n_{\text{eff}}^2 \begin{bmatrix} \frac{1}{n_{yy}^2} H_x \\ \frac{1}{n_{xx}^2} H_y \end{bmatrix} = k_0^2 \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

The theoretical basis of optical transfer in photonic crystal fiber

- **Galerkin finite element method**

The variation equation

$$\iint_{\Omega}\left\{\nabla_t\begin{bmatrix}\frac{1}{n_{zz}^2}\omega_y\left(\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}\right)\\ \frac{1}{n_{zz}^2}\omega_x\left(\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}\right)\end{bmatrix}+\nabla_t\begin{bmatrix}\frac{1}{n_{yy}^2}\omega_x\left(\frac{\partial H_x}{\partial x}-\frac{\partial H_y}{\partial y}\right)\\ \frac{1}{n_{xx}^2}\omega_y\left(\frac{\partial H_x}{\partial x}-\frac{\partial H_y}{\partial y}\right)\end{bmatrix}\right\}\mathrm{d}x\mathrm{d}y$$

$$+\iint_{\Omega}\left\{\frac{1}{n_{zz}^2}\left(\frac{\partial \omega_y}{\partial x}-\frac{\partial \omega_x}{\partial y}\right)\left(\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}\right)\right\}\mathrm{d}x\mathrm{d}y+\iint_{\Omega}\left\{k_0^2 n_{\mathrm{eff}}^2\left(\frac{\omega_x H_x}{n_{yy}^2}+\frac{\omega_y H_y}{n_{xx}^2}\right)\right\}\mathrm{d}x\mathrm{d}y$$

$$+\iint_{\Omega}\left\{\left[\frac{\partial}{\partial x}\left(\frac{\omega_x}{n_{yy}^2}\right)+\frac{\partial}{\partial y}\left(\frac{\omega_y}{n_{xx}^2}\right)\right]\left(\frac{\partial H_x}{\partial x}+\frac{\partial H_y}{\partial y}\right)-k_0^2\left(\omega_x H_x+\omega_y H_y\right)\right\}\mathrm{d}x\mathrm{d}y=0$$

The theoretical basis of optical transfer in photonic crystal fiber

- **Galerkin finite element method**

$$\nabla_t = \boldsymbol{i}\frac{\partial}{\partial x} + \boldsymbol{j}\frac{\partial}{\partial y} \qquad \omega = [\omega_x, \omega_y]^T$$

$$\Delta_x\left(\frac{1}{n_{yy}^2}\right) = \left(\frac{1}{n_{yy}^2}\right)_{x=x_{\text{int}+}} - \left(\frac{1}{n_{yy}^2}\right)_{x=x_{\text{int}-}}$$

$$\Delta_y\left(\frac{1}{n_{xx}^2}\right) = \left(\frac{1}{n_{xx}^2}\right)_{y=y_{\text{int}+}} - \left(\frac{1}{n_{xx}^2}\right)_{y=y_{\text{int}-}}$$

$$\sum_{B_e}\left\{-\int_{\Gamma_e}\frac{\omega_y}{n_{zz}^2}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right)\mathrm{d}y - \int_{\Gamma_e}\frac{\omega_x}{n_{zz}^2}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right)\mathrm{d}x\right\}$$

$$-\sum_{B_e}\left\{-\int_{\Gamma_e}\frac{\omega_x}{n_{yy}^2}\left(\frac{\partial H_x}{\partial x} - \frac{\partial H_y}{\partial y}\right)\mathrm{d}y - \int_{\Gamma_e}\frac{\omega_x}{n_{xx}^2}\left(\frac{\partial H_x}{\partial x} - \frac{\partial H_y}{\partial y}\right)\mathrm{d}x\right\}$$

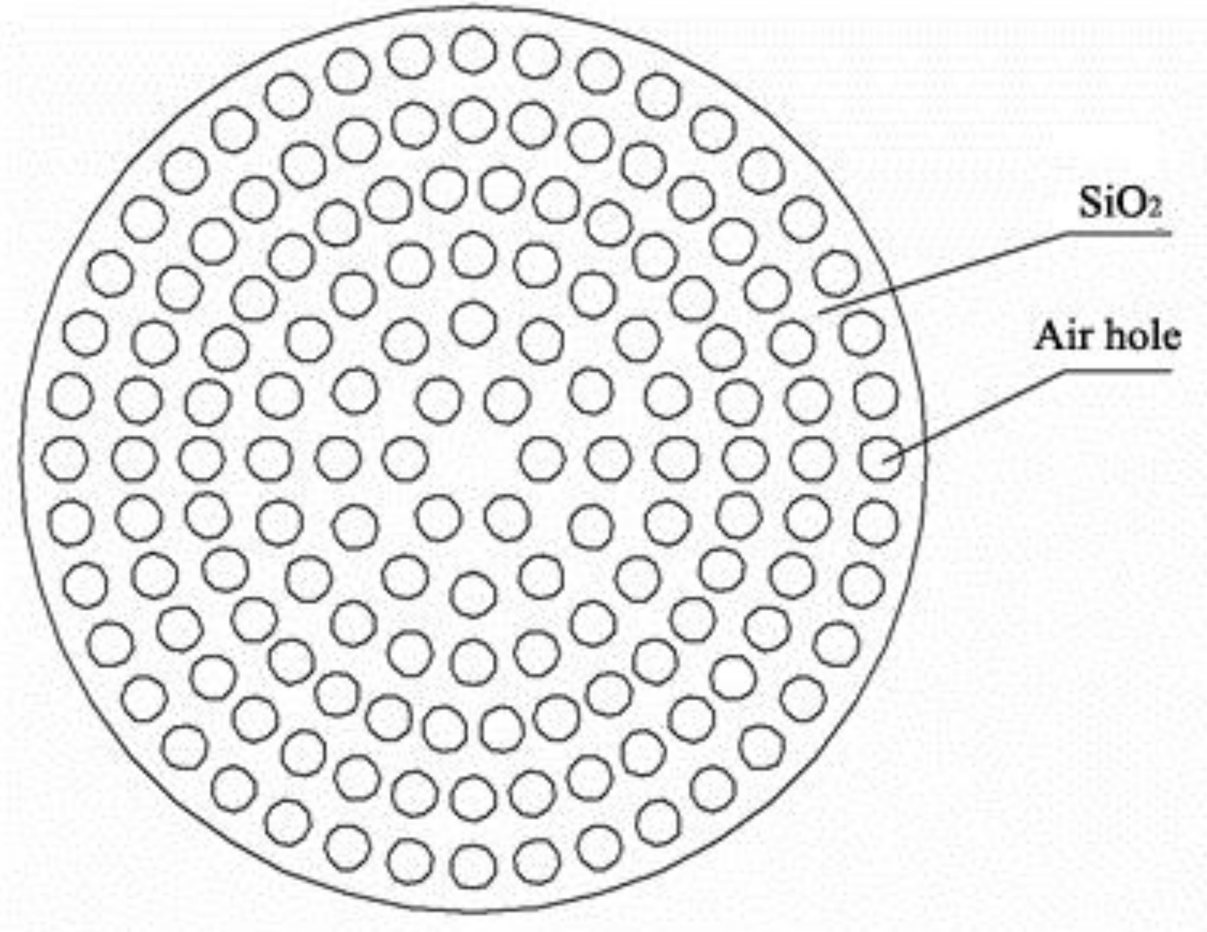
$$+\sum_{\text{int}_e}\left\{-\int_{\Gamma_{\text{int}_e}}\Delta_x\left(\frac{1}{n_{yy}^2}\right)\omega_x\left(\frac{\partial H_x}{\partial x} - \frac{\partial H_y}{\partial y}\right)\mathrm{d}y - \int_{\Gamma_{\text{int}_e}}\Delta_y\left(\frac{1}{n_{xx}^2}\right)\omega_y\left(\frac{\partial H_x}{\partial x} + \frac{\partial H_y}{\partial y}\right)\mathrm{d}x\right\}$$

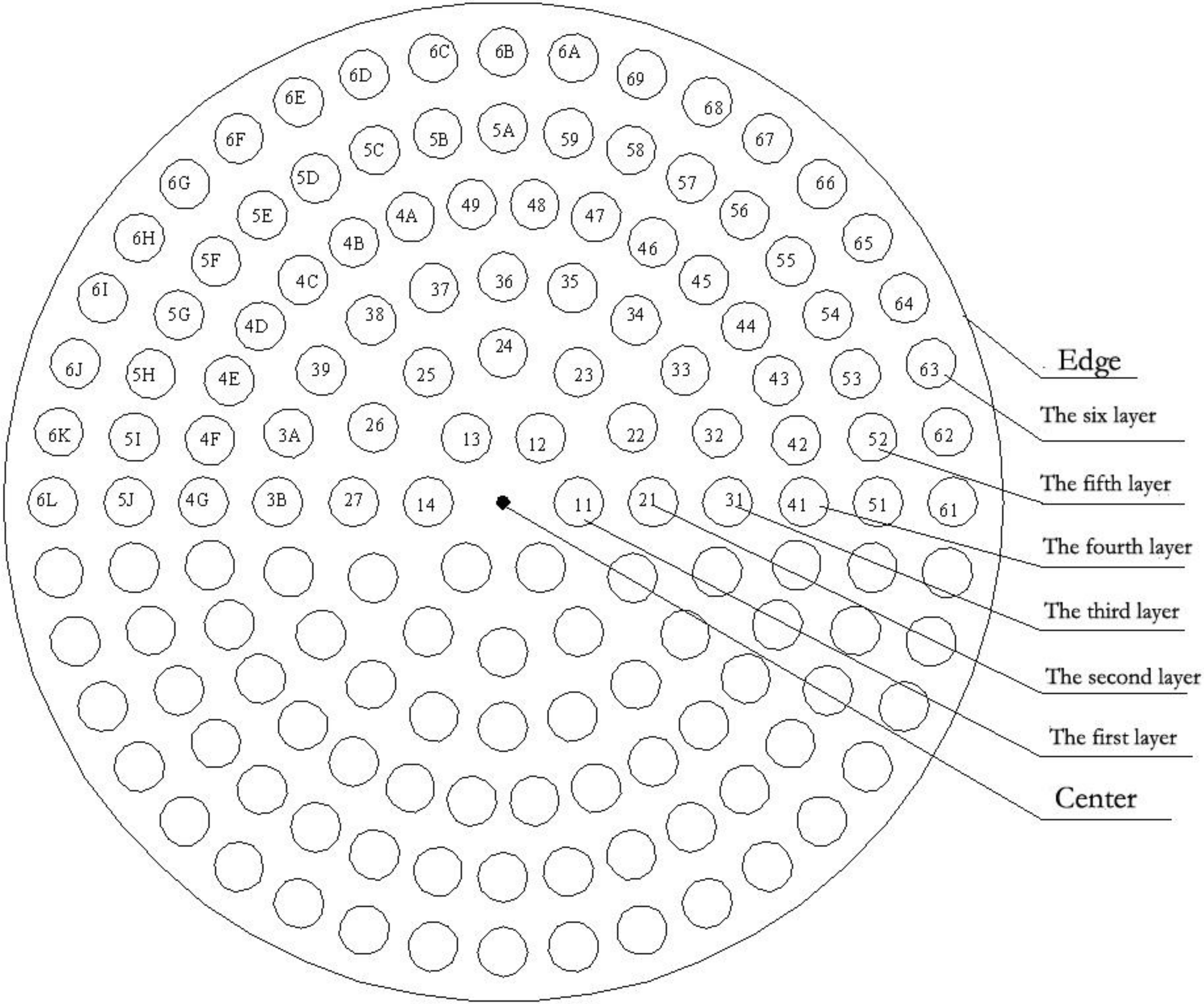
$$+\sum_{\text{int}_e}\iint_{\Omega_e}\frac{1}{n_{zz}^2}\left\{\left(\frac{\partial \omega_y}{\partial x} - \frac{\partial \omega_x}{\partial y}\right)\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right) + \left[\frac{\partial}{\partial_x}\left(\frac{\omega_x}{n_{yy}^2}\right) + \frac{\partial}{\partial_y}\left(\frac{\omega_y}{n_{xx}^2}\right)\right]\left(\frac{\partial H_x}{\partial x} + \frac{\partial H_y}{\partial y}\right)\right\}\mathrm{d}x\mathrm{d}y$$

$$+\sum_{\text{int}_e}\iint_{\Omega_e}\left[k_0^2 n_{\text{eff}}^2\left(\frac{\omega_x H_x}{n_{yy}^2} + \frac{\omega_y H_y}{n_{xx}^2}\right) - k_0^2\left(\omega_x H_x + \omega_y H_y\right)\right]\mathrm{d}x\mathrm{d}y = 0$$

The design, modeling, analysis, and calculation

- **design**
- ***n*=1.46**





Edge
The six layer
The fifth layer
The fourth layer
The third layer
The second layer
The first layer
Center
6C 6B 6A 69
6D 68
6E 67
6F 5C 5B 5A 59 58
6G 5D 57 66
5E 4A 49 48 47 56
6H 4B 46 65
5F 55
6I 4C 37 36 35 45
5G 4D 38 34 44 54 64
24
6J 5H 4E 39 25 23 33 43 53 63
6K 5I 4F 3A 26 13 12 22 32 42 52 62
6L 5J 4G 3B 27 14 11 21 31 41 51 61

The design, modeling, analysis, and calculation

- **modeling**

- **P11 (1,0); P12(0.5, 0.866025); P13(-0.5, 0.866025); P14(-1,0).**
- **P21(2,0); P22(1.732051,1); P23(1, 1.732051); P24(0, 2); P25(-1, 1.732051); P26(1.732051, 1); P27(-2,0).**
- **P31(3,0); P32(2.85317, 0.92705); P33(2.427052, 1.763354); P34(1.763354, 2.427052); P35(0.92705, 2.85317); P36(0, 3); P37(1,0); P38(-0.927051, 2.85317); P39(-1.763354, 2.4270520); P3A(-2.427052, 1.763354); P3B(-3,0).**
- **P41(4,0); P42(3.912591, 0.831646); P43(3.654182, 1.626945); P44(3.2360692, 2.3511393); P45(2.676525, 2.972577); P46(2,3.4640998); P47(1.236072, 3.80422475); P48(0.418119, 3.978087); P49(-0.418119, 3.978087); P4A(-1.236072, 3.80422475); P4B(-2,3.4640998); P4C(-2.676525, 2.972577); P4D(-3.2360692, 2.3511393); P4E(-3.654182, 1.626945); P4F(-3.912591, 0.831646); P4G(-4,0).**
- **P51(5,0); P52(4.924039, 0.86824); P53(4.698464, 1.710099) ; P54(4.330128, 2.5); P55(3.830224, 3.213936) ; P56(3.213936, 3.830224); P57(2.5, 4.330128) ; P58(1.710099, 4.698464); P59(0.86824, 4.924039) ; P5A(0, 5); P5B(-0.86824, 4.924039) ; P5C(-1.710099, 4.698464); P5D(-2.5, 4.330128) ; P5E(-3.213936, 3.830224); P5F(-3.830224, 3.213936) ; P5G(-4.330128, 2.5); P5H(-4.698464, 1.710099) ; P5I(-4.924039, 0.86824); P5J(-5,0).**

The design, modeling, analysis, and calculation

- **modeling**

- **P61(6,0); P62(5.92613, 0.938606); P63(5.70634, 1.8541) ; P64(5.3460402, 2.72394087); P65(4.854104, 3.526709) ; P66(4.2426435, 4.2426435); P67(3.5267154, 4.854099159) ; P68(2.723948, 5.346037); P69(1.8541, 5.70634) ; P6A(0.938606, 5.92613); P6B(0, 5) ; P6C(-0.938606, 5.92613); P6D(-1.8541, 5.70634) ; P6E(-2.723948, 5.346037); P6F(-3.5267154, 4.854099159) ; P6G(-4.2426435, 4.2426435); P6H(-4.854104, 3.526709) ; P6I(-5.3460402, 2.72394087); P6J(- 5.70634, 1.8541) ; P6K(-5.92613, 0.938606); P6L(-6,0).**

The design, modeling, analysis, and calculation

- **calculation**

- **The spacing between the neighbor layers *d*0=1.500μm, the diameter of the air hole *d* is between 1.12μm ~1.16μm and its step length is 0.02μm. The transferred wavelength is between 1.500μm~1.600μm and its step length is 0.001μm. There are 101 effect refractive indexes in steady state the transferred wavelength between 1.500μm~1.600μm and its step length is 0.001μm and the diameter of the air hole is 1.12μm.**

- 1.366893, 1.366810, 1.366728, 1.366645, 1.366563, 1.366480, 1.366398, 1.366315, 1.366233, 1.366150, 1.366067, 1.365985, 1.365902, 1.365819, 1.365737, 1.365654, 1.365571, 1.365489, 1.365406, 1.365323, 1.365240, 1.365158, 1.365075, 1.364992, 1.364909, 1.364826, 1.364744, 1.364661, 1.364578, 1.364495, 1.364412, 1.364329, 1.364246, 1.364163, 1.364081, 1.363998, 1.363915, 1.363832, 1.363749, 1.363666, 1.363583, 1.363500, 1.363417, 1.363334, 1.363251, 1.363168, 1.363085, 1.363002, 1.362919, 1.362836, 1.362753, 1.362672, 1.362610, 1.362574, 1.362539, 1.362505, 1.362470, 1.362435, 1.362401, 1.362366, 1.362331, 1.362297, 1.362262, 1.362227, 1.362193, 1.362158, 1.362124, 1.362089, 1.362054, 1.362020, 1.361985, 1.361950, 1.361916, 1.361881, 1.361847, 1.361812, 1.361777, 1.361743, 1.361708, 1.361674, 1.361639, 1.361605, 1.361570, 1.361535, 1.361501, 1.361466, 1.361432, 1.361397, 1.361363, 1.361328, 1.361293, 1.361259, 1.361224, 1.361190, 1.361155, 1.361121, 1.361086, 1.361052, 1.361017, 1.360983, 1.360948

The design, modeling, analysis, and calculation

- **analysis**

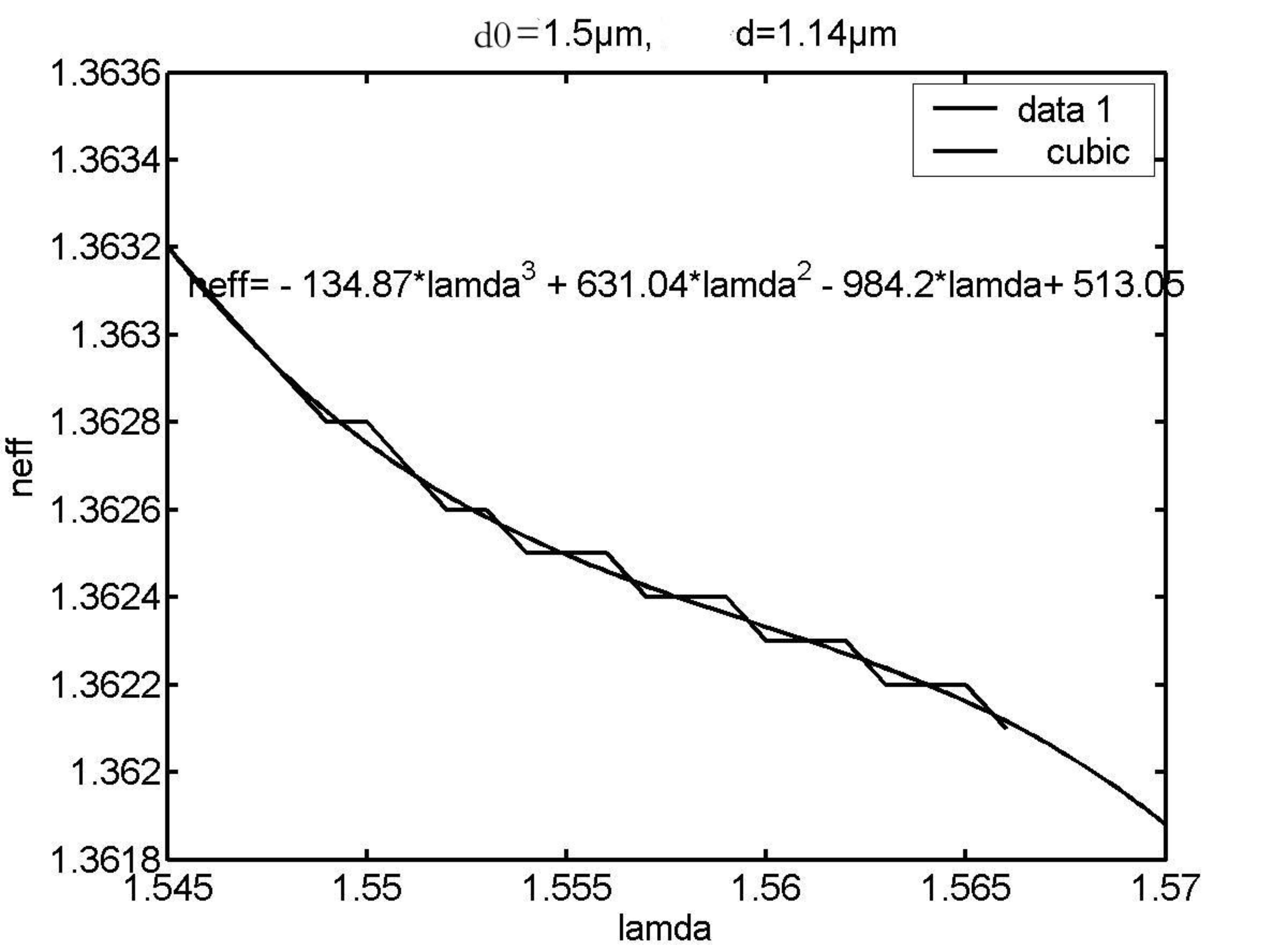
- **The wavelength scope of 1.545μm~1.566μm and the fitting cubic curve**

$$n_{\mathrm{eff}} = -134.87\lambda^3 + 631.04\lambda^2 - 984.2\lambda + 513.05$$

The dispersion coefficient is

$$D = -\frac{\lambda}{c}\frac{\mathrm{d}^2}{\mathrm{d}\lambda^2}n_{\mathrm{eff}} = -\frac{\lambda}{c}(-134.87\times 6\lambda + 631.04\times 2)$$

The dispersion coefficient is D=-65207.4ps/(nm·km)



d0=1.5μm, d=1.14μm
data 1
cubic
neff= - 134.87*lamda^3 + 631.04*lamda^2 - 984.2*lamda+ 513.05
neff
lamda
1.3636
1.3634
1.3632
1.363
1.3628
1.3626
1.3624
1.3622
1.362
1.3618
1.545
1.55
1.555
1.56
1.565
1.57

Conclusion

The software system of COMSOL Multiphysics® is used for modeling, analysis, and calculation after the multilayer circle asymmetry photonic crystal fiber being designed. The negative dispersion coefficient is to -65207.4ps/(nm·km) at transfer wavelength being 1550nm. The result is 40 times than that of the reference [8] and is 1.1 times than that of the reference [6]. The 1 meter of the designed structure is suit for the 3260 meters compensation the dispersion of the single optical fiber G. 652.

Reference

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