

## Negative curvature hollow core fibers for Raman lasing in the mid IR spectral range

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**Abstract.** In this paper we consider a problem of using negative curvature hollow-core fibers for creation of Raman lasers in the mid IR spectral range. New designs of this type of fibers with cladding formed by one layer of double nested capillaries are discussed and their optical properties are investigated numerically and experimentally. It will be shown that it is possible to reduce the Raman generation threshold by decreasing an effective mode area in such fibers using nested capillaries in the cladding.

### 1. Introduction

Gas lasers based on negative curvature hollow-core fibers (NC-HCFs) have many advantages over traditional gas cells, for example, the long interaction length, high efficiency, low threshold. Moreover, the size of such laser systems can be reduced to a great extent compared with other types of the gas cells and damage threshold and nonlinear limits of hollow-core fibers (HCFs) are much higher compared to usual solid fibers.

As it is known the first fabricated microstructured HCF was hollow core photonic crystal fiber (HC-PCF) [1]. Several years ago a new type of HCF was proposed and fabricated in several laboratories [2], [3], [4], [5]. The key feature of these HCFs was so called ‘negative curvature’ (NC) of the core – cladding boundary (when the normal vector to the inner surface of the core – cladding boundary is oppositely directed to a radial unite vector). Such design of the core – cladding boundary allowed to localize 99.993% of the air core mode radiation in the air [6]. Due to very weak interaction of the air core modes with the core – cladding boundary NC-HCFs have dispersion curves with very low slopes and values [7]. At the present time, there are several well known types of NC-HCFs, namely, revolver NC-HCF - fibers with cladding consisting of one row of capillaries [4], NC-HCF with elements in cross – section in the form of ‘ice cream cone’ [5] and hypocycloid-core Kagome lattice hollow core fiber [3]. The strong localization of the radiation in the NC-HCFs made of silica glass compared to HC-PCFs allowed to transmit light in the mid IR spectral range where material loss of silica glass is very high[8]. Moreover, the strong light localization in the NC-HCF air core allows to transmit high power radiation [9].

Mid-infrared spectral region (mid-IR) is very interesting for development of a new laser technologies. Different laser sources can operate in this spectral range such as quantum cascade lasers



or systems based on nonlinear conversion. But unlike these laser sources, gas hollow core fiber lasers much more robust and have tremendous potential for scalability in power and wavelength in the mid-IR.

Stimulated Raman scattering in HC-PCF was firstly reported in [10]. A Raman laser based on NC-HCF was firstly reported in [11]. In this work stimulated Raman scattering (SRS) at 1.9  $\mu\text{m}$  was generated in a 6.5 m long hydrogen-filled at 23 bars NC-HCF, pumped by a 1064 nm microchip laser. 1500 W peak power of pure vibrational Stokes SRS at 1907 nm was measured with a corresponding quantum conversion efficiency above 48 %. Another Raman laser based on NC-HCF filled with hydrogen with higher pump-to-Stokes conversion quantum efficiency 60% was demonstrated in [12]. In this work the steady-state (pump pulse  $\tau = 125$  ns) 1.06-1.9  $\mu\text{m}$  SRS conversion in a hydrogen-filled revolver-type hollow-core fiber was demonstrated. The average output Stokes power was 330 mW, corresponding to 3 kW of peak power at a Stokes pulse duration of 93 ns.

It worth noting, that mid-IR radiation can be generated also using stimulated transitions in gas-filled HCFs. In [13] 3.1-3.2  $\mu\text{m}$  mid-infrared emission with in the single pass of silica revolver NC-HCF filled with acetylene gas was reported. The maximum power conversion efficiency of the single-pass amplified spontaneous emission (ASE) was approximate 30%, with respect to the absorbed pump power in a 10.5 m length of fiber at pressure of 0.7 mbar. The minimum pump pulse energy required was less than 50 nJ (pump pulse duration  $\tau = 20$  ns). Also 3.1-3.2  $\mu\text{m}$  mid-infrared gas laser based on two types of NC-HCFs filled with acetylene with a ring cavity was demonstrated in [14].

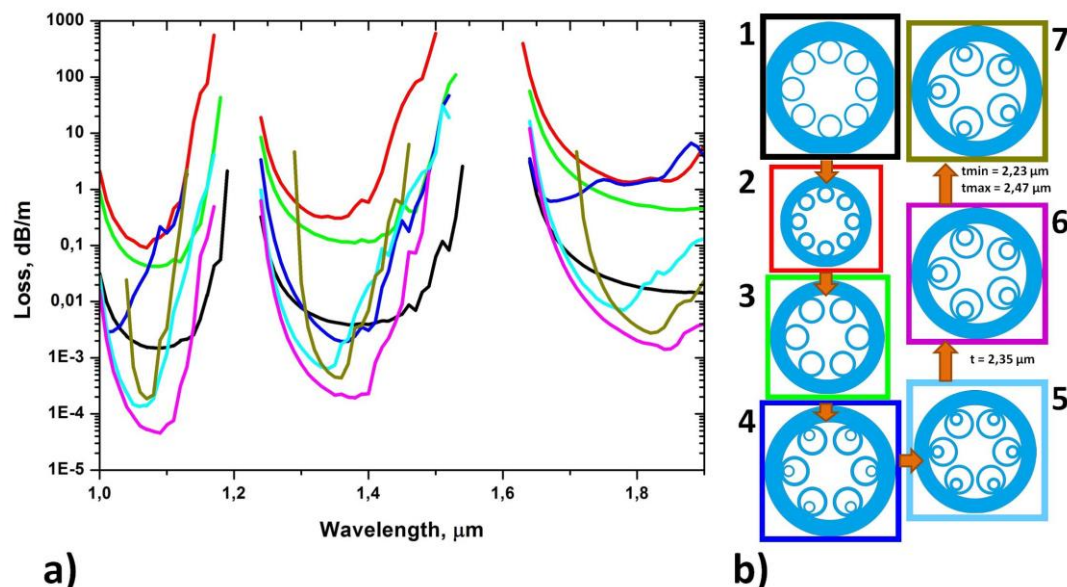
Traditional electrical gas discharge for gas lasers are also being explored in gas laser with NC-HCF filled with Helium-Xenon[15].

## 2. Comparison of different structures

The aim of this work is the development and creation of the hollow-core fiber for efficient Raman conversion of laser radiation in gas-filled hollow core. Problems related to non-linear effects require a high-intensity radiation. One way to increase the radiation intensity in case of using hollow-core fibers is to decrease diameter of the hollow core and, respectively, decrease the effective mode area. It is known that waveguide losses in the hollow-core fibers (like inset b1 in Fig. 1b) depend on core diameter approximately at least as  $D^{-4}$  [16], i.e. reduction of the hollow-core diameter strongly increase the waveguide losses. Accordingly, the authors had to compare different variants of the hollow fiber cross-section structures to select one that would ensure a minimum level of the waveguide loss with reducing the effective mode area. Since the experimental search of the optimal design is very complex, initially numerical simulation of the most promising designs was conducted. We used the finite-element method (Comsol Multiphysics) to perform our numerical analysis.

As a starting point in our analysis, we used structure of a revolver NC-HCF (revolver fiber 1 – RF1) in which we had already achieved an efficient Raman conversion [12]. Cladding of RF1 consists of eight capillaries, the core diameter is 57  $\mu\text{m}$  (Fig. 1b1), the loss at 1.06 and 1.9  $\mu\text{m}$  was found to be 0.25 and 0.1 dB/m respectively (Figure 1a, black line). Simple reduction of the fiber core diameter to 29  $\mu\text{m}$  with the same number of capillaries (Fig. 1b2) leads to a significant increase in the waveguide loss (Fig. 1a, red line). Reducing the number of capillaries to six with the same diameter of the hollow core leads to a slight reduction of the level of losses (Fig. 1a, green line), but their level is still significantly higher than in the original fiber (Figure 1a, black line). Further reduction of losses in such a structure with the same diameter of the hollow core is possible if its cladding will consist of double nested capillaries as was proposed and made in [17], thoroughly discussed in [18] and made in [19]. Maximal distance between inner and outer capillaries (distance between capillaries' walls in radial direction) should be approximately a half of the core diameter[18]. We used approximately the same values of this parameter in structures of computational and real experimental fibers. For convenience of manufacturing, it is desirable that the thickness of the internal capillary wall would be twice thinner than the external capillary wall (Fig. 1b4). The loss spectrum of such optical fiber was calculated.

As it can be seen from Fig. 1a (dark blue line), loss spectrum of this optical fiber is strongly distorted and has areas with both lower and higher losses compared with the loss spectrum shown in Figure 1a, green line. Such a distortion, obviously, occurs due to appearance of additional resonant electromagnetic field states excited in the walls of internal capillaries and shift of the boundaries of their transmission bands with respect to the transmission bands of the outer capillaries. Thus, to match their transmission bands it is necessary to match their thickness. Loss spectrum of a fiber with six double nested capillaries with the same wall thickness is shown in Fig. 1a, blue line. It was observed that a decrease in the number of capillaries in this case leads to a reduction of loss level. The loss spectrum of hollow-core fiber with a core diameter of  $29\text{ }\mu\text{m}$  and five double nested capillaries in the cladding (Fig. 1b6) is represented in Fig. 1a, purple line. Optical loss in this fiber around the considered spectral region is lower than in the case of the fibers mentioned above. Moreover, its loss on the average is much lower than the losses in the original fiber with a core diameter of  $57\text{ }\mu\text{m}$ . Thus, such fiber structure allows to reduce by half the core diameter and keep the total loss at an acceptable level.



**Figure 1.** a) optical losses calculated for different fiber cladding structures shown in b); b) different fiber cross-sections and the order of calculation. The color of the frame corresponds to the color of the line in the graph. In cross-section b1 –  $D_{out}=155\text{ }\mu\text{m}$  (outer diameter of the fiber),  $D_{core}=57\text{ }\mu\text{m}$ . In cross-sections b2-b7 –  $D_{core}=29\text{ }\mu\text{m}$ .

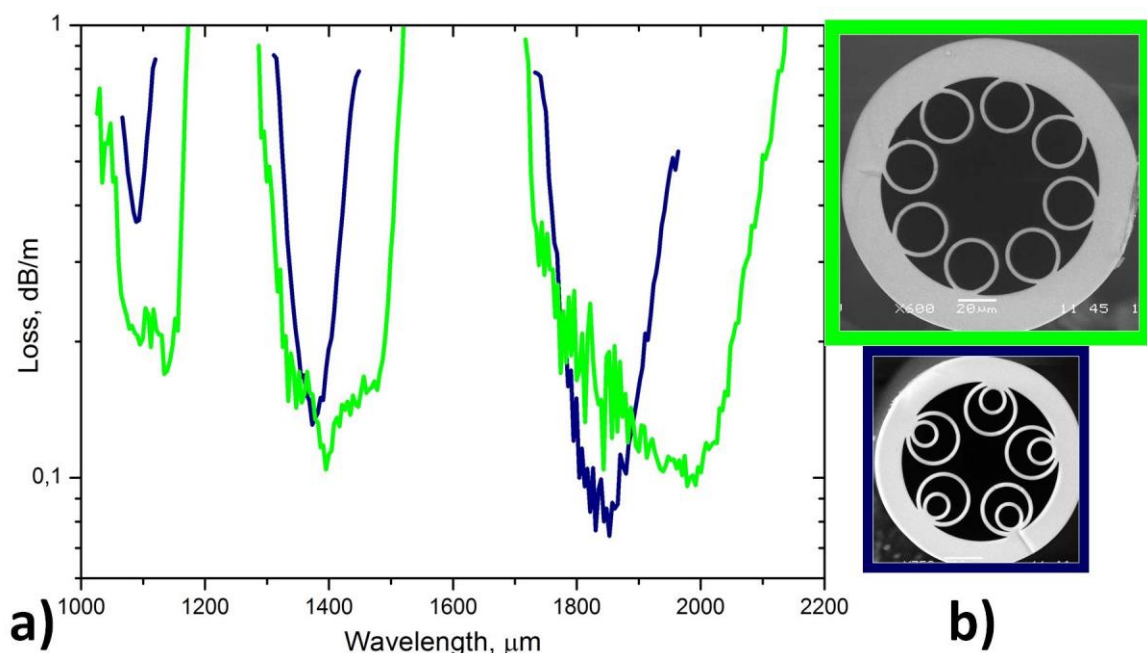
However, the optical loss in real fibers is always higher than the calculated one. This is due to the fact that the cladding structure of the real fiber is changed during the drawing process and become different from the ideal used in the calculations (wall thickness of the capillary and distance between them varies, cross-section of the capillary differs from a circle). Because it is important to analyze in what extent the losses of the selected structure are sensitive to deviations of cladding geometrical parameters mentioned above, we tried to take account of these factors in the calculations.

We identified the variations in the fiber cladding geometrical parameters by careful analysis of the cross-section of the real fibers. However, our model only takes into account variations over the cross section and does not account variations in the length, which also occur in the drawing process and also increase the loss level. The resulting loss spectrum of fiber with non-ideal cladding and its cross section are shown in Fig. 1a, olive line and Fig. 1b7 respectively. As can be seen from the graph, the introduction of inhomogeneities in the structure increases the level of losses and makes the transmission bands narrower, but wavelengths we are interested in ( $1.06$  and  $1.9\text{ }\mu\text{m}$ ) are still fall into the transmission bands and its losses are approximately the same level as that in the original fiber (Fig. 1a, black line).

On the basis of the calculation given above, corresponding preform was assembled and drawn. The loss spectrum and cross-section of the resulting revolver fiber (RF2) are shown in Fig.2 (Fig. 2a, dark blue line and 2b in dark blue frame). The cladding of RF2 is comprised of five double nested non-touching capillaries, the core diameter is  $D_c = 25 \mu\text{m}$ , the outer diameter of the fiber is  $110 \mu\text{m}$ , outer diameter of the large and small capillaries 29 and  $15 \mu\text{m}$  correspondently, the average wall thickness of the capillaries is  $2.3 \mu\text{m}$ . SEM image of a cross section of RF2 is shown in Fig. 2b in dark blue frame. Fiber losses were measured by «cut-back» method using a fiber piece of 57 m length. The measurements were carried out using monochromator, a source of supercontinuum radiation (Fianium) was used as a light source and InGaAs detector was taken as a detector.

Loss measured in real fiber was higher than loss calculated for model of this fiber in which the non-ideal structure was taken into account. We attribute this to the fact that fiber cladding can also has non-uniformity in length, that increase the level of losses but which are difficult to take into account in the calculations. In addition, uncontrolled excitation of higher modes is possible in method used for loss measurements, which can also lead to higher values of losses.

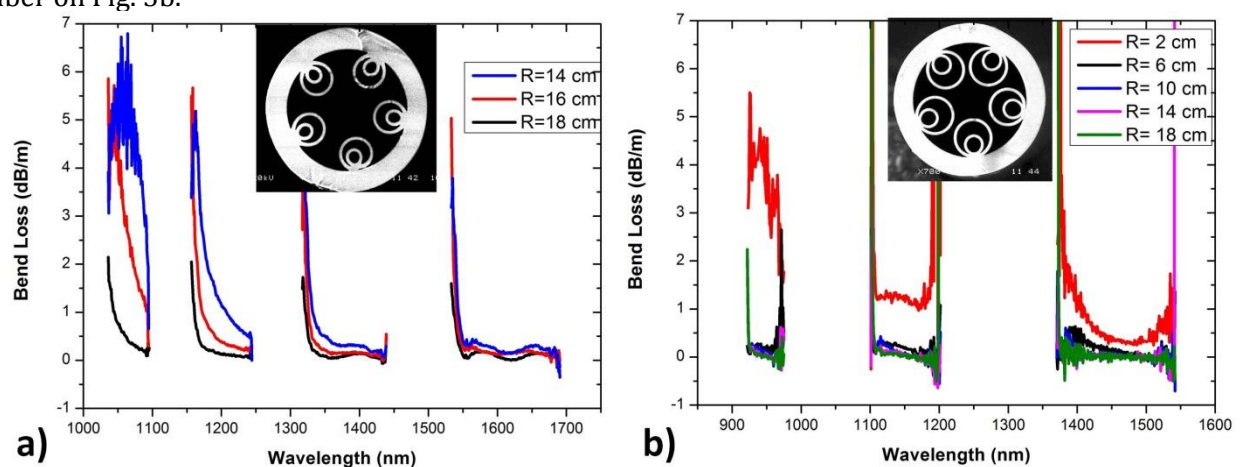
It is interesting to compare the spectra of optical loss of two hollow-core fibers: with double nested capillaries in the cladding (RF2 in Fig. 2b, dark blue frame) and fiber with a single layer of capillaries in the cladding (RF1 in Fig. 2b, green frame). The capillaries wall thicknesses in both fibers are close (about  $2.3 \mu\text{m}$ ) and positions of their bandwidths are approximately the same (Fig. 2a). Their minima optical losses are also close:  $\sim 100 \text{ dB/km}$  at a wavelength of about  $2 \mu\text{m}$  in RF1 and  $74 \text{ dB/km}$  at a wavelength of 1.8 microns in RF2. But core diameter of RF2 is  $25 \mu\text{m}$  what is more than two times smaller than the core diameter of RF1 ( $57 \mu\text{m}$ ). According to estimations given in [16], with this reduction of the core diameter, loss in the hollow-core fiber with one layer of single capillaries in the cladding (revolver NC-HCF) would become  $\sim 27$  times higher. Therefore, the introduction of double nested capillaries allows to significantly reduce the effective mode area without significantly increasing of the optical loss.



**Figure 2.** a) measured loss spectra for revolver NC-HCFs with single (RF1) and double nested capillaries (RF2). b) SEM images of the corresponding fibers( in one scale). Green frame - revolver NC-HCF (RF1) with single capillaries in the cladding,  $D_{\text{core}}=57 \mu\text{m}$ ; dark blue frame - revolver NC-HCF(RF2) with double nested capillaries in the cladding,  $D_{\text{core}}=26 \mu\text{m}$ [19]. The color of the frame corresponds to the color of the line in the graph.

### 3. Bend loss

To measure and compare bend loss we used two different revolver fibers with double nested capillaries in the cladding (not the same as above). Transmission under different bend radii was measured for both fibers (Fig. 3). For the experiment 5 meter long fiber was taken and 4 meter of the fiber was always under bend. Halogen lamp was taken as a light source and a spectrum analyzer as a light detector. Measurements were carried out with fibers with five capillaries in the cladding. First one (RF3) has core diameter 50  $\mu\text{m}$  and the capillary wall thickness 3.7  $\mu\text{m}$ , second one (RF4) has core diameter 30  $\mu\text{m}$  and the capillary wall thickness 2.6  $\mu\text{m}$ . Figure 3 shows a strong difference in the bend losses between two fibers. Such a strong difference arises due to difference in the core diameter, capillary wall thickness and probably because of different gap between double nested capillaries. Bend losses increase with increase of order of the resonance in the capillary wall. In the fiber on Fig. 3a order of this resonance higher than in the fiber on Fig. 3b.



**Figure 3.** Measured bend loss spectra for two different revolver fibers (RF3 and RF4) under different bend radii. a) measured bend loss spectra for RF3; b) measured bend loss spectra for RF4 (curves for R=18,14,10 cm are coincide). Insets – SEM images of the according fibers.

### 4. Conclusions

In conclusion, we investigated optical properties of several negative curvature hollow core fibers to obtain an optimal geometry of the cross-section for Raman lasing at the Stokes wavelength  $\lambda = 1.9 \mu\text{m}$ . It was shown that minimal total loss level can be obtained for the revolver negative curvature hollow core fiber with double nested capillaries and with uniform thickness of the cladding capillaries walls. Such fiber allows to achieve a low value of the effective mode area at the pump and 1-st Stokes wavelengths compared with the conventional design of the revolver fiber with single capillaries and strong resistivity to the bending. Our investigation have demonstrated that the negative curvature hollow core fibers have great potential for laser applications in the mid IR spectral range.

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