NANO-TAILORING OF PHOTONIC CRYSTAL FIBERS

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1. Introduction

We present the study of nano- tailored Photonic Crystal Fibers' (PCF) properties [1,2]. We have focused on the influence of ring nano- structure implementation on dispersion (1) and effective area (2).

$$D = -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2} = -\frac{2\pi c}{\lambda^2}\frac{d^2\beta}{d\omega^2} \qquad (1) \qquad\qquad A_{eff} = \frac{\left(\iint_{-\infty}^{\infty} |F(x,y)|^2 dx\,dy\right)^2}{\iint_{-\infty}^{\infty} |F(x,y)|^4 dx\,dy} \qquad (2)$$

where c is the speed of light in vacuum, ω is optical frequency, λ is wavelength, β is propagation constant, $F(x,y)$ represents $\boldsymbol{E}$ and $\boldsymbol{H}$ field of the mode.

We have used Finite Elements Method [3] to calculate field profiles of fiber modes. This method solves vectorial wave equation (3) and finds the solution in a form of (4).

$$\vec{\nabla} \times \left[\frac{1}{\mu}\left(\vec{\nabla} \times \mathbf{E}(\vec{r})\right)\right] = k_0{}^2 \varepsilon_r(\vec{r})\mathbf{E}(\vec{r}) \qquad (3) \qquad\qquad \alpha = \delta^z + j\beta = -\lambda \qquad (4)$$

where μ is permeability, $\boldsymbol{E}$ is electrical intensity, k_0 is free space wavenumber, ε_r is relative permittivity, α, λ is an eigenvalue, β is propagation constant, δ^z represents damping.

We have simulated ideal structures therefore we have exploited fiber symmetry and consequently applied appropriate boundary conditions. Our study considered only fundamental mode which possess both symmetries thus we applied symmetric and anti-symmetric boundary conditions in a form of perfect electric and perfect magnetic conductor on the quarter- section boundaries (vertical and horizontal) of the fiber.

2. "Standard" Photonic Crystal Fibers

One of the ways to modify the properties of PCFs is to change their geometry. Our silica PCF is composed of triangularly arranged cladding holes in five rings. We define d/Λ as a ratio of cladding holes diameter d and Λ*-pitch* as a center- to– center hole spacing (Fig.1-left). We have calculated fiber properties with various air-filling fractions and also with scaled geometry (changing Λ).

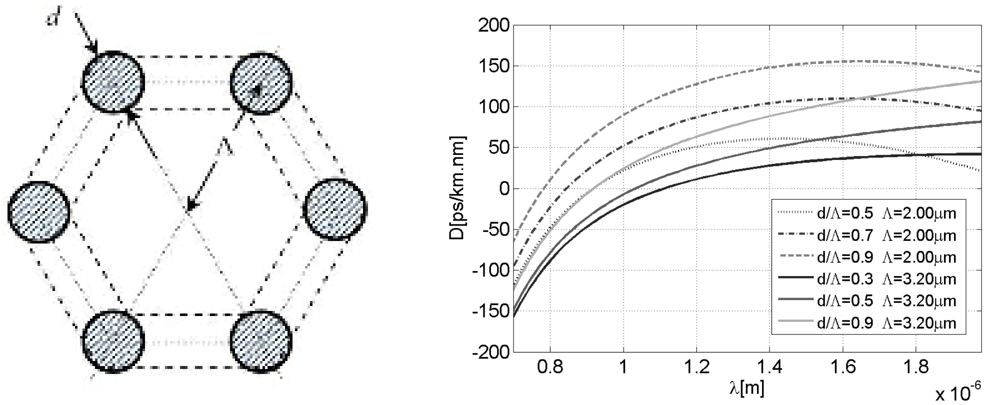

Fig. 1: *1st ring of triangular PCF cross-section with parameters d and Λ (left); Dispersion profiles of fibers with different parameters (right).*

From (Fig.1-right) we can see stronger dispersion for higher *d/Λ* ratio. Pitch changes cause shaping of dispersion curves; e.g. fiber with *Λ*=2 μm has more flattened profile than fiber with *Λ*=3.2 μm. Impact of geometry is visible also in mode field distribution. Better localization of mode inside the core is observed in PCF with lower pitch; higher pitch causes leakage of the guided mode into the structure.

3. Ring nano- structure

We have chosen nano- geometry of twelve nano- holes hexagonally arranged which form two hexagons exactly related by 90° rotation (Fig.2- left). We used Λ_n hole-to-center distance from values between 0,2 and 0,8 μm and d_n/Λ_n, which determines hole diameter in dependence on Λ_n parameter, from 0,1 to 0,45. From these parameters it is not difficult to infer range of nano- defects diameters (from 40 to 360 nm). In addition, pitch parameter of cladding was 2μm.

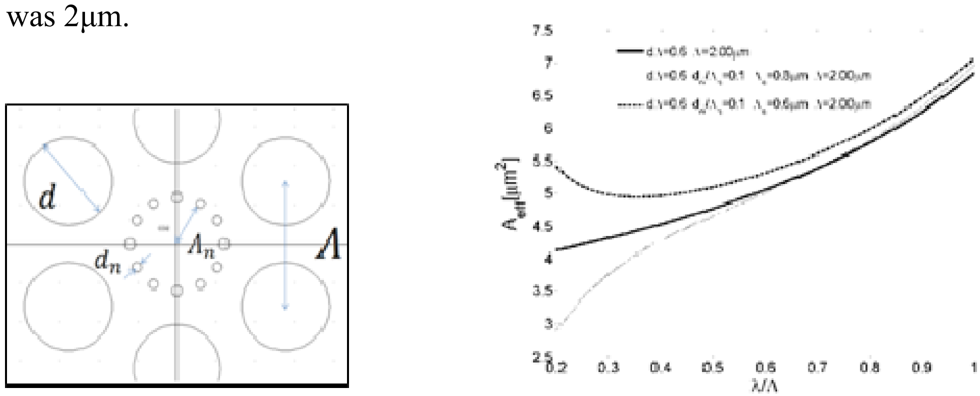

Fig. 2: *Cross-section of a core with added "ring" nanostructure and defined parameters (left); impact of Λ_n on modal area at shorter wavelengths (right.)*

We focus on structures where the peak of light intensity is localized inside nano- ring also at higher frequencies. The only fiber structures capable of such guidance were those with ultimately small relative hole sizes (d_n/Λ_n=0.1) located farther from core (Λ_n=0.6 to 0.8 μm). The holes gently release mode confinement in the region roughly above 1400nm (Fig.3- right). As can be seen on (Fig.2- right) the for shorter nano-holes distance A_{eff} has rising tendency at the shortest wavelengths of studied spectrum, while curve for Λ_n=0.8 has counteractive profile. This structure managed to constrain light into the effective modal area below 3 μm^2.

We have calculated dispersion of proposed fiber geometry and found out that it exhibits very special features at "resonance" part of the spectrum for particular geometry parameters. It turns out that implemented nano- structure breaks orthogonality of cladding and core modes and even more enables high coupling efficiency from one to another and vice versa at specific wavelengths. We present the dispersion plot for various fiber geometry parameters in (Fig.4) where one can see dramatic change in dispersion at following parameters: d/Λ=0.6, d_n/Λ_n=0.4, Λ_n=0.6 μm. We have done simulations focused on these parameters and studied the effect of fine change in d_n/Λ_n and Λ_n separately; we plot the results in (Fig.5).

By changing the diameter of nano-holes we are able to shift the minimum of the curve within remarkable range and thereby strengthening negative dispersion at mentioned range.

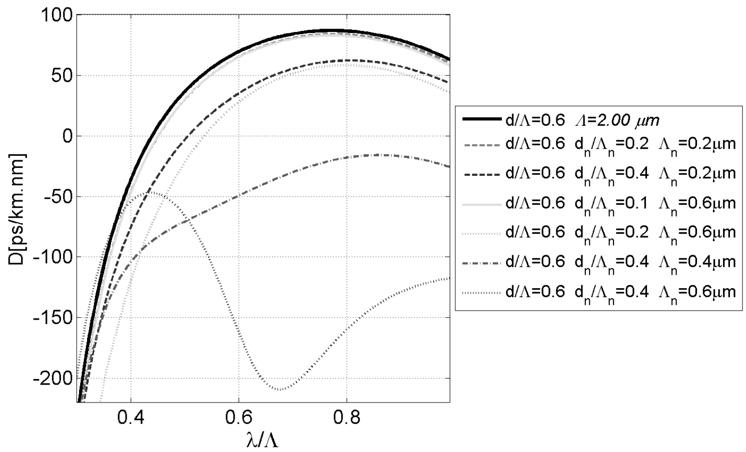

Fig. 3: *Dispersion profiles for various core hole parameters, with fixed d/Λ=0.6*

By increasing the radius of the ring we obtained dispersion curves deepening their minima from -154 ps/(km.nm) for Λ_n=0.55 μm to -223 ps/(km.nm) for Λ_n=0.65 μm. However the minima of the dispersion curve travel across wavelength range thus these effects cannot be totally separated.

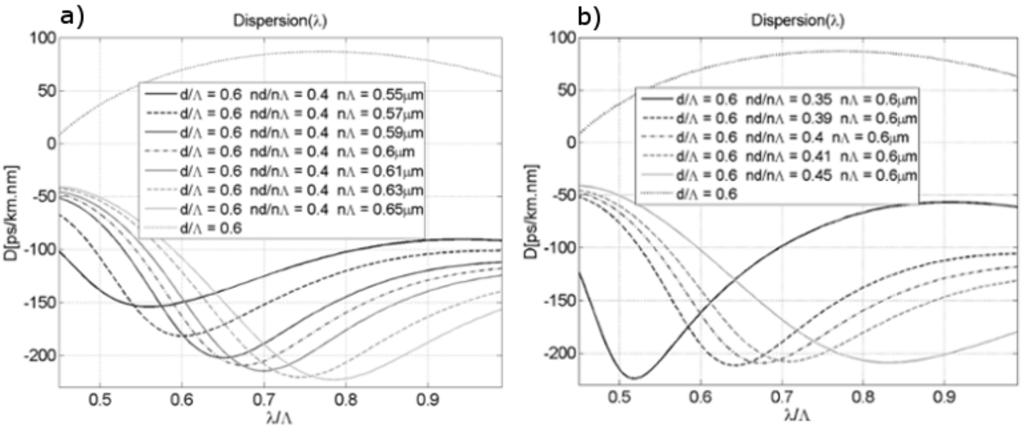

Fig. 4: *Dispersion for structures close to the parameters set: $d/\Lambda=0.6$, $d_n/\Lambda_n=0.4$, $\Lambda_n=0.4$ μm; a)Λ_n changing b) d_n/Λ_n changing*

4. Conclusion

Nano-tailoring technique showed itself to be very sensitive even to tiny nano-scale changes however using state-of-the-art technology one can draw fibers with sufficient precision. The ring nano-structure introduces possibilities of decreasing the level of dispersion in the range of 1300 nm using very small nano-holes (around 70 nm) localized 600 to 800 nm from the center.

One of these structures tends to compress the modal area at shorter wavelengths. Placing larger nano-holes more close to the center leads to splitting the core into two areas for mode guiding and pushing the highest power fractions into the gap between ring and cladding, which is in opposite to expected reaction.

We have presented very flexible and powerful tool which can be utilized in PCF design for various industrial applications such as sensors, telecommunication fibers with special properties etc.

Acknowledgements

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References

[1] A.B.Fedotov et.al.: *Laser Phys. Lett.*, **6**, 301 (2006).

[2] G.S.*Wiederhecker et.al.: Nature Photonics, 1, 115 (2007).*

[3] [ONLINE] http://www.comsol.com/