Fabrication of the hollow all-polymer Bragg fibers

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Abstract *Drawing of the PMMA/PS and PVDF/PC based, hollow all-polymer Bragg fibers are demonstrated. Effects of core collapse and multilayer nonuniformity on fiber transmission are considered. Non-newtonian dynamics modelling of Bragg fiber drawing is performed.*

Introduction

Hollow core multilayer and microstructured optical fibers (MOF) for radiation guiding in the near and mid-infrared (IR) [1-9] have recently received close attention as they promise considerable advantage over their solid core counterparts in applications related to power guidance at almost any IR wavelength for military, industry and medical applications, IR imaging and sensing, and even THz transmission. Due to its complexity, fabrication of such waveguides remains an active field of research.

Polymer Bragg fiber fabrication

In our research group we study fabrication of all-polymer hollow multilayer fibers. Although refractive index contrast between layers in an all-polymer Bragg fiber is relatively small (at most 1.3/1.7), as demonstrated in [10] liquid core all-polymer Bragg fibers can be designed to guide very well both TE and TM like modes, while gas filled all-polymer Bragg fibers can guide effectively a TE polarized mode. We believe that fabrication simplicity, and potential bio-compatibility of such fibers can be attractive for applications in bio-medical sector. Recently, we have succeeded in developing two methodologies for fabrication of multilayered all-polymer hollow performs and fibers. One approach uses consecutive deposition of layers of two different polymers by solvent evaporation on the inside of a rotating polymer cladding tube. Orthogonal solvents were found, and solvent evaporation process was developed for both PMMA/PS(Polystyrene) and PVDF/PC(Polycarbonate) material combinations. In the left of Fig.1(a), a 30cm long preform with 10 consecutive PMMA/PS layers deposited on the inside of a PMMA cladding tube is presented; on the right, preform crossection is shown. In the left of Fig.1(b), again a 30cm long all-polymer preform with 15 consecutive PVDF/PC layers deposited on the inside of a PC cladding tube is presented; while on the right, preform crossection is shown. Alternative preform fabrication method uses a co-rolling of two dissimilar polymer films similarly to [9], where both commercial and home-made films were used. In the left of Fig.1(c), an end part of an all-polymer preform with 19 consecutive PVDF/PC layers is presented; in the middle of the figure a crossection of a drawn fiber is shown with a drawdown ration of 1:20; finally in the right of Fig.1(c) another drawn fiber with 32 layers PMMA/PS layers is demonstrated.

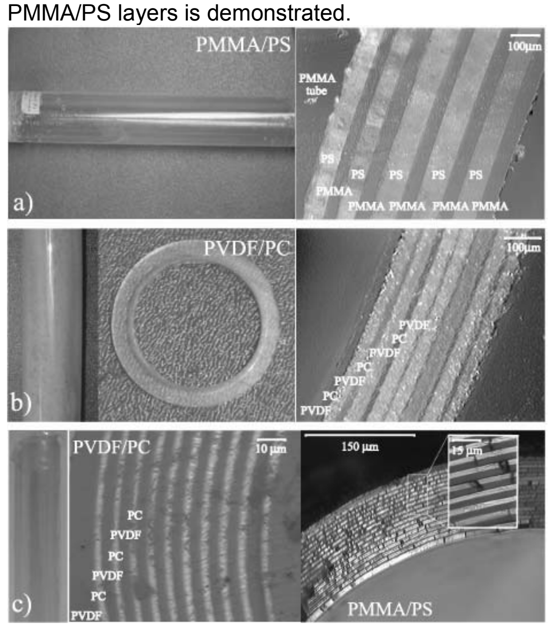

Fig.1 a) Left - preform with 10 consecutive PMMA/PS layers deposited on the inside of a PMMA cladding tube. Right - preform crossection. b) Left - preform with 15 consecutive PVDF/PC layers deposited on the inside of a PC cladding tube. Right - perform crossection c) Left - rolled 19 layer PVDF/PC preform. Middle - crossection of a drawn PVDF/PC fiber. Right - crossection of a drawn PMMA/PS fiber.

Effect of core collapse on fiber transmission

For the problem of hollow Bragg fiber drawing, geometries of all the resultant fibers can be simply parametrized by only two parameters – a drawdown ratio, and a core collapse parameter. We further demonstrate that fiber transmission properties depend strongly on a core collapse parameter which can only be controlled indirectly during drawing process. In [11] we modelled non-Newtonian fluid dynamics of multilayer polymer Bragg fiber drawing and established that hole collapse can be effectively controlled by such parameters as temperature distribution in a furnace, fiber drawing and preform feed velocities, as well as pressurization of the hollow core. Moreover, if several materials are used in a preform, hole collapse can be controlled by the mismatch in the material viscosities. In what follows we discuss the effect of a hole collapse on the transmission properties of a hollow Bragg fiber.

Core collapse and draw induced non-uniformity of a multilayer reflector have direct impact on the transmission properties of a hollow photonic crystal fiber. We define r^f_i and r^f_o to be the inside and outside radii of a hollow Bragg fiber (insets in Fig.2), while r^p_i and r^p_o are the corresponding radii of a hollow preform. The first parameter that relates preform and fiber dimensions is a drawdown ratio D which is defined as a ratio of the outside preform diameter to that of a fiber $D=r^p_o/r^f_o$. Drawdown ratio can be set during drawing process. The second parameter characterizes hollow core collapse in a fiber as compared to a preform, and is defined as $C_r=(r^f_i/r^f_o)/(r^p_i/r^p_o)$. Thus, $C_r=0$ signifies that during drawing, fiber core collapseds completely resulting in a solid core fiber; while $C_r=1$ signifies that there is no core collapse and all the fiber dimensions can be calculated from the corresponding perform dimensions by a simple division by a drawdown ratio. Given these two drawing parameters and assuming that all the materials in a melted state are incompressible fluids, then a circular contour of radius r^p in a preform translates into a circular contour of radius r^f in a fiber, and they are related by:

$$\left(r^f\right)^2 = \left(\frac{r^p}{D}\right)^2 - \left(1-C_r^2\right)\left(\frac{r_i^p}{D}\right)^2 \frac{\left(r_o^p\right)^2-\left(r^p\right)^2}{\left(r_o^p\right)^2-\left(r_i^p\right)^2}$$

To understand the effect of a core collapse on the transmission properties of the resultant fibers, in Fig.2 we present a set of theoretical curves showing radiation losses of the TE_{01} core modes for the fibers drawn with different values of C_r, while featuring the same outside diameter r^f_o. In this example, $C_r=1$ corresponds to a target hollow core fiber with a strictly periodic 15 layer quarter-wave reflector having material refractive indexes $n_h=2.0$, $n_l=1.5$ and thicknesses d_h^t =144nm, d_l^t =224nm. Target fiber inside and outside radii are chosen to be $r^{ft}_i=5\mu m$, $r^{ft}_o=12.72\mu m$. By design, such a fiber has a large band gap centered at $\lambda^t_c=1\mu m$.

In the presence of a core collapse $C_r<1$ (assuming the same value of a drawdown ratio D) two major changes in the fiber geometry happen. First, while the outside fiber radius is fixed r^{ft}_o, the fiber core radius is reduced $r^f_i=r^{ft}_i C_r$. Second, it can be shown that thicknesses of the reflector layers become non-uniform, increasing towards the fiber core, while, on average, layer thicknesses increase as $d_{h,l}\sim d^t_{h,l}/C_r$. These geometrical changes can significantly modify fiber transmission spectra.

As the center wavelength of a photonic bandgap λ_c is proportional to the average reflector layer thickness, then, in the presence of a core collapse, λ_c is expected to shift to the longer wavelengths $\lambda_c\sim\lambda^t_c/C_r$ (Fig.2), with a relative bandgap size almost unaffected. Another prominent effect of a core collapse is on the core mode radiation losses. Radiation losses of the bandgap guided core modes scale as $(\lambda_c)^{p-1}/(r^f_i)^p$, where exponent *p* equals 3 for the TE_{0n} modes, while for the other modes it is in the range [1,3]. Thus, in the presence of a core collapse, due to reduction of the core radius, and due to shift in the center of a bandgap, we expect core mode radiation loss to increase as $Loss\sim C_r^{-(2p-1)}$, which for TE_{01} mode gives $Loss\sim C_r^{-5}$. From detailed simulations we find that for TE_{01} mode, scaling exponent varies between -5 when $C_r\sim1$ and -7 when $C_r\sim0.5$ signifying additional degradation of modal confinement due to nonuniformity in the reflector layer thicknesses.

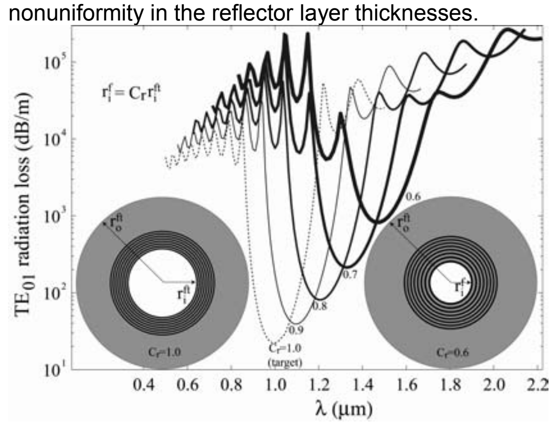

Fig.2 Radiation loss of the bandgap guided TE_{01} core modes for the fibers with different core collapse ratios C_r, while the same outside radii r^{ft}_o. Core collapse leads to the shift of a bandgap center into the longer wavelength, as well as to a considerable increase in the modal radiation losses.

From the analysis above it follows that core collapse leads to the shift of the bandgap center frequency to the longer wavelengths, and a superlinear increase in the radiation losses of the core guided modes.

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