arranged at a distance from the ferrule structure center axis, however for most applications it is desired that the PCF center axis at the first fiber end section and the ferrule structure center axis are coincident, thereby making the assembling simpler.

In the assembling the first fiber end section is mounted and anchored in the inner ferrule rear section. Subsequently, prior to or simultaneously the first fiber end section is mounted in the inner ferrule front section and the first fiber end is aligned to a desired position in the z-direction. Thereafter the outer ferrule arrangement is mounted to hold the inner ferrule front section and the inner ferrule rear section in position relative to each other and thereby to fix the first fiber end alignment relative to the ferrule structure. By providing the direct anchoring of the fiber exclusively to the inner ferrule rear section a much simpler alignment of the fiber end facet may be obtained since the distance between the inner ferrule front section and the inner ferrule rear section may be adapted to position the fiber end facet at a desired position in z-direction before fixing the distance between the inner ferrule front section and the inner ferrule rear section by mounting the inner ferrule front section and the inner ferrule rear section to the outer ferrule arrangement.

In an embodiment the inner ferrule front section and the inner ferrule rear section are not directly fixed to each other, but they are merely coupled and held in position by the outer ferrule arrangement. Preferably the inner ferrule front section and the inner ferrule rear section are arranged to have an intermediate gab in the axial direction. The gap advantageously provides a distance in the axial direction between the inner ferrule front section and the inner ferrule rear section. The distance is preferably in the range from about 1 mm to about 10 cm, such as from about 5 mm to about 2 cm.

In an embodiment the intermediate gap between the inner ferrule front section and the inner ferrule rear section extends partly around the PCF, for

example to form a semi-annular gap. In an embodiment the gap extends fully around the PCF to form an annular gap and thereby a distance between the inner ferrule front section and the inner ferrule rear section. In both instances a part of the first fiber end section is not covered by the inner ferrule arrangement.

In an embodiment the assembly further comprises an alignment sleeve arranged between the inner ferrule front section and the first fiber end section. Thereby the inner ferrule front section supports the first fiber end section proximally to the first fiber end via the alignment sleeve. The alignment sleeve is preferably arranged to surround and support the first fiber end section at the first fiber end.

In the assembling the alignment sleeve is mounted to the first fiber end section in a desired position in z-direction relative to the first fiber end and thereafter the inner ferrule front section is mounted.

The alignment sleeve and the use thereof has been found to be very beneficial because PCFs generally differ much in outer diameter and therefore without an alignment sleeve would require individual sizes of inner ferrule front sections. Further –as explained below – the alignment sleeve may be provided to fit to PCFs with different outer diameters e.g. by crimping the alignment sleeve around the fiber to provide sufficient support.

Advantageously the alignment sleeve supports the first fiber end section, by being collapsed onto the first fiber end section in its whole length or in the support section thereof. Suitable material for the alignment sleeve therefore includes material which may be crimped or collapsed onto the first fiber end section e.g. by application of heat. The alignment sleeve is advantageously not fixed or anchored to the first fiber end section but is preferably held mechanically in position to provide a desired axial support to the fluorophores.

In an embodiment the alignment sleeve is fused to the PCF.

The passage into the end cap space for injecting and/or withdrawing fluids may advantageously be applied for injecting or flushing with suitable gasses e.g. to ensure a moisture free hollow core. Suitable gasses include air, argon, nitrogen or mixtures comprising any of the mentioned gasses. Optionally, the cap space for injecting and/or withdrawing fluids are arranged for generating a hollow core 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 of 0.01 mbar or less at standard temperature.

Optionally the cap space for injecting and/or withdrawing fluids are arranged for generate a hollow core pressure of up to 2 bars, such as up to about 1.5 bars at standard temperature.

In an embodiment the inner ferrule arrangement comprises at least one passage into the gap between the inner ferrule front section and the inner ferrule rear section. The passage is advantageously a passage through the inner ferrule rear section, preferably in the form of a through hole e.g. parallel to the center axis of the ferrule structure. The injecting and/or withdrawing of fluids, such as injecting and/or withdrawing of the gasses mentioned above. In an embodiment the inner ferrule arrangement comprises at least two passages into the gap between the inner ferrule front section and the inner ferrule rear section for flushing the gap e.g. for drying out the gap and/or for heat dissipation.

In an embodiment the inner ferrule front section has a rear end where at least an in radial direction outer part of the rear end is angled relative to the center axis of the ferrule structure to out-couple light, such as light propagating in the inner ferrule arrangement. In an embodiment the inner ferrule front section has a rear end where at least an in radial direction outer semi annular or annular in radial direction outer part of the rear end is angled relative to the center axis of the ferrule structure to out-couple light. The light

high index material and or/a scattering layer applied in contact with the optical fiber at the mode stripper length section and/or the fiber in the mode stripper length section has a roughness Ra value of at least about 0.1 µm.

The high roughness Ra value may e.g. be provided by etching (e.g. laser etching or chemical etching) or mechanical grinding. The Ra-value may be measured in accordance with the ISO 4287, DIN 4762 and/or DIN 4768 standards.

The mode stripper length section reduces or fully prevents forward propagating cladding light. The mode stripping high index material may for example be glue with silica particles e.g. doped to increase the refractive index and/or chemical glass.

In an embodiment the mode stripper length section of the PCF is positioned between the inner ferrule front section and the inner ferrule rear section.

In an embodiment at least one of the inner ferrule front section and the inner ferrule rear section has a carving exposing the PCF the mode stripper length section of the PCF.

Advantageously the carving preferably partly surrounds the fiber preferably such that it extends at least about 20 degrees and e.g. up to about 350 degrees, preferably from about 20 degrees to about 90 degrees in the direction around the PCF.

In an embodiment the ferrule structure comprises a mode stripper coating arranged in direct contact with an outer surface of the inner ferrule front section, the mode stripper coating is preferably contained between the inner ferrule front section and the outer ferrule arrangement.

In an embodiment the ferrule structure comprises an outer alignment jacket surrounding the outer ferrule arrangement, the outer alignment jacket

Fig. 8 is a cross sectional view of an eighth embodiment of a PCF assembly according to the invention, where the PCF assembly comprises an end cap mounted to the inner ferrule front section.

Fig. 9 is a cross sectional view of a ninth embodiment of a PCF assembly according to the invention, where the PCF assembly comprises an end cap mounted to the outer ferrule front section.

Fig. 9a is a cross sectional view of a PCF assembly which is a variation of the ninth embodiment shown in Fig. 9.

Fig. 10 is a cross sectional view of a tenth embodiment of a PCF assembly according to the invention, where the PCF assembly comprises an outer alignment jacket.

Fig. 11 is a cross sectional view of an eleventh embodiment of a PCF assembly according to the invention, where the PCF assembly comprises an alignment sleeve.

Fig. 12 is a cross sectional view of a twelfth embodiment of a PCF assembly according to the invention, where the PCF assembly comprises an alignment sleeve and the PCF comprises a section of hollow core capillary.

Fig. 12a is a cross sectional view is an enlarged cross sectional view of the alignment sleeve and supported first fiber end section of the PCF assembly of Fig. 12.

Fig. 13 is a cross sectional view of a thirteenth embodiment of a PCF assembly according to the invention, where the PCF assembly comprises an alignment sleeve with a collapsed supporting section.

Fig. 13a is a cross sectional view is an enlarged cross sectional view of the alignment sleeve and supported first fiber end section of the PCF assembly of Fig. 13.

Figs. 14a, 14b, 14c and 14d show schematic cross sectional views of PCF fiber end sections.

Fig. 15 is a schematic drawing of a laser system of an embodiment of the invention and a user apparatus.

Fig. 16 is a schematic drawing of an apparatus of an embodiment of the invention and a user apparatus.

Figs. 17a and 17b are schematic drawings of an apparatus of an embodiment of the invention and a user apparatus where the laser system is a supercontinuum laser system.

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

The PCF assembly of Fig. 1 comprises a photonic crystal fiber (PCF) assembly PCF with a first fiber end section 1 with a first fiber end 1a and a ferrule structure. The ferrule structure comprises an inner ferrule arrangement comprising an inner ferrule front section 2 proximally to the first fiber end and 1a an inner ferrule rear section 3 distally to first fiber end 1a. The inner ferrule front section 2 and the inner ferrule rear section 3 respectively comprises hollow through holes 2a, 3a coincident with center axes of the inner ferrule front section 2 and inner ferrule rear section. The PCF first fiber end section is mounted in said hollow through holes 2a, 3a, such that the inner ferrule arrangement surrounds the first fiber end section.

The inner ferrule rear section 3 is anchored in an anchor length section 3b to said first fiber end section 1, and from a point 1c of the PCF and to the first fiber end the PCF is free of polymer coating. The inner ferrule front section 2 supports the first fiber end section 1 proximally to the first fiber end 1a by mechanically holding said first fiber end section proximally to the first fiber end in axial position. As it can be seen the front of the inner ferrule front

section and the first fiber end are aligned in a plane perpendicular to the PCF center axis.

The ferrule structure further comprises an outer ferrule arrangement 5 arranged to surround the inner ferrule arrangement. The outer ferrule arrangement 5 is fixed to each of the inner ferrule front section 2 and the inner ferrule rear section 3 to hold them in a fixed position relative to each other and to form a gap 4 there between. The outer ferrule arrangement 5 is fixed by solder 6 at each of its ends to the respective sections 2, 3 of the inner ferrule arrangement.

The PCF first fiber end section is advantageously held relatively straight in the gap 4 between the inner ferrule front section 2 and the inner ferrule rear section 3. In an alternative not shown embodiment the PCP has a surplus length between the inner ferrule front section 2 and the inner ferrule rear section 3.

The in radial direction inner part 2c of the rear end of the inner ferrule front section 2 is angled relative to the center axis to form a funnel shape, which makes it simpler to feed the PCF 1 into the inner ferrule front section during assembling. The in radial direction outer part 2d of the rear end of the inner ferrule front section 2 is advantageously coated with angled reflective coating to back-reflect light propagating in the inner ferrule arrangement.

Further the front end 2e of the inner ferrule front section2 is preferably coated with a reflective coating to protect the ferrule structure against incident and/or back-reflected light and the front end 3e of the inner ferrule rear section is preferably coated with a reflective coating to protect against incident and/or back-reflected light.

The PCF assembly of Fig. 2 comprises a photonic crystal fiber (PCF) assembly PCF with a first fiber end section 11 with a first fiber end 11a and a ferrule structure. The ferrule structure comprises an inner ferrule arrangement

The ferrule structure further comprises an outer ferrule arrangement 25 fixed to each of the inner ferrule front section 22 and the inner ferrule rear section 23 to hold them in a fixed position relative to each other and to form a gap 24 there between. The outer ferrule arrangement 25 is fixed by solder 26 at each of its ends to the respective sections 22, 23 of the inner ferrule arrangement.

The front end 23e of the inner ferrule rear section 23 is angled relative to the center axis of the ferrule structure to form an outwards facing facet for out-coupling light propagating in the inner ferrule arrangement and reduce back reflections. The inner ferrule rear section 23 further comprises a passage 23f into the gap 24 between the inner ferrule front section 22 and the inner ferrule rear section 25. The passage may be used to fill in or withdraw fluids from the gap 24 as described above. The PCF at its first fiber end section 21 has a mode stripper section 27 and the inner ferrule front section 22 has a carving 27a exposing the PCF mode stripper length section 27.

A sensor 28 is mounted to the outer ferrule arrangement 25 above the carving 27a exposing the PCF mode stripper length section for monitoring the out-coupling efficiency of the mode stripper 27.

The PCF assembly of Fig.4 comprises a photonic crystal fiber (PCF) assembly PCF with a first fiber end section 31 assembled with a ferrule structure comprising an inner ferrule arrangement comprising an inner ferrule front section 32 proximally to the first fiber end and an inner ferrule rear section 33 distally to first fiber end and surrounding the first fiber end section 31.

The inner ferrule rear section 33 is anchored to the first fiber end section 31, and from a point 31c of the PCF and to the first fiber end the PCF is fee of polymer coating. The inner ferrule front section 32 supports the first fiber end section 31 proximally to the first fiber end 31a by mechanically holding said first fiber end section proximally to the first fiber end in axial position.

The ferrule structure further comprises an outer ferrule arrangement 75, 75a comprising an outer ferrule front section 75a and an outer ferrule rear section 75. The outer ferrule rear section 75 is fixed to each of the inner ferrule front section 72 and the inner ferrule rear section 73 to hold them in a fixed position relative to each other and to form a gap 74 there between. The outer ferrule rear section 75 is fixed by solder 76 at each of its ends to the respective sections 72, 73 of the inner ferrule arrangement and the outer ferrule front section 75a is fixed by solder 76 to the inner ferrule front section 72.

The ferrule structure further comprises an end cap 77a arranged in front of the first fiber end 71c. The end cap 77a is mounted with a distance to the inner ferrule front section 72, thereby forming an end cap space 78 between the end cap 77a and the inner ferrule front section 72. The end cap is fixed to the outer ferrule front section 75a of the outer ferrule arrangement. Thereby the outer ferrule front section 75a of the outer ferrule arrangement holds the end cap 77a in a desired position relative to the inner ferrule front section 72 and the first fiber end section 71c. As explained above this embodiment is particularly beneficial where the PCF is a hollow core PCF.

The inner ferrule arrangement 72, 73 comprises a passage into the end cap space 78 for injecting and/or withdrawing fluids. The passage is provided by additional through holes 72f, 73f in each of the inner ferrule front section 72 and the inner ferrule rear section 73. Advantageously a not shown valve arrangement is arranged to ensure a desired open/closing function into the through holes 72f, 73f and the end cap space 78.

The PCF assembly shown in Fig. 9 a, differs from the PCF assembly of Fig. 9 in that the end cap is a lens 77, preferably the lens 77 comprises an antireflective coating on both of its sides.

The PCF assembly of Fig. 10 comprises a photonic crystal fiber (PCF) assembly PCF with a first fiber end section 81 assembled with a ferrule

PATENT CLAIMS

1. A photonic crystal fiber (PCF) assembly comprising a PCF and at least one ferrule structure, said PCF has a center axis and comprises a core region and a cladding region and a first fiber end section with a first fiber end, said ferrule structure has a center axis and is mounted to said first fiber end section, said ferrule structure comprises an inner ferrule arrangement and an outer ferrule arrangement surrounding the first fiber end section, said inner ferrule arrangement comprises an inner ferrule front section proximally to said first fiber end and an inner ferrule rear section distally to said first fiber end, each of said inner ferrule sections have an inner diameter and in at least a length thereof fully surrounds the PCF, said inner ferrule rear section is anchored in an anchor length section to said first fiber end section and said inner ferrule front section supports said first fiber end section proximally to said first fiber end, wherein said first fiber end section has at least one mode stripper length section and at least one of said inner ferrule front section and said inner ferrule rear section has a carving exposing said mode stripper length section of said PCF.

2. The PCF assembly of claim 1, wherein said carving partly surrounds the fiber, such that said carving extends at least 20 degrees.

3. The PCF assembly of claim 1 or claim 2, wherein said mode stripper length section comprises a mode stripping high index material and/or a scattering layer applied in contact with the optical fiber at said mode stripper length section and/or said fiber in said mode stripper length section has a roughness Ra value of at least 0.1 µm.

4. The PCF assembly of any one of the preceding claims, wherein said assembly further comprises an alignment sleeve arranged between the inner ferrule front section and the first fiber end section, such that the inner ferrule front section supports said first fiber end section proximally to said first fiber end via said alignment sleeve.

5. The PCF assembly of claim 4, wherein said inner ferrule front section supports said first fiber end section via said alignment sleeve and mechanically holds said alignment sleeve in axial position.

6. The PCF assembly of the preceding claims 4-5, wherein said alignment sleeve has a length in the axial direction which is up to the length of the inner ferrule front section.

7. The PCF assembly of any one of the preceding claims 4-6, wherein said alignment sleeve supports said first fiber end section, by having an inner diameter at least along a support section thereof which is up to 0.1 mm larger than the PCF diameter.

8. The PCF assembly of any one of the preceding claims 4-7, wherein said alignment sleeve is of glass.

9. The PCF assembly of any one of the preceding claims 4-8, wherein said alignment sleeve is of down doped silica.

10. The PCF assembly of any one of the preceding claims 4-9, wherein said alignment sleeve has a refractive index which is less than an effective refractive index of the cladding region.

11. The PCF assembly of any one of the preceding claims, wherein said inner ferrule front section and said inner ferrule rear section are not directly fixed to each other.

12. The PCF assembly of any one of the preceding claims, wherein said ferrule structure comprises a hermetic solder element arranged to surround said first fiber end section to form an annular hermetic seal between the first fiber end section and said inner ferrule rear section, said hermetic solder element is arranged closer to a front annular section than the anchor length section of the inner ferrule rear section.

13. The PCF assembly of any one of the preceding claims, wherein said PCF is free of polymer coating in the first fiber end section from an anchoring section of the inner ferrule rear section to the first fiber end.

14. The PCF assembly of any one of the preceding claims, wherein said inner ferrule front section is of an at least partly transparent material at a wavelength between 200 nm and 4 µm, said inner ferrule front section is of fused or crystallized quartz.

15. The PCF assembly of any one of the preceding claims, wherein said inner ferrule rear section is of fused or crystallized quartz or of a metal or alloy.

16. The PCF assembly of any one of the preceding claims, wherein said outer ferrule arrangement is fixed to each of said inner ferrule front section and said inner ferrule rear section of said inner ferrule arrangement to hold them in a fixed position relative to each other.

17. The PCF assembly of any one of the preceding claims, wherein said first fiber end section is mounted in said ferrule structure without any direct bonds to the fiber beyond one or more bonds to the inner ferrule rear section including the anchoring.

18. The PCF assembly of any one of the preceding claims, wherein said ferrule structure comprises an end cap arranged in front of said first fiber end, said end cap being mounted with a distance or without a distance to the inner ferrule front section.

19. The PCF assembly of claim 18, wherein said end cap is fixed to said outer ferrule front section of the outer ferrule arrangement.

20. The PCF assembly of any one of the preceding claims, wherein said PCF has a core diameter of less than 100 µm.

21. The PCF assembly of claims 18-20, wherein the PCF is a hollow core fiber and said end cap is fixed to said outer ferrule front section of the outer ferrule arrangement to provide an end cap space between said end cap and said inner ferrule front section.

22. The PCF assembly of claim 21, wherein the inner ferrule arrangement comprises a passage into said end cap space for injecting and/or withdrawing fluids.

23. The PCF assembly of any one of the preceding claims, wherein said first fiber end section has an further mode stripper length section positioned between said inner ferrule front section and said inner ferrule rear section.

24. The PCF assembly of any one of the preceding claims, wherein the ferrule structure comprises a mode stripper coating arranged in direct contact with an outer surface of the inner ferrule front section.

25. A laser system comprising a PCF assembly according to any one of the preceding claims, wherein said laser system comprises a laser light source, said PCF assembly being optically connected to said laser light source for receiving light from said laser light source and being adapted for delivering said light to a light employing station of an apparatus.