

HOLLOW CORE OPTICAL FIBER AND A LASER SYSTEM

TECHNICAL FIELD

- 5 The invention relates to a hollow core photonic crystal fiber and a laser system comprising such hollow core optical fiber.

BACKGROUND ART

- Hollow core photonic crystal fibers (PCF) have been known for many years and in some applications are very attractive to use compared to solid core
10 PCF due to their very low propagation loss, low nonlinear effects and high damage threshold.

- A hollow-core fiber is an optical fiber which guides light essentially within a hollow region, so that only a minor portion of the optical power propagates in solid fiber material surrounding the core. The hollow region may be filled with
15 air or any other gas or it may be evacuated to have a very low gas pressure.

Over the years several types of hollow core PCFs have been developed, such as hollow-core photonic bandgap fibers e.g. as described in US 6892018, Kagome design type fibers e.g. as described in US 8306379.

- The kagome type fiber guides light by means of an anti-resonant effect and
20 allows for a substantially broader spectral transmission than that achieved in photonic bandgap fibers.

In recent years such hollow core anti-resonant fibers (ARFs) have been studied intensively in particular with the aim of further improving the fiber with respect to low loss and broad spectral transmission.

- 25 In an attempt to reduce the attenuation Kolyadin et al, Optics Express, Vol 21, pages 9514 to 9519, 2013 suggested a hollow core fiber with a hollow core surrounded by eight identical capillaries. It was concluded that to reduce loss,

a larger core size is preferred and by increasing the number of capillaries in the cladding a reduced loss could be achieved.

Another drawback of prior art hollow core anti-resonant fibers is that they are not purely single mode waveguides because they also support some higher-order modes (HOMs). Since these HOMs often have a relatively low loss, it is very difficult to launch a pure LP₀₁ mode without HOM contamination and further HOMs can be excited by bending or external stress.

In an attempt to solve this problem and to achieving the highest possible suppression of HOMs while maintaining a reasonably low loss for the LP₀₁ mode, a modified fiber design was suggest in "Broad-band robustly single-mode hollow-core PCF by resonant filtering of higher order modes" by Günedi et al., Cornell university library arXiv:1508.06747 [physics.optics], 27 Aug 2015. The ARR fiber described in this article comprises a central hollow core (inner diameter D) surrounded by six evenly spaced and non-touching capillaries (in the following also called hollow tubes) with a wall thickness t and an inner diameter d, supported within a thick-walled supporting capillary. The non-touching glass elements had modes which were tailored to ensure resonant phase-matched coupling to higher-order core modes, causing them to leak at a very high rate into the supporting solid glass sheath. It was found that extremely high suppression of HOMs could be achieved over broad wavelength bands where the fiber guides with a low loss, provided the ratio $d/D \approx 0.68$ and the walls of the tubes walls T were thin enough i.e. $t/D = 0.01$.

WO15185761 describes a similar anti-resonant hollow-core fiber comprising a first tubular, cladding element which defines an internal cladding surface, a plurality of second tubular elements which are attached to the cladding surface and together define a core with an effective radius, the second tubular elements being arranged in spaced relation and adjacent one of the second tubular elements having a spacing there between, and a plurality of

third tubular elements, each nested within a respective one of the second tubular elements. It was concluded that the optimal number of tubes for suppressing HOMs was six.

DESCRIPTION OF THE INVENTION

- 5 The object of the invention is to provide a hollow core PCF which alleviates at least one of the drawbacks described above.

In an embodiment it is an object to provide a hollow core PCF which has a high spectral transmission and a high suppression of HOMs.

- 10 In an embodiment it is an object to provide a hollow core PCF which has a high single mode transmission efficiency and is substantially insensitive to bending.

- In an embodiment it is an object to provide a hollow core PCF which in a simple way can be designed to have a desired low loss transmission band with a bandwidth of at least about 50 nm and preferably with a transmission
15 loss of less than about 50 dB/Km.

In an embodiment it is an object to provide a hollow core PCF which has a transmission band comprising wavelengths in the range of from about 400 nm to about 1200 nm.

- 20 These and other objects have been solved by the invention or embodiments thereof as defined in the claims and as described herein below.

It has been found that the invention or embodiments thereof have a number of additional advantages which will be clear to the skilled person from the following description.

- 25 The phrase "radial distance" means distance determined in radial direction from the center axis of the hollow core. The phrase "radial direction" is a direction from the core center axis and radially outwards.

The term “substantially” should herein be taken to mean that ordinary product variances and tolerances are comprised.

5 The term “about” is generally used to include what is within measurement uncertainties. The term “about” when used in ranges should herein be taken to mean that what is within measurement uncertainties are included in the range.

10 It should be emphasized that the term “comprises/comprising” when used herein is to be interpreted as an open term, i.e. it should be taken to specify the presence of specifically stated feature(s), such as element(s), unit(s), integer(s), step(s) component(s) and combination(s) thereof, but does not preclude the presence or addition of one or more other stated features.

Throughout the description or claims, the singular encompasses the plural unless otherwise specified or required by the context.

15 Diameters, thickness and other structural values are seen in a cross sectional view of the hollow core PCF unless otherwise specified or clear from the context.

20 The hollow core photonic crystal fiber (PCF) according to an aspect of the invention comprises an outer cladding region and 7 hollow tubes surrounded by the outer cladding region each of said hollow tubes having an average outer diameter d_2 and an average inner diameter d_1 . Each of the hollow tubes is fused to the outer cladding to form a ring defining an inner cladding region and a hollow core region surrounded by the inner cladding region. The hollow tubes are not touching each other, wherein said average outer tube diameter relative to a core diameter D of the hollow core region d_2/D is from 25 0.5 to 0.75, and wherein all of the hollow tubes are free of a nested sub tube. It has been found to be advantageous for suppressing of undesired higher order modes that the hollow tubes each has an average outer diameter which is referred to as d_2 and an average inner diameter which is referred to as d_1 . The ration d_1/d_2 is equal to or larger than about 0.8.

30 The average outer diameter d_2 and/or the average inner diameter of the respective hollow tubes may be equal or different from hollow tube to hollow tube.

In an embodiment d_1 and/or d_2 is/are substantially identical for at least three of the hollow tube, such as for all of the seven hollow tubes.

According to embodiments of the invention and against all teaching of prior art hollow core PCF it has surprisingly been found that a hollow core PCF with
 5 a non-touching inner cladding structure where there are seven non-touching tubes may provide a highly increased suppression of higher order modes (HOMs) than the above described hollow core PCF with six 6 non-touching inner cladding tubes. In particular – and as shown in the example – it has been found that the hollow core PCF of the invention with seven non-touching
 10 tubes has an increased suppression of HOMs with azimuthal number above 1, such a third order HOMs while simultaneously having low loss in the fundamental mode of at least a transmission band below $2\text{ }\mu\text{m}$, preferably below $1.5\text{ }\mu\text{m}$.

The term “transmission band” is herein used to mean a band with a
 15 bandwidth of at least about 10 nm, such as at least about 25 nm and preferably at least about 50 nm or even at least about 100 nm of transmission wavelength.

The term “low loss transmission band” means a transmission band for light in its fundamental mode with a transmission loss of less than about 100 dB/km,
 20 preferably less than about 60 dB/km and more preferably less than about 50 dB/km.

It has further been found that by increasing the ration d_1/d_2 the low loss transmission band may be achieved at even lower wavelengths such as a low loss transmission band comprising wavelengths below 1200 nm, such as
 25 below $1\text{ }\mu\text{m}$, such as below $800\text{ }\mu\text{m}$, such as below 600 my. Advantageously the ration d_1/d_2 is equal to or larger than about 0.85, such as equal to or larger than about 0.9.

The outer cladding comprises solid cladding material and is preferably entirely of solid material.

In an embodiment the hollow tubes are arranged with a substantially equal distance to adjacent hollow tubes. Thereby a very high Gaussian beam quality may be obtained. In an alternative embodiment the hollow tubes are arranged with different distances to adjacent hollow tubes. In the latter

5 embodiment the variation in distance between adjacent hollow tubes is provided by having different outer diameters d_2 of the tubes. Where the inner diameter d_1 and/or the outer diameter d_2 of the hollow tubes differs, the inner diameter d_1 , respectively the outer diameter d_2 is calculated as the average d_1 and d_2 values, unless the calculation is the hollow tube thickness

10 or otherwise specified. Accordingly the ration d_1/d_2 is determined by the average d_1 and d_2 values. It has been found that the optimal suppression of HOMs requires that the minimum distance between adjacent hollow tubes is relatively low and preferably less than about half the outer diameter d_2 of the hollow tubes. On the other hand, the distance should not be too narrow

15 because this may result in the risk of fully eliminating the distance along parts of or along the whole fiber length due to surface tension and material attraction during drawing of the fiber. To avoid such risk it is desired that the minimum distance between adjacent hollow tubes is at least 0.01 times d_2 .

Advantageously the minimum distance between adjacent hollow tubes is at

20 least about 0.1 μm , such as at least about 1 μm , such as at least about 2 μm , such as at least about 5 μm .

In an embodiment the minimum distance between adjacent hollow tubes is about 5 μm or less, such as about 4 μm or less.

It has been found to be optimal that the center to center distance Λ between

25 adjacent hollow tubes is between about $1.01 \cdot d_2$ and about $1.5 \cdot d_2$, such as between $1.05 \cdot d_2$ and $1.2 \cdot d_2$.

The hollow tubes advantageously have substantially parallel center axis. In practice the center axis of the hollow tubes may deviate slightly from being straight due to process variations. The hollow tubes may for example be

helical around the core with a very long pitch, such as a pitch of up to 1 km, such as from 1 cm to 100 m.

Due to the structure of the hollow core PCF the core may in principle be designed with any diameter of the core region. The core region is

5 advantageously substantially circular. In an embodiment the core region is not circular, but rather oval or angular, such as substantially pentagonal. The core diameter D is defined as the diameter of the largest circle inscribed by the 7 hollow tubes.

Advantageously the hollow core region has a core diameter D of from about
10 10 μm to about 100 μm , such as from about 10 μm to about 60 μm .

It has been found that the optimal core diameter D is scalable with the central wavelength of the transmission band of the hollow core PCF.

For a central wavelength of about 1.0 μm , the core diameter D is advantageously as from about 20 μm to about 50 μm , such as from about 25
15 μm to about 40 μm . The preferred core diameter D is directly proportionally scaled with the central wavelength of the transmission band of the hollow core PCF.

It has been found that the hollow core PCF may have a very high beam quality even where the core is relatively large. In an embodiment the beam
20 quality M^2 is about 1.75 or less, such as about 1.6 or less, such as about 1.5 or even less.

In an embodiment the average outer tube diameter relative to the core diameter d_2/D is from about 0.5 to about 0.75, such as from about 0.65 to about 0.72, thereby a desired minimum distance between the hollow tubes
25 and a very effective suppression of HOMs – in particular of 3rd and 4th HOMs - are ensured.

Further the mode quality of the beam obtained with a hollow core PCF average outer tube diameter relative to the core diameter d_2/D is from about 0.5 to about 0.75 has shown to be very high.

5 It has been found the wall thickness of the hollow tubes largely influences the low loss transmission band or bands of the hollow core PCF. In fact, the wall thickness t of relevance has been found to be the core center facing region of the wall of the hollow tubes.

Thus it has been found that the wall thickness t (or the average value of t) of the core center facing region of the hollow tubes mainly affects the location
10 with respect to wavelengths of the low loss transmission bands. In general the hollow core PCF may have one or several low loss transmission bands, such as 1, 2, 3, 4 or even further low loss transmission bands.

Advantageously the hollow core PCF has at least 3 low loss transmission bands, such as at least 4 low loss transmission bands. For obtaining one or
15 more low loss bands below $1.2\ \mu\text{m}$ it is desired that the wall thickness t is up to about $2.1\ \mu\text{m}$, such as up to about $1\ \mu\text{m}$, such as in the range from about 150 to about 350 nm or in the range from about 650 to about 850 nm or in the range from about 900 to about $2.1\ \mu\text{m}$.

For example it has been found that for a hollow core PCF of an embodiment
20 of the invention the fiber has a low loss transmission at 1030-1064 nm for a wall thickness $t = 150 - 350\ \text{nm}$, preferably $200-300\ \text{nm}$ (low loss transmission band with highest wavelengths—band I), for a wall thickness $t = 650-850\ \text{nm}$, preferably $700-800\ \text{nm}$ (2nd highest wavelengths low loss transmission band—band II), and for a wall thickness of 5 times first range
25 for a third transmission band comprising 1030-1064 nm i.e. $5 \cdot 150\ \text{nm}$ to $5 \cdot 350\ \text{nm}$, seven times first range for a fourth transmission band comprising 1030-1064 nm and so on).

Advantageously the hollow core PCF is designed such that the hollow core guides light in the fundamental mode and comprises at least one wavelength

between 200 nm and 4000 nm wavelength, such as between 400 and 2000 nm, such as between 800 and 1600 nm, such as between 1000 and 1100 nm, where the loss is less than about 1000 dB/km.

Advantageously the hollow core PCF has a low loss transmission band for the
5 fundamental mode with a transmission loss of less than about 100 dB/km, preferably less than about less than 60 dB/km and more preferably less than 50 dB/km comprising wavelengths in the interval between 1000 and 1100 nm and preferably comprising at least the wavelengths 1030-1064 nm

In an embodiment the hollow core PCF has a transmission loss for HOMs in its
10 low transmission band for the fundamental mode of larger than about 2000 dB/km, thereby ensuring an effective single mode transmission.

It has further been found that the hollow core PCF is substantially insensitive to bending, for example it has been found that the hollow core PCF of an embodiment of the invention has a low loss which is less than about 5 %/km
15 at 1030-1060 nm when coiled at a diameter of about 6 cm.

Advantageously the wall thickness t of each of the hollow tubes is substantially identical. Preferably the hollow tubes are substantially identical and are arranged with identical distance to adjacent hollow tubes. Thereby the hollow core PCF becomes simpler to design for a desired wavelength
20 transmission.

In an embodiment at least one of the tubes has a different wall thickness t than at least one other of the hollow tubes. Preferably 3 of the hollow tubes have a wall thickness and the remaining 4 hollow tubes have another wall thickness. It has been found that by this arrangement the hollow core PCF
25 may become birefringent, largely depending on the difference in wall thickness t and the relative position of the hollow tubes with larger and smaller wall thickness t .

In an embodiment at least one of the hollow tubes has a wall thickness which is at least about 5 % larger than the wall thickness of at least one of the other hollow tubes, preferably at least one of the hollow tubes has a wall thickness which is at least about 10 % larger than the wall thickness of at least one other of the hollow tubes.

In an embodiment each of the hollow tubes is substantially circular. In practice it is very difficult to obtain absolutely circular hollow tubes, first of all due to a slight deformation where the respective hollow tubes are fused to the inner side of the outer cladding and secondly because the hollow tubes may be attracted to adjacent hollow tubes during the drawing of the fiber.

In an embodiment each of the hollow tubes has a long inner diameter D_l and a short inner diameter D_s perpendicular to the long inner diameter D_l , wherein D_l is determined in radial direction from the hollow core center axis.

Advantageously the ration D_s/D_l is from about 0.5 to about 0.99, such as from about 0.8 to about 0.99.

In an embodiment the D_s/D_l ratio is larger than about 0.9, such as larger than about 0.95 which in practice is simpler to produce.

In an embodiment the D_s/D_l ratio is smaller than about 0.95, such as smaller than 0.9 which results in a relative large core diameter D and thereby may add to reduce transmission loss for the fundamental mode.

In an embodiment at least one of the hollow tubes comprises at least one nested sub tube arranged in the hollow structure of the hollow tube wherein the sub tube is fused to the hollow tube, preferably aligned with the fusion to the outer cladding i.e. farthest from the core region.

The hollow tubes with one or more nested tubes may for example be as described for the PCF of WO15185761 comprising second tubular elements with third tubular elements nested within respective second tubular elements,

with the difference that the hollow core PCF has 7 second tubular elements with nested third tubular tubes.

The sub tube advantageously has an average outer diameter d_{sub} , which is substantially smaller than the average inner diameter d of the hollow tube.

- 5 The average outer diameter $d_{2\text{sub}}$ is preferably up to about $0.9 \cdot d_2$ of the hollow tube, such as up to about $0.9 \cdot d_2$, preferably the internal sub tube is fused to the hollow tube at its maximal radial distance to the core center axis.

- In an embodiment at least one of the hollow tubes comprises one or more nodules arranged at a core center facing region of one or more of the hollow tubes, preferably the nodules are arranged at a boundary of the hollow core region, the nodules are preferably arranged to be anti-resonant at an operating wavelength, so that light of a fundamental mode is substantially excluded from the nodules. Thereby an even stronger confinement of the fundamental mode may be obtained to further reduce loss of light in the
- 10 fundamental mode transmitted in the core region of the hollow core PCF.
- 15

- The nodules may advantageously be in form of nodule-like, or bead-like, formation or a locally thicker region of the wall extending along at least a part of the length of the fiber. Such nodules are sometimes referred to as nodes or bobbies in the prior art optical fibers e.g. as described in US 7,321,712. The nodules and the remaining parts of the hollow tubes advantageously are of identical material.
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- The core region and/or the hollow tubes may in principle comprise any fluid. Preferably the core region and/or the hollow tubes independently of each other comprise gas determined at standard ambient temperature and pressure (SATP) as a temperature of 25 °C and an absolute pressure of exactly 100 000 Pa. Suitable gasses include air, argon, nitrogen or mixtures comprising any of the mentioned gasses. Optionally the hollow core region and/or the hollow tubes independently of each other are vacuumated (evacuated to have a very low gas pressure) or filled with pressurized gas.
- 25

In an embodiment the hollow core region and/or the hollow tubes are vacuumated to a pressure of about 1 mbar or less, such as to a pressure of about 0.1 mbar or less, such as to a pressure of about 0.01 mbar or less at standard temperature.

- 5 In an embodiment the hollow core region and/or the hollow tubes are pressurized to a pressure of up to 2 bars, such as up to about 1.5 bars at standard temperature.

The outer cladding region may in principle have any size provided that it provides the hollow core PCF with a sufficient mechanical support for the
10 hollow tubes. In an embodiment the outer cladding region has an outer diameter of at least about 125 μm , 150 μm , such as at least about 200 μm .

In general it is desired that the hollow core PCF is of one single material which is preferably glass, more preferably silica, optionally doped with a refractive index modifying dopant. In an embodiment one or more, such as all
15 of the hollow tubes are of doped silica and the outer cladding region is of undoped silica. The dopant may for example include index changing materials such as F, Ge, P, B or combinations thereof.

Further it has been found that confinement loss may be reduced by providing the outer cladding region to comprise a photonic bandgap structure
20 surrounding said inner cladding region.

The photonic bandgap structure may be provided by any means, e.g. by providing the outer cladding region with an index grating comprising concentric rings with different refractive index and/or by including microstructures having different index.

- 25 In an embodiment the outer cladding region comprises an outer background material having a refractive index N_{oc} and a plurality of inclusions having a refractive index different from the refractive index of the background material. The inclusions advantageously have a lower refractive index than the

refractive index of the background material. The inclusions are preferably extending substantially parallel with the core region. The inclusions may extend in a length section of the hollow core PCF or in substantially the entire length of the hollow core PCF.

- 5 In an embodiment the plurality of inclusions in the outer background material is arranged in a cross-sectional pattern comprising at least two rings of inclusions surrounding the inner cladding region, such as at least 3 rings, such as at least 4 rings of inclusions.

The phrase "ring of inclusions" refers to inclusions of the outer cladding
10 inclusions having substantially equal radial distance to the core and being aligned in a ring configuration surrounding the core. Typically, a ring of inclusions is not fully circular, but rather is shaped with a number of soft angles, such as in a hexagonal shape. Preferably all the inclusions of a ring of inclusions are of substantially the same size and preferably of same solid
15 material, voids and/or gas.

The background material may advantageously be silica, such as un-doped silica or doped silica. The dopant may for example include index changing materials such as F, Ge, P, B or combinations thereof.

- In an embodiment the plurality of inclusions in the outer background material
20 is arranged in a substantially hexagonal pattern.

In an embodiment the plurality of inclusions are voids or of gas, such as air.

The diameter(s) of the inclusions is/are advantageously selected to minimize loss of a selected wavelength or a range of wavelengths. Thus the diameter(s) may be selected to optimize for a desired transmission profile.

- 25 In an embodiment the inclusions have substantially identical diameters.

Advantageously the plurality of inclusions have an average diameter (d_{inc}) of up to about 2.5 μm , such as up to about 2 μm , such as between about 1.1 μm

and 1.8 μm , such as between about 1.15 μm and about 1.7 μm , such as between about 1.2 μm and about 1.5 μm , such as about 1.3 μm .

Also the distance(s) between the respective inclusions has shown to be relevant for optimizing (minimizing) confinement loss. In an embodiment for
5 optimizing confinement loss the plurality of inclusions are arranged at a pitch (Λ_{inc}) of up to about 6 μm , such as up to about 5 μm , such as up to about 4 μm , such as between about 2 μm and 4 μm .

In an embodiment the inclusions are arranged at a pitch (Λ_{inc}) of up to about 3.5 μm , such as up to about 3 μm , such as up to about 2.5 μm , such as
10 between about 1.1 μm and 2 μm .

The invention also comprises a laser system for delivering laser light to a user apparatus, the laser system comprising a laser light source and a fiber delivery cable for delivering light from the laser light source to the user apparatus, wherein the fiber delivery cable comprises a hollow core PCF as
15 described above.

The fiber delivery cable comprising the hollow core PCF may preferably have a length of up to 50 m, such as from about 0.3 m to about 20 m, such as from about 1 m to about 15 m.

Advantageously the laser light source is configured for generating laser light
20 pulses and is optically connected to the fiber delivery cable, preferably the laser light source is a femtosecond laser source.

The laser light source may in an embodiment be arranged for directly feed the light to the hollow core PCF e.g. by being fused to the hollow core PCF. In an embodiment the laser light source is arranged for feeding the light to the
25 hollow core PCF via one or more optical elements and/or via free space.

In an embodiment the laser light source has a pump duration of from about 30 fs to about 30 ps, such as from about 100 fs to about 10 ps.

In an embodiment the laser light source has a peak power determined at the exit of the laser light source which is at least about 5 kW, such as at least about 10 kW, such as at least about 30 kW, such as at least about 50 kW.

The laser light source is advantageously a mode-locked laser light source. In
5 an embodiment laser light source is an actively mode locked laser. In an embodiment the laser light source is a passively mode locked laser. The mode locked laser preferably comprises one or more amplifiers.

In an embodiment the hollow core PCF is configured for guiding light – preferably single mode light -comprising at least one wavelength in the range
10 from about 200 nm to about 4.5 μm , preferably at least one wavelength in the range from 1000 nm to about 1100 nm.

In an embodiment the hollow core PCF is configured for guiding a continuum of light wavelengths, preferably spanning over at least about 0.1 μm , such as at least about 0.3 μm , such as at least about 0.5 μm .

15 In an embodiment the hollow core PCF has a first fiber end which is adapted for being connected to the user apparatus and a second fiber end optically connected to an output fiber of the laser light source via a fiber coupling structure. The fiber coupling structure preferably provides a protection of the first fiber end and preferably of a facet of the first fiber end to ensure that the
20 facet and or the hollow core is not contaminated with dust, moisture or similar. Further to ensure a safe low loss connection the coupling structure may comprise a lens, such as a focusing lens, a graded-index element or other elements such as it is known in the art for coupling structures for hollow core fibers in general.

25 In an embodiment the fiber coupling structure comprises a focusing lens, for example such as it is described in US 8,854,728.

In an embodiment the fiber coupling structure comprises a graded-index element (GRIN) such as it is described in US 2003/0068150.

In an embodiment the fiber coupling structure comprises a protection element such as it is described in US 7,373,062.

In a preferred embodiment the first fiber end is mounted in a ferrule structure, preferably with a ferrule structure as described in PA 2015 70876 DK with the
5 title "PHOTONIC CRYSTAL FIBER ASSEMBLY" and which application is hereby incorporated by reference into this disclosure with the proviso that in case of any inconsistency between the subject matter explicitly disclosed herein and the incorporated subject matter, the content of the subject matter explicitly disclosed herein prevail.

10 The hollow core PCF as described herein may advantageously be produced by drawing from a preform wherein the drawing is performed while controlling the pressure within the hollow tubes for example as described in US 6,954,574, US 8215129, US 7,793,521 and/or in PA 2016 70262 DK with the
15 title "A RING ELEMENT FOR A PREFORM, A PREFORM AND AN OPTICAL FIBER DRAWN FROM THE PREFORM"

The preform is advantageously produced by providing a hollow tube for the outer cladding region and 7 hollow tubes for the inner cladding, wherein the hollow tube for the outer cladding region has an inner diameter which is larger than two times, such as at least 3 times, such as at least 4 times larger
20 than the outer diameter of the 7 hollow tubes - or if different - of the largest outer diameter of the 7 hollow tubes for the inner cladding. Preferably the outer cladding region has an inner diameter which is sufficiently large to arrange the 7 hollow tubes inside and in contact with the hollow tube for the outer cladding region such that the 7 hollow tubes are not touching each
25 other. To arrange the 7 hollow tubes inside the hollow tube for the outer cladding region a short section of support elements (e.g. tubes or rods of glass) may be arranged at each end of the hollow tubes. After having fused the 7 hollow tubes to the hollow tube for the outer cladding region, the ends of the fused hollow tubes comprising the support elements may be cut off.

The preform may then be drawn in a fiber drawing tower preferably by simultaneously individual or common pressure control of the pressure within the respective hollow tubes.

5 In an embodiment the pressure control of each of one or more of the hollow tubes of the preform, also referred to as "elongate holes" or merely "holes", is provided by arranging a pressure tube between the hole and a pressure supply. The pressure supply ensures that the pressure within the hollow tube is controlled to a desired level via the pressure tube during the drawing of the fiber from the preform.

10 The pressure tube is advantageously a hollow pressure tube. The phrase "in the tube" refers to in the hollow part of the pressure tube.

Thus in an embodiment the method comprises inserting a first end of a pressure tube into the hole of the preform at a first end of the preform and subjecting the hole of the preform to a controlled pressure via the pressure
15 tube during drawing. Advantageously at least a pressure tube length section comprising the first end of the pressure tube is inserted into the elongate hole of the preform. The pressure tube length section should preferably have a length of at least about 0.5 mm, such as from about 1 mm to about 20 cm, such as from about 2 mm to about 5 cm, such as from 0.5 to 1 cm.

20 In practice it is desired that the pressure tube length section has a length which is sufficient to provide a seal between the pressure tube length section and the elongate hole and yet it should not be too long since the length part of the preform comprising the pressure tube length section may in an embodiment not be drawn to fiber or if – in an alternative embodiment – it is
25 drawn to fiber, the resulting fiber will then have different characteristics than the fiber drawn from preform material without the tube length section(s)

It has been found that a safe gas connection may be obtained between the elongate hole and the pressure tube by simply inserting the first end of the

pressure tube into the hole and optionally providing that the pressure tube length section is expanded such that its outer surface fits to the periphery surface of the elongate hole and/or applying a sealing material, such as glue, epoxy, grease and/or rubber or any other pliable sealing material.

- 5 The pressure tube advantageously has an outer diameter and periphery selected such that it fits into the hole of the preform. The cross sectional shape of the hole may be round or oval or any other suitable shape. The surface defining the hole is also referred to as the periphery surface of the elongate hole. The pressure tube preferably has an outer cross sectional
- 10 shape corresponding to the cross sectional shape of the hole of the preform, however with an average diameter slightly smaller than the average diameter of the hole of the preform, such that the first end of the pressure tube can be inserted into the hole.

- In an embodiment the pressure tube or at least the pressure tube length
- 15 section of the pressure tube has an average outer diameter which is from about 80 % up to 100 % of an average inner diameter of the hole, such as from about 90 % to about 99% of the average diameter of the hole.

- Advantageously the pressure tube has a supply section which is outside the hole i.e. the part of the pressure tube which leads from the hole to a gas
- 20 connection to the pressure supply.

In an embodiment the supply section of the pressure tube has a supply opening which is in gas connection with a pressure source for controlling the pressure within the hole.

- In an embodiment the supply section of the pressure tube has a supply
- 25 opening which is within a pressure regulating chamber. By regulating the pressure within the pressure regulating chamber e.g. by the pressure source, the pressure within the pressure tube is also regulated and thereby the pressure within the elongate hole is regulated.

In an embodiment the supply section of the pressure tube has a supply opening which is directly connected to a pressure source for regulating the pressure within the pressure tube and thereby the pressure within the elongate hole is regulated.

- 5 The pressure tube can in principle be of any material. In an embodiment the pressure tube is of a thermo-moldable material, e.g. a material which may be molded or drawn at a fiber drawing tower. Advantageously the pressure tube is of silica optionally comprising a polymer coating. In an embodiment at least the supply section of the pressure tube has an outer polymer coating and
10 optionally the pressure tube length section is free of polymer coating. The polymer coating increases the pliability of the pressure tube and reduces the risk of rupture of the pressure tube.

- By providing the pressure tube of silica with a pressure tube length section with an uncoated pressure tube length section and a pressure tube supply
15 section with a polymer coating, a desirably large hollow part cross-sectional diameter of the pressure tube may be obtained while at the same time the pressure tube supply section may be desirably pliable and rupture resistant.

- As mentioned above several holes of the preform may be pressure controlled with pressure tubes as described above. The pressure tubes may be
20 connected to the same pressure supply or to different pressure supplies.

All features of the invention and embodiments of the invention as described above including ranges and preferred ranges can be combined in various ways within the scope of the invention, unless there are specific reasons not to combine such features.

25 **Brief description of the drawings**

The above and/or additional objects, features and advantages of the present invention will be further elucidated by the following illustrative and non-

limiting detailed description of embodiments of the present invention, with reference to the appended drawings.

Fig. 1 shows a cross-section of an embodiment of a hollow core PCF of the invention where one of the hollow tubes is enlarged to show the inner
5 diameter d_1 , the outer diameter d_2 and the wall thickness t .

Fig. 2 shows a cross-section of an embodiment of a hollow core PCF of the invention where some of the hollow tubes have a larger wall thickness t than other of the hollow tubes.

Fig. 3 shows a cross-section of an embodiment of a hollow core PCF of the
10 invention where the hollow tubes are oval.

Fig. 4 shows a cross-section of an embodiment of a hollow core PCF of the invention where the hollow tubes comprise nested sub tubes arranged in the hollow structure of hollow tubes and fused to the hollow tubes.

Fig. 5 shows a cross-section of an embodiment of a hollow core PCF of the
15 invention where the hollow tubes comprise nodules arranged at a core center facing region.

Fig. 6 shows a cross-section of an embodiment of a hollow core PCF of the invention where single mode light has been fed to the hollow core PCF.

Fig. 7 is a graph showing several low loss transmission bands of a hollow core
20 PCF of an embodiment of the invention.

Fig. 8 is a graph showing a broad low loss transmission band of a hollow core PCF of an embodiment of the invention.

Fig. 9 is a graph showing the suppression of HOMs of a prior art hollow core PCF with six hollow tubes.

25 Fig. 10 is a graph showing the suppression of HOMs of hollow core PCF of an embodiment of the invention with seven hollow tubes.

Fig. 11 is a schematic drawing of a laser system of an embodiment of the invention as well as a user apparatus.

Fig. 12 illustrates a first end of a preform for an embodiment of a hollow core PCF of the invention with 7 hollow tubes forming 7 elongate holes and where
5 the first ends of the respective pressure tubes are inserted into respective holes for pressure controlling of the holes during drawing.

Fig. 13a illustrates a hollow core PCF of an embodiment of the invention comprising an outer cladding region comprising a photonic band gap structure.

Fig. 13b is a graph showing the transmission loss for two variations of the
10 hollow core PCF of the embodiment Fig. 13a.

Fig. 14 is a graph showing a measurement of the beam quality M^2 of the fiber fabricated in EXAMPLE 1.

The figures are schematic and simplified for clarity. Throughout, the same reference numerals are used for identical or corresponding parts.

15 The hollow core PCF of the invention shown in Fig. 1 comprises an outer cladding region 1 and seven hollow tubes 2 surrounded by said outer cladding region. Each of the hollow tubes 2 is fused at fusing point 3 to the outer cladding 1 to form a ring defining an inner cladding region and a hollow core region 4 surrounded by the inner cladding region and having a core diameter
20 D.

The hollow tubes are not touching each other and are generally referred to as non-touching hollow tubes. As shown in the enlargement of a hollow tube, each of the hollow tubes 2 has an average outer diameter d_2 and an average inner diameter d_1 and a wall thickness t in the center facing region of the
25 respective hollow tubes 2. The outer cladding 1 has an inner diameter ID and an outer diameter OD. In this embodiment the hollow tubes 2 are identical and are substantially circular in cross section.

In the embodiment shown in Fig. 2 the hollow core PCF comprises an outer cladding region 11 and seven non-touching hollow tubes 12a, 12b surrounded by said outer cladding region where the hollow tubes 12a, 12b are fused at fusing point 13 to the outer cladding 11 to form a ring defining an inner cladding region and a hollow core region 14 surrounded by the inner cladding region. Three of the non-touching hollow tubes 12a have a larger wall thickness t than the remaining four of the non-touching hollow tubes 12b. As shown each of the respective seven non-touching hollow tubes 12a, 12b is uniform in thickness, thereby providing a simpler production of the hollow core PCF.

In the embodiment shown in Fig. 3 the hollow core PCF comprises an outer cladding region 21 and seven identical non-touching hollow tubes 22 surrounded by said outer cladding region, and the hollow tubes 22 are fused to the outer cladding 21 to form a ring defining an inner cladding region and a hollow core region 24 surrounded by the inner cladding region. The hollow tubes 22 are oval and each of the hollow tubes 22 has a long inner diameter D_l and a short inner diameter D_s perpendicular to the long inner diameter D_l , wherein D_l is determined in radial direction.

In the embodiment shown in Fig. 4 the hollow core PCF comprises an outer cladding region 31 and seven identical non-touching hollow tubes 32 surrounded by said outer cladding region, and the hollow tubes 32 are fused at fusing points 33 to the outer cladding 31 to form a ring defining an inner cladding region and a hollow core region 34 surrounded by the inner cladding region. The hollow tubes 32 comprise nested sub tubes 35 arranged in the hollow structure of the hollow tubes and fused to the hollow tubes at the fusing points 33 at their respective maximal radial distance to the core center axis.

In the embodiment shown in Fig. 5 the hollow core PCF comprises an outer cladding region 41 and seven non-touching hollow tubes 42a, 42b surrounded

by said outer cladding region where the hollow tubes 42a, 42b are fused to the outer cladding 41 to form a ring defining an inner cladding region and a hollow core region 44 surrounded by the inner cladding region. Four of the non-touching hollow tubes 12a are uniform in thickness of their respective
5 walls whereas the remaining three of the non-touching hollow tubes 42b comprise nodules 45 arranged at a core center facing region of the respective hollow tubes. Since the outer diameter d2 of the respective non-touching hollow tubes 42a, 42b is substantially identical, the nodules 45 are arranged at a boundary of the hollow core region.

10 In the embodiment shown in Fig. 6 the hollow core PCF mainly has a structure as the hollow core PCF of Fig. 1. A not shown single mode laser source is arranged to laser light to the PCF at wavelength in a low loss transmission band of the PCF. After 5 m or even 10 the beam transmitted in the PCF as indicated with ref. 6 has a Gaussian beam quality and is fully
15 single mode. After 10 m of transmission the loss in the fundamental mode is very low e.g. with a transmission efficiency of more than 85 %, such as more than 90%.

The graph of Fig. 7 shows several low loss transmission bands of a fiber with the structure shown in Fig. 1 and a core size D of about 30 μm and $t=750\text{nm}$.
20 Bands are numbered from longest wavelength band to shorter wavelength bands with increasing number. As seen the hollow core PCF has four bands of low loss transmission, wherein 3 of the low loss transmission bands comprise wavelengths below 1.2 μm .

The graph of Fig. 8 shows a closer view of a transmission loss of the hollow
25 core PCF of Fig. 1 with $D=30\text{ }\mu\text{m}$ and $t=750\text{nm}$ of transmission band II. It can be seen that the low loss transmission band is very broad with a bandwidth of 200-250 nm around 1.064 μm .

A simulation was made for a hollow core PCF with six hollow tubes (prior art hollow core PCF) and with a hollow core PCF with seven hollow tubes (an

embodiment of the invention). The simulation was done with $D=30\mu\text{m}$,
 $t=750\text{nm}$, @1032nm.

Figs. 9 and 10 show HOM extinction ratio relative to d/D ($D = D_{\text{core}}$) of the
prior art hollow core PCF with six hollow tubes (Fig. 9) and the hollow core
5 PCF of an embodiment of the invention with seven hollow tubes (Fig. 10).

As it can be seen in Fig. 10 an optimal ratio d/D between 0.6 and 0.75
ensures that Lp11-like modes and several other HOMs of higher order are
resonantly coupled to cladding modes.

In fig. 9 it can be seen that use of six hollow tubes allows achieving a partly
10 suppression of the Lp11-like modes. However, modes with a higher
azimuthal number remain unperturbed limiting the overall HOM extinction.

Thus it is clearly shown that the hollow core PCF of the invention with seven
hollow tubes has much improved properties for suppression of HOMs than the
prior art hollow core PCF with six hollow tubes.

15 Further comparison between hollow core PCF of an embodiment of the
invention and hollow core PCF having six hollow tubes are disclosed in the
article "Hollow-core fibers for high power pulse delivery" by Michieletto et al.
Optics Express 7103-7119, March 2016. The content of this article is hereby
incorporated by reference into this disclosure with the proviso that in case of
20 any inconsistency between the subject matter explicitly disclosed herein and
the incorporated subject matter, the content of the subject matter explicitly
disclosed herein prevail.

The laser system shown in Fig. 11 comprises a laser light source 51 and a
fiber delivery cable 52 for delivering light from the laser light source 51 to a
25 user apparatus 54. The fiber delivery cable 52 comprises as its waveguide a
hollow core PCF as described above with one or more low loss transmission
bands correlated to the user apparatus. As indicated the fiber delivery cable
52 may be rather long while still delivering single mode light with high

efficiency and low loss in the fundamental mode to the user apparatus 54.

The fiber delivery cable 52 has a first end 53a and a second end 53b. In the shown embodiment each of the first end 53a and the second end 53b are mounted in a ferrule structure for connecting respectively to the user

5 apparatus 54 and the laser light source 5.

In an alternative not shown embodiment the second end of the fiber delivery cable 52 is spliced to a fiber output of the laser light source 51.

The preform shown in Fig. 12 is a preform for an embodiment of the hollow core fiber as described herein.

10 The preform comprises a preform outer cladding region 165 and 7 hollow preform tubes 161a, 161b arranged in a non-touching ring (i.e. the tubes are not touching each other) surrounded by and fused to the preform outer cladding region 165.

Pressure tubes 164 are arranged to connect each of three of the preform
15 tubes 161a (primary hollow tubes) to a not shown pressure supply for controlling the pressure in the primary hollow tubes 161a during drawing. A pressure tube length section 164a inserted into the hole of each primary hollow tube 161a is advantageously uncoated silica, whereas the remaining part of the pressure tube 164, referred to as the pressure tube supply section
20 is polymer coated silica. The pressure in the secondary hollow tubes 161b may advantageously be controlled in a pressure chamber such as shown in Figs. 15 and 16 of PA 2016 70262 DK with the title "A RING ELEMENT FOR A PREFORM, A PREFORM AND AN OPTICAL FIBER DRAWN FROM THE PREFORM".

25 In the embodiment shown in Fig.13a the hollow core PCF comprises an outer cladding region 171 and seven non-touching hollow tubes 172 forming an inner cladding region and surrounded by said outer cladding region 171. The hollow tubes 172 are fused at fusing points 173 to the inner side of the outer

cladding 171 to form the inner cladding region and a hollow core region 174 surrounded by the inner cladding region. The outer cladding region comprises a photonic band gap structure in the form of microstructures (inclusions) 175a having different index than the cladding background material 175b.

- 5 The photonic bandgap (PBG) structure may be provided by any means, e.g. by providing the outer cladding region with an index grating comprising concentric rings with different refractive index and/or by including.

The inclusions 175a in the outer background material 175b are arranged in a cross-sectional pattern comprising about 5 rings.

- 10 As mentioned it is preferred that the inclusions are voids or of gas and have a relatively small diameter and are arranged with short for optimizing (minimizing) confinement loss of the desired wavelength or range of wavelength.

- Fig 13b shows the transmission loss for two variations of the hollow core PCF of the embodiment Fig. 13a. wherein the two variations of the hollow core PCF with PBG structure in their respective cladding have been optimized for reducing the confinement loss around a desired center wavelength of respectively 1064 nm (left) and 1550 nm (right). As it can be seen the loss is very low. Further it is found that this approach to reduce the confinement loss
15
20 can be also be exploited in polarization maintaining antiresonant fibers.

Further it was found that the confinement loss appears to be arbitrary reduced by increasing the total thickness of the photonic band gap structure.

EXAMPLE 1

- A hollow core PCF having a structure as shown in Fig. 1 was fabricated using the stack and raw technique. The fabricated fiber shown has a core diameter
25 of approximately 30 μm , $d_2 \sim 17 \mu\text{m}$ with a $d_2/D \sim 0.57$. The mode field diameter measured at 1064 nm is 2.2 μm . The tubes present minor size

differences, nonetheless the fiber shows remarkable low loss and bend loss and good mode quality. The mode quality factor of the fabricated fiber was measured the mode quality factor with a camera—based M^2 measurement system (Spiricon M2-200S) with a laser at a wavelength of 1064 nm and a 5 m FUT. We performed the measurements: with the fiber coiled on a standard 8 cm spool and no further coils. The results are summarized in Table I and shown in Fig. 14. The fiber output beam presents negligible astigmatism and asymmetry and a M^2 of 1.2.

Table 1

Asymmetry	Astigmatism	M^2 X	M^2 Y
1.02	0.01	1.22	1.2

PATENT CLAIMS

1. A hollow core photonic crystal fiber (PCF) comprising an outer cladding region and 7 hollow tubes surrounded by said outer cladding region, each of said hollow tubes having an average outer diameter d_2 and an average inner diameter d_1 , wherein each of said hollow tubes is fused to said outer cladding region to form a ring defining an inner cladding region and a hollow core region surrounded by said inner cladding region, wherein said hollow tubes are not touching each other, wherein said average outer tube diameter relative to a core diameter D of the hollow core region d_2/D is from 0.5 to 0.75, and wherein all of the hollow tubes are free of a nested sub tube.
2. The hollow core PCF of claim 1, wherein d_1/d_2 is equal to or larger than 0.8, or equal to or larger than 0.85, or equal to or larger than 0.9.
3. The hollow core PCF of claim 1 or claim 2, wherein said hollow tubes have a center to center distance Λ between adjacent hollow tubes which is between $1.01*d_2$ and $1.5*d_2$, or between $1.05*d_2$ and $1.2*d_2$.
4. The hollow core PCF of any one of the preceding claims, wherein said core diameter D is from 10 μm to 100 μm and said average outer tube diameter relative to the core diameter d_2/D is from 0.65 to 0.72.
5. The hollow core PCF of any one of the preceding claims, wherein each of said hollow tubes comprises a core center facing region with a wall thickness t , wherein said wall thickness is up to 2.1 μm , or up to 1 μm , or in the range from 150 to 350 nm or in the

range from 650 to 850 nm or in the range from 900 to 2.1 μm .

6. The hollow core PCF of claim 5, wherein at least one of the hollow tubes has a different wall thickness t than at least one other of the hollow tubes, or wherein 3 of the hollow tubes have a wall thickness and the
5 remaining 4 hollow tubes have another wall thickness.
7. The hollow core PCF of any one of the preceding claims, wherein a minimum distance between adjacent hollow tubes is at least 0.1 μm , or at least 1 μm , or at least 2 μm , or at least 5 μm .
8. The hollow core PCF of any one of the preceding claims, wherein the
10 hollow core region and said hollow tubes independently of each other comprise gas selected from air, argon, nitrogen or mixtures comprising any of the mentioned gasses, or said hollow core region and said hollow tubes independently of each other are vacuumated or filled with pressurized gas.
9. The hollow core PCF of any one of the preceding claims, wherein the
15 outer cladding region has an outer diameter of at least 125 μm , or 150 μm , or at least 200 μm .
10. The hollow core PCF of any one of the preceding claims, wherein the outer cladding region and/or the hollow tubes comprise a solid glass material, wherein said solid glass material is of silica or silica doped with refractive
20 index modifying dopant.
11. The hollow core PCF of any one of the preceding claims, wherein the outer cladding region comprises a photonic bandgap structure surrounding said inner cladding region.

12. The hollow core PCF of any one of claims 9-11, wherein the outer cladding region comprises an outer background material having a refractive index N_{oc} and a plurality of inclusions having a refractive index different from the refractive index of the outer background material, and/or said plurality of
- 5 inclusions in the outer background material is arranged in a cross-sectional pattern comprising at least two or three or four rings of inclusions surrounding the inner cladding region.
13. The hollow core PCF claim 12, wherein said plurality of inclusions have an average diameter (d_{inc}) of up to 2.5 μm , or up to 2 μm , or between 1.1 μm
- 10 and 1.8 μm , or between 1.15 μm and 1.7 μm , or between 1.2 μm and 1.5 μm , or 1.3 μm .
14. The hollow core PCF of any one of claims 12-13, wherein said plurality of inclusions are arranged at a pitch (Λ_{inc}) of up to 6 μm , or up to 5 μm , or up to 4 μm , or between 2 μm and 4 μm .
- 15 15. A laser system for delivering laser light to a user apparatus, said laser system comprising a laser light source and a fiber delivery cable for delivering light from the laser light source to the user apparatus, wherein said fiber delivery cable comprises a hollow core PCF according to any one of the preceding claims.

16. The laser system of claim 15, wherein said laser light source has a pump duration of from 30 fs to 30 ps and a peak power determined at the exit of the laser light source which is at least 5 kW, or at least 10 kW, or at least 30 kW, or at least 50 kW.
- 5 17. The laser system of any one of claims 15-16, wherein said hollow core PCF has a first fiber end which is adapted for being connected to said user apparatus and a second fiber end optically connected to an output fiber of said laser light source via a fiber coupling structure, wherein said fiber coupling structure comprises at least one of
- 10 a focusing lens,
a graded-index element (GRIN),
a protection element, or
a ferrule structure.