Development of silicate hollow core photonic crystal fiber

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Abstract— In this paper we report on fabrication and characterization of a large core hollow core photonic crystal fiber. The fiber is designed and modeled using a finite element method taking into account material dispersion of the glass. A sodium-calcium silicate glass SK222 is used for photonic crystal fiber development. The hollow core is made by omitting 37 central capillaries and it has the diameter of 26 mm. The hexagonal photonic cladding is composed of 12 rings with the lattice pitch of 2.8 μm with the filling factor of 0.86. We have measured a large band gap in the range 560÷670nm with a center wavelength at 630 nm for the measured fiber.

Hollow core photonic crystal fibers (PCF) are one of the most interesting types of fibers with unique properties of light guidance in the air. A photonic band gap effect in the periodic structure of the photonic cladding allows light guidance in the low index core [1,2].

Hollow core PCFs allow a reduction of all phenomena related to the interaction between glass and light, since most of energy propagates in the air. Therefore dispersion, multiphoton absorption, Raman scattering and other nonlinear effects are dramatically reduced. A silica based hollow core PCF achieves a very low attenuation of 1.2 dB/km for 1.62 μm [3]. In this case 99,5% of energy in the fundamental mode propagates in the air. Further reduction of the attenuation to gain the attenuation level of standard telecommunication optical fibers at 0.1 dB/m is uncertain because surface modes are created at the glass-air border near the core. Since their propagation constants can be very similar to the fundamental guiding mode, the modes can be coupled and energy is transferred from the fundamental to the surface modes [4].

Hollow core PCFs made of soft glasses witness higher attenuation since the attenuation of glass itself is much higher. However, due to their higher refractive index they are attractive components from which to build a new type of devices infiltrated with polymer or liquids e.g. liquid crystals [5]. In this paper we present the development and characterisation of a hollow core PCF with a large hollow core based on silicate glass.

For the PCF fabrication a sodium-calcium silicate glass SK222 (68.4% SiO_2, 2.4%Al_2O_3, 2% B_2O_3, 12.3% Na_2O, 0.7% K_2O) is used. The SK222 glass is an ideal test bed material for the development of fabrication technology of soft glass based PCFs due to its low costs and very good rheological properties. On other hand, the attenuation in the glass as high as 15dB/m at λ=1,55μm. The properties of SK222 glass investigated by the differential thermal analysis are shown in Table 1.

Glass type	SK222
Refractive index n_D	1.520
Linear expansion coefficient for temperature range: 20÷450°C [$10^{-7}K^{-1}$]	89.0
Transition ttemperature Tg [°C]	542
Dylatometric softening temperature DST [°C]	610

Tab.1. Thermal properties of SK222 glass

A hollow core PCF labeled PBF3 is successfully fabricated using a stack-and-draw technique.

The structure of the fiber is designed as a hexagonal lattice with 31 capillaries on the diagonal. The hollow core is created by omitting 37 central capillaries. Therefore the photonic cladding is built by 12 rings of holes. The thickness of a glass layer surrounding the hollow core is decreased to a level of (Λ-d)/2 to reduce losses related to surface modes. The design of the fiber structure and cross section of a developed subpreform is presented in Fig. 1.

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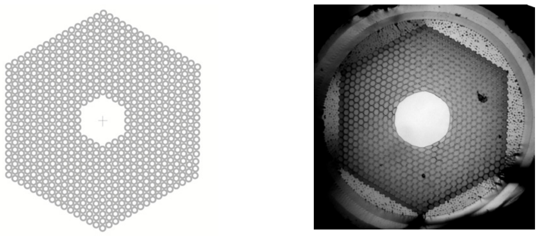
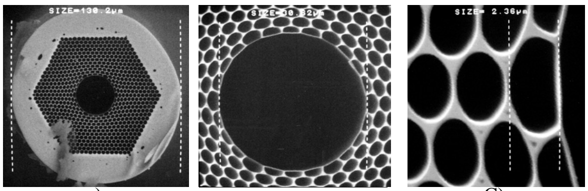


a) b)

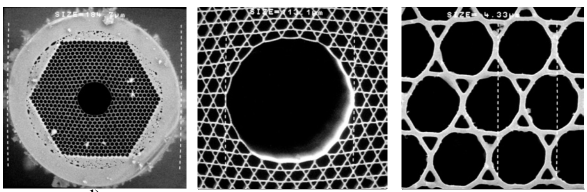
Fig.1. The hollow core fiber labeled PBF3. a) a design of the fiber structure, b) the cross section of the subpreform

A correct structure without deformations and brakes is achieved in the subpreform. Using this subpreform a few series of hollow core PCFs are drawn with a diameter in the range 120÷200μm (Fig.2 and Fig. 3). The technological challenge of this fabrication is related to influence control of drawing process parameters on a structure filling factor, holes and core sizes and regularity of the crystal lattice. The final PCFs have a regular structure and the filling factor in the range 0.84-0.93. The thickness of glass walls surrounding the hollow core is lower than that in the photonic cladding (Fig. 2c, 3c). The hexagonal and kagome lattices obtained are based on the same preform with various drawing conditions (Fig.2 and Fig. 3). The hollow core diameter is at the 30μm level for both types of lattices. The structure parameters of selected PCFs are presented in Table 2.



a) b) C)

Fig.2. Hollow core PCF with hexagonal lattice labeled PBF3A2: a) the cross-section of the fiber, b) the hollow core, c) the photonic cladding



d) e) f)

Fig.3. Hollow core PCF with kagome lattice labeled PBF3B1: a) the cross-section of the fiber, b) the hollow core, c) thephotonic cladding

The hollow core PCF PBF3A2 is further selected for optical characterization. A broadband supercontinuum is used as light source in the measurement setup. It covers range from 500 to 1100nm. A spectrum of this supercontinuum source is presented in Fig.4. The collimated supercontinuum beam is coupled into the hollow core PCF with a 40x microscope objective. The output signal is delivered to spectrometers (VIS and NIR range: 400-1100nm) by a multimode optical fiber. The measurement setup is presented in Fig.5.

	PBF3A2	PBF3B1
Fiber diameter [μm]	130	185
Diameter of photonic cladding [μm]	98-103	139
Core diameter [μm]	30-31	36.5
Wall thickness round the core [μm]	0,15-0,2	0,16-0,2
Walls thickness within photonic cadding (Λ-d) [μm]	0,22	0,4
The diameter of the holes (d) [μm]	2,75	3.93
Lattice constant (Λ) [μm]	2,97	4.33
Filling factor (d/Λ)□	0,93	0,91

Tab.2. Geometrical parameters of PBF3 hollow core PCFs.

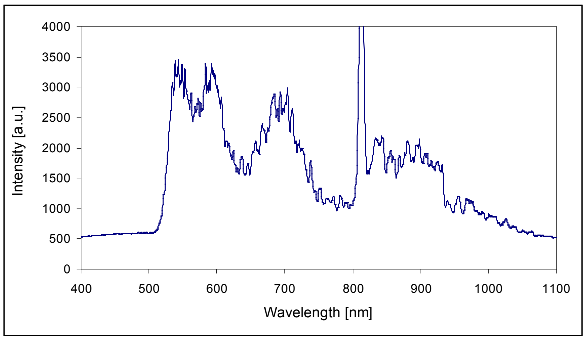


Fig.4. A spectrum of the supercontinuum source used in the experiment setup. A high pick for λ=805nm denotes a pump peak.

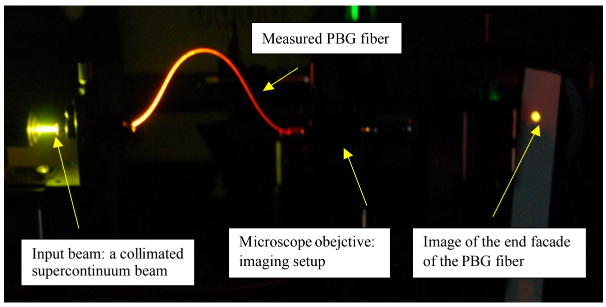


Fig.5. The setup for transmission and attenuation measurements in the hollow core PCFs.

An imaging system composed of a microscope objective and magnifying lens is built behind the hollow core fiber. The system allows observing a near-field distribution at the end facet of the fiber and is used for the optimisation of fiber coupling. With the imaging system we can actively align the fiber with respect to the laser beam to selectively couple light into the core without excitation of the fiber cladding (Fig. 6).

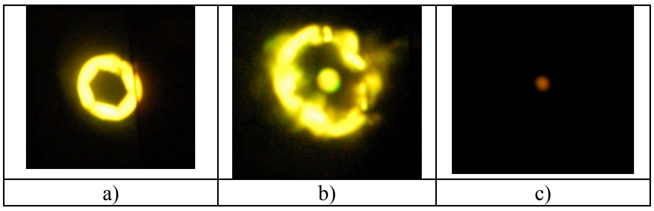


Fig.6. Alignment procedure for transmission measurement in the hollow core PCFs. The near field distribution and the end facet of the hollow core fiber PBF3A2.: a): step1: light is coupled into the fiber cladding, b) step2: light is coupled into the fiber cladding and the hollow core, c) step 3 : light is coupled into the hollow core.

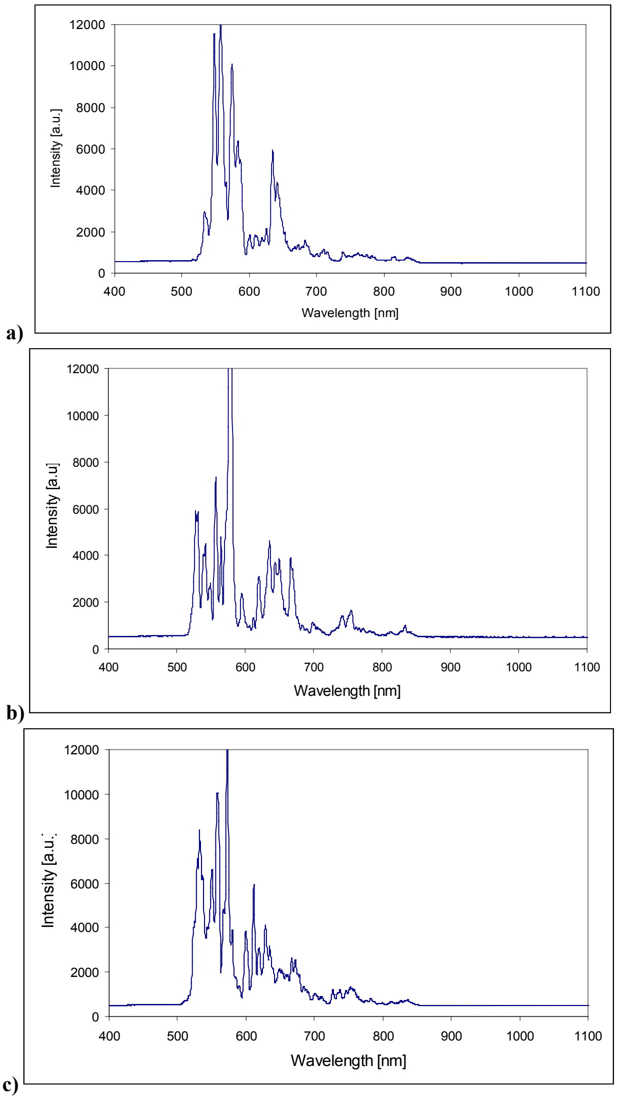


Fig.7. Measurements of transmission spectra in a hollow core of the PBF3A2 fiber. For different lengths: a) 103 cm, b) 38 cm, c) 32cm.

Measurement results of transmission of the broadband spectrum in PBF3A2 fiber are shown in Fig.7. The guidance of light in the range 560-670nm is observed in a fiber sample 103cm long. Similar spectra ranges are also registered for shorter samples – 38 and 32cm. The constant range of guided spectra demonstrates the position of a photonic band gap and good homogeneity of the fabricated structure. The experimental results are in good agreement with the modeling of the considered fiber performed with the finite element method (Fig. 8).

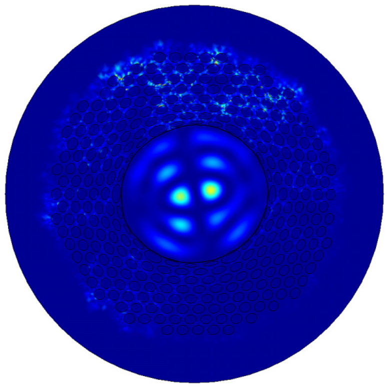


Fig.8. Calculated intensity distribution in the hollow core PCF PBF3A2 at λ=635 nm.

The transmitted spectra are measured for a different length of the fiber sample with the same coupling conditions. Using cut-back technique attenuation of 2.1dB/m is defined. This value is very high with respect to reported pure silica hollow core PCFs [3]. However, it is drastically smaller than the attenuation of bulk SK222 glass used for the PCF fabrication and proves good light confinement in the air core and week coupling to the surface modes..

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