Optical properties of liquid filled photonic crystal fibers

Ron Spittel*, Klaus Mörl, Hartmut Lehmann, Julia Mörbitz, Hartmut Bartelt
*Institute of Photonic Technology (IPHT), Jena
mailto:ron.spittel@ipht-jena.de

We investigate the optical properties of photonic crystal fibers filled with liquids of refractive indices close to that of fused silica. Taking in account the material dispersion of silica and the liquids we will show that this leads to wavelength and temperature dependent switches and filters.

1 Introduction

Photonic crystal fibers (PCFs) are optical fibers with a hexagonal lattice of air holes of diameter d and pitch Λ running along the fiber axis (fig. 1). The light is guided in a lattice defect region, also called the core. Since their first report of fabrication in 1996 [1], PCFs found their way into a wide spectrum of applications like e.g. supercontinuum generation [2], endlessly single-mode fibers, zero-dispersion wavelength shifting towards the VIS [3] or sensing applications [4].

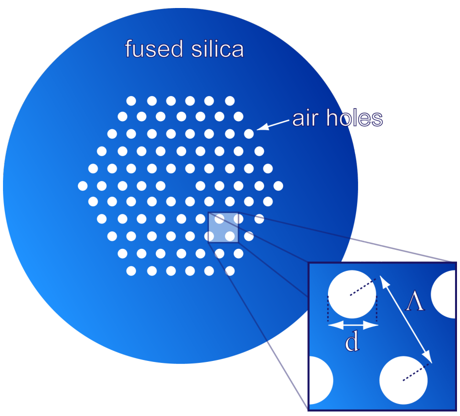

Fig. 1 *Cross section of a solid core photonic crystal fiber with hole diameter d and pitch Λ.*

The optical properties of PCFs can be modified in a wide range by just vary the geometrical parameters d and Λ. In this paper we will fix these but use another degree of freedom by successively increasing the refractive index of the holes from air ($n_{\text{fill}} = 1$) to that of the surrounding fused silica and above.

Practically this is done by filling the holes with liquids which have a refractive index which has a high temperature dependency of about $\frac{dn}{dT} = 4 \cdot 10^{-4}/$℃. These fluid filled photonic crystal fibers (ffPCFs) can be applied as sensor elements, the tuning of light propagation properties or the switching of guided light and spectral filtering.

2 Modeling

For our simulations we assumed a PCF with $\Lambda = 5.0\mu\text{m}$ and large diameter-pitch ratio of $d/\Lambda = 0.90$. The calculations were done with a commercial finite element method (FEM) software [5]. Due to symmetry reasons it is sufficient to calculate only one quarter of the PCF structure (see insets of fig. 2).

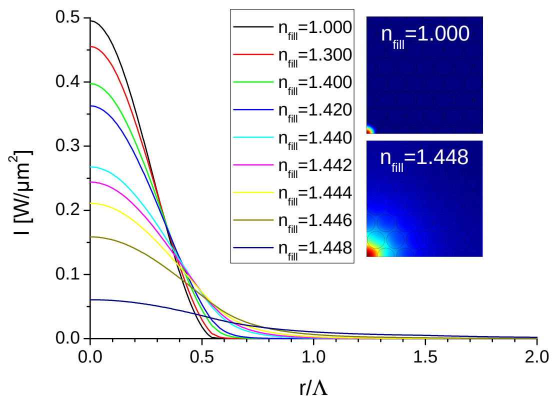

Fig. 2 *Cross section of intensity distribution along the x-axis of the fundamental core mode for different refractive indices inside the holes at $\lambda = 1000nm$. The refractive index of silica was taken as $n_{\text{SiO}_2} = 1.450$*

Figure 2 shows the calculated intensity distributions of the fundamental core mode at a fixed wavelength of $\lambda = 1000\text{nm}$. One can see that the mode field diameter (MFD) doesn't change significantly for $n_{\text{fill}} < 1.40$ but increases very strong if the refractive index of the holes converges to n_{SiO_2}. In case of exceeding this limit, no light can be confined in the core since the condition for total internal refraction is not given anymore. However, the cladding now works as an array of (coupled) waveguides itself and so the light can be confined in it. One can use this effect for in-fiber switching purposes.

Due to the wavelength dependent refractive indices of the fluid and silica, one can calculate the losses of the fundamental core mode that arise from the increasing MFD in a fiber with finite cladding. Figure 3 shows these losses for a refractive index oil filling ($n_D = 1.460$ @ 25 ℃) at 3 different temperatures. Since the refractive index of the silica core is larger than that of the ffPCF cladding only in a small wavelength range, one can see a combination of low and high pass filter effects whose cutoff wavelengths can be thermally tuned.

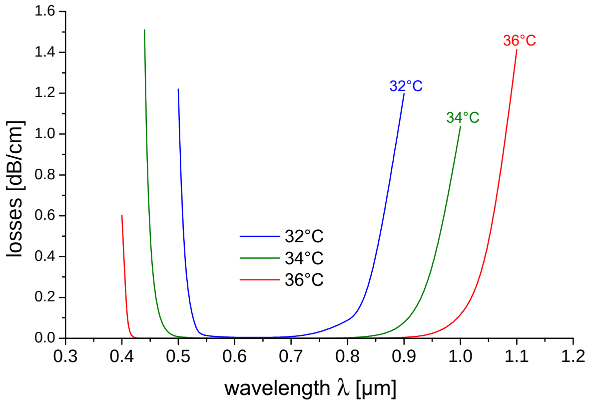

Fig. 3 *Losses of the fundamental core mode for different temperatures*

3 Experiments

The technique of filling holes of photonic crystal fibers with liquids is quite simple due to the use of capillary forces [6]. We filled the PCF over a length of 5 cm with the same refractive index oil as assumed in the simulations ($n_D = 1.460$ @ 25 ℃). To obtain best results, the absorption of the oil is small in the visible wavelength range.

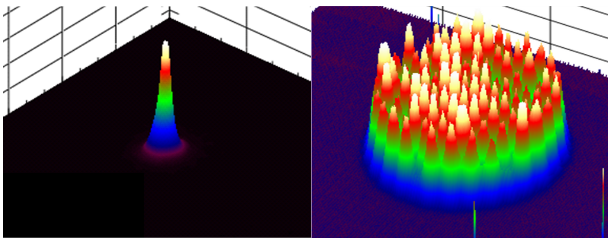

Fig. 4 *Near field images of a PCF with $n_{fill} < n_{SiO_2}$ (left) and $n_{fill} > n_{SiO_2}$ (right).*

Figure 4 shows two near field images of a ffPCF explaining the cases of light propagation in it. On the left, the refractive index of the core is larger than that of the ffPCF cladding and so a core mode can exist, whereas in the right image the cladding has a higher refractive index than the core and will act as waveguide. This confirms the switching process that was predicted in the numerical computations.

4 Conclusion

We showed a new way of manipulating the optical properties of a PCF after manufacturing in a quite simple matter. By introducing a dielectric liquid into the fiber holes one changes guiding characteristics of the PCF and obtains an optical switch and filter of the core intensity. We also have shown that these switches and filters are strongly temperature dependent.

References

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