HOLLOW-CORE ANTI-RESONANT OPTICAL FIBER WITH SINGLE-MODE AND ULTRA-LOW LOSS

Field of the Invention

The present disclosure relates to a hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss, which belongs to the technical field of optical communication and transmission.

Background of the Invention

A hollow-core anti-resonant optical fiber has a unique microstructure design, can confine transmitted optical waves in an air fiber core, and has important applications in fields such as light-matter interaction, nonlinear optics, gas detection, gas laser generation, and optofluidics. Due to its unique structure and light guidance mechanism, the hollow-core anti-resonant optical fiber can obtain ultra-low Rayleigh scattering, a low nonlinear coefficient, and tunable chromatic dispersion, offering a higher laser-induced damage threshold, so that it is potentially applied in high-power laser transmission, ultraviolet/mid-infrared light transmission, pulse compression, and optical soliton transmission. The air core has an ultra-low loss, low chromatic dispersion, low nonlinearity, and a propagation speed close to the speed of light, and can realize the transmission of hollow-core optical fiber communication and the development of devices for communication, thereby laying a foundation for the construction and development of the next-generation ultra-high-capacity, low-latency, high-speed optical communication systems.

Even though the hollow-core optical fiber has a unique and great advantage in design and application, since it inherently lacks a higher-order mode cutoff condition, a higher-order mode in the hollow-core optical fiber cannot be effectively filtered out in the same way as in a solid-core single-mode optical fiber. This will significantly limit its application in short-distance transmission scenarios. Recent studies show that, the leakage loss of the higher-order mode can be enhanced to a certain extent by a reasonable structural design, thereby achieving an effect similar to an effect produced by a single-mode after transmission over a certain distance.

A current commonly used approach for filtering out the higher-order mode is to select a cladding mode with a high attenuation, and the cladding mode is highly phase-matched with an LP11 mode in the fiber core by a structural design, thereby

effectively enhancing the leakage loss of the LP11 mode. Key factors in this design approach are the intrinsic attenuation of the cladding mode and the degree of phase matching between the cladding mode and the LP11 mode. Generally, the higher the attenuation of the cladding mode and the higher the degree of phase-matching between the cladding mode and the LP11 mode are, the greater the enhancement to the leakage of the LP11 mode, and the better the single-mode performance.

A US patent US11733451B2 discloses a single-ring hollow-core anti-resonant optical fiber. This patent proposes using a high-loss anti-resonant element (ARE) mode to highly phase-match with the LP11 mode in the fiber core. This structure is very simple, is easy to fabricate via fiber drawing, and can achieve an ultra-high higher-order mode suppression ratio. When a dimension ratio of a cladding tube to a fiber core is 0.68, a broadband high single-mode performance can be achieved, and the attenuation of the LP11 mode can reach the magnitude of 10^2 dB/m. However, this structure struggles to achieve ultra-low attenuation transmission, currently has a lowest attenuation of 4.3 dB/km (1080 nm) in the near-infrared band and an even higher attenuation in the communication band and has a poor bending resistance, and thus has limited advantages for many applications in the near-infrared band.

A Chinese patent CN110515152B discloses a hollow-core nested anti-resonant nodeless fiber (NANF) and a hollow-core double nested anti-resonant nodeless fiber (DNANF). These two structures effectively reduce the transmission loss of a fundamental mode by increasing the number of anti-resonant layers. With respect to the NANF, its lowest attenuation has reached 0.22 dB/km, and the DNANF has even broken the minimum attenuation record of the conventional solid-core fiber, reaching 0.11 dB/km. However, the above two optical fibers also keep the loss of the LP11 mode at a relatively low level while achieving an ultra-low attenuation. When the NANF structure achieves an optimal resonant leakage design in the LP11 mode, the theoretical LP11 attenuation is at the magnitude of about 10^2 to 10^3 dB/km, and under actual fabrication and placement conditions, the current highest attenuation can reach 2.6 dB/m. The intrinsic attenuation of its cladding mode has been significantly reduced as the number of structural layers increases, so the attenuation of the LP11 mode cannot reach a sufficiently high level. This situation is even more severe in the DNANF structure: first, the attenuation of the cladding mode is further reduced in the DNANF structure; second, the cladding region of DNANF structure no longer has sufficient space for the LP11 mode and cladding mode to achieve adequate phase

matching, and the theoretical attenuation of the LP11 mode has been less than 10^2 dB/km, which means that the higher-order mode cannot be filtered out in the DNANF, thereby severely affecting the signal transmission quality.

Summary of the Invention

The problem to be solved in the present disclosure is to provide a hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss in view of the shortcomings existing in the prior art, which increases a loss of a higher-order mode while reducing a loss of a fundamental mode by changing a structure of a cladding and thus achieves transmission with a low loss under a high-purity single-mode.

In order to solve the above problems, the technical solution adopted in the present disclosure is as follows. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss includes an outer cladding and an inner cladding which is formed by nested structural elements arranged circumferentially at an interval along an internal surface of the outer cladding and connected to the internal surface of the outer cladding and clads a central cavity to form an equivalent circular fiber core cavity, the nested structural element including two or more layers of nested glass tubes having different radii, characterized in that, an auxiliary inner cladding is disposed along a circumference of the internal surface of the outer cladding and includes auxiliary nested structural elements, the auxiliary nested structural elements are arranged at an interval along the circumference of the internal surface of the outer cladding in an alternate manner with the nested structural elements and are connected to the internal surface of the outer cladding, and an equivalent circular mode-filtering cavity, tangent to an auxiliary nested structural element and nested structural elements on two adjacent sides, is formed between the auxiliary nested structural element and the nested structural elements on two adjacent sides.

According to the above solution, the auxiliary nested structural element includes one or more layers of nested glass tubes having different radii.

According to the above solution, the nested glass tubes include an outer nested glass tube and an inner nested glass tube from outside to inside.

According to the above solution, there are one or more auxiliary nested structural elements, each of which is located between two adjacent nested structural elements.

According to the above solution, the auxiliary nested structural element is arranged symmetrically between two adjacent nested structural elements, that is, a

geometric centerline of the auxiliary nested structural element coincides with a geometric centerline of the two adjacent nested structural elements.

According to the above solution, the inner cladding includes three to five nested structural elements, and the auxiliary inner cladding correspondingly includes three to five auxiliary nested structural elements.

According to the above solution, the nested structural elements are arranged at an interval circumferentially and uniformly along the internal surface of the outer cladding.

According to the above solution, the nested structural element includes three layers of nested glass tubes having different radii, i.e., including an outer nested glass tube, a first inner nested glass tube, and a second inner nested glass tube from outside to inside.

According to the above solution, the outer cladding and the internal surface are both circular.

According to the above solution, the nested glass tubes include circular nested glass tubes having different radii, respective circular nested glass tubes are tangent, and the outer nested glass tube is tangent to an inner cavity surface of the outer cladding.

According to the above solution, the nested glass tubes include circular-arc nested glass tubes having different radii and circular nested glass tubes having different radii, wherein respective circular-arc nested glass tubes intersect with the internal surface of the outer cladding or intersect with adjacent nested glass tubes on the outside, and respective circular nested glass tubes are tangent to respective circular nested glass tubes or tangent to the internal surface of the outer cladding.

According to the above solution, the nested glass tubes include circular-arc nested glass tubes having different radii, and respective circular-arc nested glass tubes intersect with the internal surface of the outer cladding.

According to the above solution, a base material of the outer cladding, a base material of the inner cladding, and a base material of the auxiliary inner cladding are all pure silica glass.

According to the above solution, single-side wall thicknesses of the inner nested glass tubes, the outer nested glass tubes constituting, the nested structure elements and the auxiliary nested structure elements are consistent or have a difference of less than 20%.

According to the above solution, single-side wall thicknesses of the inner nested glass tubes and the outer nested glass tubes constituting the nested structure elements and the auxiliary nested structure elements and a single-side wall thickness of the outer cladding are from 0.3 μm to 1.5 μm.

According to the above solution, the nested structure element includes three layers of nested glass tubes having different radii, wherein the outer nested glass tube and the first inner nested glass tube are circular glass tubes having different radii, and a support pad is disposed at a connection between the outer nested glass tube and the first inner nested glass tube.

According to the above solution, there are one or more support pads distributed along a circumference.

According to the above solution, a cross section of the support pad is approximately circular, oval, rhombic, or rectangular.

According to the above solution, a ratio of a diameter of the equivalent circular fiber core cavity to a diameter of the equivalent circular mode-filtering cavity is 1:0.4 to 0.7.

According to the above solution, a ratio of a diameter of a circular fiber core to a diameter of the outer nested glass tube of the nested structural element is 1:1.2 to 1.5.

According to the above solution, a ratio of a diameter of the outer nested glass tube of the nested structural element to a diameter of the first inner nested glass tube of the nested structural element is 1: 0.55 to 0.75.

According to the above solution, a ratio of a diameter of the first inner nested glass tube of the nested structural element to a diameter of the second inner nested glass tube of the nested structural element is 1: 0.4 to 0.7.

According to the above solution, a fiber core cavity region and other cavity regions in the outer cladding are filled with a gas.

According to the above solution, the gas is argon, nitrogen, helium, air or a mixture of multiple gases.

According to the above solution, a loss of a fundamental mode of the optical fiber is less than 0.5 dB/km, and preferably the loss of the fundamental mode of the optical fiber is less than 0.15 dB/km.

According to the above solution, a loss of a higher-order mode of the optical fiber is greater than 6 dB/m; and preferably the attenuation of the higher-order mode of the optical fiber is greater than 10 dB/m.

The present disclosure has the following beneficial effects. 1. An auxiliary inner cladding is disposed to form a circular mode-filtering cavity between the auxiliary inner cladding and nested structural elements as a higher-order mode resonance filtering-out unit, the cavity region is close to the outermost side of a microstructure, and a fundamental mode in the region has an ultra-high attenuation; phase-matching between a mode of an air region and a higher-order mode of the fiber core is further designed, enabling more efficient leakage of the higher-order mode of the fiber core, significantly enhancing the attenuation of the higher-order mode, and an excellent single-mode transmission performance; and a single-mode performance of a hollow-core optical fiber can be enhanced significantly while achieving transmission with an ultra-low loss. 2. With respect to the fundamental mode, the cladding of the present disclosure includes multiple layers of anti-resonant silica walls and an air layer, the transmitted fundamental mode is effectively confined in the fiber core to restrict the reduction of the loss and achieve transmission with an ultra-low loss, and the optimized support pad can further reduce the attenuation of the optical fiber. 3. The single-mode performance of the present disclosure is not wavelength-selected, and high single-mode transmission can be achieved within an operating wavelength. The loss of the higher-order mode is enhanced while reducing the loss of the fundamental mode, so as to achieve transmission with a low loss under a high-purity single-mode, providing a transmission medium having an excellent performance for fields such as high-speed communication, high-power transmission, gas laser, and gas detection.

Brief Description of the Drawings

Fig. 1 is a structural diagram of a radial section in Embodiment One of the present disclosure.

Fig. 2 is a loss spectrum of the LP01 mode in Embodiment One of the present disclosure.

Fig. 3 is a loss spectrum of the LP11 mode in Embodiment One of the present disclosure.

Fig. 4 is a structural diagram of a radial section in Embodiment Two of the present disclosure.

Fig. 5 is a structural diagram of a radial section in Embodiment Three of the present disclosure.

Fig. 6 is a loss spectrum of the LP01 mode in Embodiment Three of the present disclosure.

Fig. 7 is a structural diagram of a radial section in Embodiment Four of the present disclosure.

Fig. 8 is a structural diagram of a radial section in Embodiment Five of the present disclosure.

Fig. 9 is a structural diagram of a radial section in Embodiment Six of the present disclosure.

Fig. 10 is a structural diagram of a radial section in Embodiment Seven of the present disclosure.

Fig. 11 is a structural diagram of a radial section in Embodiment Eight of the present disclosure.

Detailed Description of the Embodiments

The present embodiment is further described in detail below in conjunction with embodiments of the present disclosure and the accompanying drawings.

Embodiment One: Fig. 1 shows a hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss, which includes an outer cladding 1 and an inner cladding which is formed by four nested structural elements arranged circumferentially and uniformly at an interval along an internal surface of the outer cladding and connected to the internal surface of the outer cladding. The nested structural element includes three layers of circular nested glass tubes having different radii, i.e., including a circular outer nested glass tube 201, a circular first inner nested glass tube 202, and a circular second inner nested glass tube 203 from outside to inside. The outer nested glass tube is tangent to an inner cavity surface of the outer cladding, and respective circular nested glass tubes are tangent at the same point. An (equivalent) circular fiber core cavity 4, which is tangent to respective nested structural elements, is formed in the center cladded by the four nested structural elements. An auxiliary inner cladding is disposed along a circumference of the internal surface of the outer cladding, and the auxiliary inner cladding includes four auxiliary nested structural elements. The auxiliary nested structural elements are arranged at an interval along the circumference of the internal surface of the outer cladding in an alternate manner with the nested structural elements. The auxiliary nested structural element is disposed symmetrically between two adjacent nested

structural elements. That is, a geometric centerline of the auxiliary nested structural element coincides with a geometric centerline of the two adjacent nested structural elements. The auxiliary nested structural element includes one layer of circular nested glass tube 301. That is, the auxiliary nested structural element is formed by one circular outer nested glass tube, and is tangent to the internal surface of the outer cladding. An (equivalent) circular mode-filtering cavity 5, tangent to an auxiliary nested structural element and nested structural elements on two adjacent sides, is formed between the auxiliary nested structural element and the nested structural elements on two adjacent sides. Four circular mode-filtering cavities distributed symmetrically are formed in the entire cavity of the outer cladding. A ratio of a diameter of the equivalent circular fiber core cavity to a diameter of the equivalent circular mode-filtering cavity is 1:0.4 to 0.7. A ratio of a diameter of the equivalent circular fiber core cavity to a diameter of the outer nested glass tube of the nested structural element is 1:1.2 to 1.5. A ratio of a diameter of the outer nested glass tube of the nested structural element to a diameter of the first inner nested glass tube of the nested structural element is 1: 0.55 to 0.75. A ratio of a diameter of the first inner nested glass tube of the nested structural element to a diameter of the second inner nested glass tube of the nested structural element is 1: 0.4 to 0.7. A base material of the outer cladding, a base material of the inner cladding, and a base material of the auxiliary inner cladding are all pure silica glass. Single-side wall thicknesses of the inner nested glass tubes and the outer nested glass tubes constituting the nested structure elements and the auxiliary nested structure elements are consistent or approximately consistent. A fiber core cavity region and other cavity regions in the outer cladding are filled with a gas.

Specific structural parameters in Embodiment One are as follows: a diameter of the equivalent circular fiber core cavity is 28 μm; an outer diameter of the outer nested glass tube is 40 μm, an outer diameter of the first inner nested glass tube is 30 μm, and a ratio of the outer diameter of the first inner nested glass tube to the outer diameter of the outer nested glass tube is 0.75; an outer diameter of the second inner nested glass tube is 16 μm, and an inner diameter of the outer cladding is 105 μm. The auxiliary nested structural element includes one layer of circular nested glass tube 301 having an outer diameter of 7.6 μm. An interval between outer nested glass tubes of two adjacent nested structural elements is greater than 8 μm, so that the optical fiber has a more stable structure and is easy to draw in the process of drawing. In the

present embodiment, single-side wall thicknesses of the inner nested glass tubes and the outer nested glass tubes are 1.1 μm, and when a second resonant operating band is extended to 1310 nm, respective wall thicknesses should be 0.95 μm; and when a first anti-resonant window is used as an operating band for communication, respective wall thicknesses should be 0.5 μm. The present disclosure has a rational and fabricable shape of a cladding wall, an optimized combination of dimensions, and an innovative mode-filtering cavity design, which collectively produce the following technical effects: significantly enhancing the leakage loss of the LP11 mode, reducing the transmission loss of the fundamental mode, and finally effectively improving the single-mode performance of the optical fiber. As shown in Fig. 2, the present embodiment can achieve ultra-low attenuation transmission of less than 0.1 dB/km within a bandwidth of about 400 nm. As shown in Fig. 3, the attenuation of the LP11 mode has a leakage loss of greater than 10 dB/m within a light guide band and close to 100 dB/m within a broadband range, and high-performance single-mode transmission can be achieved.

Embodiment Two: As shown in Fig. 4, the present embodiment differs from Embodiment One mainly in the following aspects. The nested structural element includes three layers of circular-arc nested glass tube and circular nested glass tubes having different radii, i.e., including a circular-arc outer nested glass tube 201 and circular first inner nested glass tube 202 and a circular second inner nested glass tube 203 from outside to the inside. The circular-arc outer nested glass tube intersects with the internal surface of the outer cladding, and respective circular inner nested glass tubes are tangent at the same point on the internal surface of the outer cladding. The present embodiment has a circular fiber core cavity 4 having a diameter the same as the diameter in Embodiment One, but the inner diameter of the outer cladding 1 is smaller. A ratio of a diameter of the equivalent circular fiber core cavity to a diameter of the equivalent circular mode-filtering cavity is 1:0.5 to 0.7. A ratio of a diameter of a circular fiber core to a diameter of the outer nested glass tube of the nested structural element is 1:1.2 to 1.5. Other structures are the same as the structures in Embodiment One.

Embodiment Three: As shown in Fig. 5 and Fig. 6, the present embodiment differs from Embodiment One in the following aspects. The nested structural element includes three layers of circular nested glass tubes having different radii, i.e., including a circular outer nested glass tube 201, a circular first inner nested glass tube

202, and a circular second inner nested glass tube 203 from outside to the inside. The outer nested glass tube is tangent to an inner cavity surface of the outer cladding, and respective circular nested glass tubes are tangent at the same point. A support pad 204 is disposed at a connection between the outer nested glass tube and the first inner nested glass tube, the number of the support pad is one. A cross section of the support pad is approximately oval. The first inner nested glass tube and the second inner nested glass tube are both externally tangent at an inner-side tangent point on the support pad, and the outer nested glass tube and the inner cavity surface of the outer cladding are both internally tangent at an outer-side tangent point on the support pad. The inner-side tangent point and the outer-side tangent point are located on the same radial line. This structure allows the outer nested glass tube and the first inner nested glass tube to distribute at approximately equal intervals. Specific structural parameters are as follows: a diameter of the equivalent circular fiber core cavity is 28 μm; an outer diameter of the outer nested glass tube is 42 μm, and an outer diameter of the first inner nested glass tube is 27.3 μm, a ratio of the outer diameter of the first inner nested glass tube to the outer diameter of the outer nested glass tube is 0.65; an outer diameter of the second inner nested glass tube is 12 μm, and an inner diameter of the outer cladding is 110 μm. In the present embodiment, the support pad is a solid oval having a long axis of 9 μm and a short axis of 4 μm, and a material of the support pad is pure silica glass. The auxiliary nested structural element includes one layer of circular nested glass tube 301 having an outer diameter of 8.2 μm. An interval between outer nested glass tubes of any two adjacent nested structural elements is greater than 8 μm, so that the optical fiber has a more stable structure and is easy to draw in the process of drawing. In the present embodiment, single-side wall thicknesses of the inner nested glass tubes and the outer nested glass tubes are 1.1 μm, and when a second resonant operating band is extended to 1310 nm, respective wall thicknesses should be 0.95 μm; and when a first anti-resonant window is used as an operating band for communication, respective wall thicknesses should be 0.5 μm.

The present disclosure has a rational and fabricable shape of a cladding wall, an optimized combination of dimensions, and an optimal dimension of the silica pad, which collectively produce the following technical effects: significantly enhancing the leakage loss of the LP11 mode, reducing the transmission loss of the fundamental mode, and finally effectively improving the single-mode performance of the optical fiber. An interval between any two adjacent nested structural elements is greater than

8 μm, which greatly reduces the difficulty of drawing and is beneficial to large-scale and long-distance production. The introduction of the silica support pad can further reduce the attenuation of the optical fiber, and meanwhile enhance the leakage efficiency of the higher-order mode of the fiber core. As shown in Fig. 6, the present embodiment can achieve ultra-low attenuation transmission of less than 0.1 dB/km within a bandwidth of about 400 nm.

Embodiment Four: As shown in Fig. 7, Embodiment Four differs from Embodiment Three in the shape of the support pad. In the present embodiment, a cross section of the support pad is a solid circle having a diameter of 5 μm.

Embodiment Five: As shown in Fig. 8, Embodiment Five differs from Embodiment Three in the shape of the support pad. In the present embodiment, a cross section of the support pad is a solid rectangle.

Embodiment Six: As shown in Fig. 9, in order to increase the structural stability, in Embodiment Six, on the basis of Embodiment Four, the number of the solid-circle support pad is increased to two, and two support pads are disposed symmetrically at two sides of the inner nested glass tube.

Embodiment Seven: As shown in Fig. 10, in order to increase the structural stability, in Embodiment Seven, on the basis of Embodiment Five, the number of the rectangular support pad is increased to two, and two support pads are disposed symmetrically at two sides of the inner nested glass tube.

Embodiment Eight: As shown in Fig. 11, in order to increase the structural stability, in Embodiment Eight, on the basis of Embodiment Five, the number of the rectangular support pad is increased to three.

Claims

1. A hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss, comprising:

an outer cladding; and

an inner cladding which is formed by nested structural elements arranged circumferentially at an interval along an internal surface of the outer cladding and connected to the internal surface of the outer cladding and clads a central cavity to form an equivalent circular fiber core cavity, the nested structural element comprising two or more layers of nested glass tubes having different radii, wherein an auxiliary inner cladding is disposed along a circumference of the internal surface of the outer cladding and comprises auxiliary nested structural elements, the auxiliary nested structural elements are arranged at an interval along the circumference of the internal surface of the outer cladding in an alternate manner with the nested structural elements and are connected to the internal surface of the outer cladding, and an equivalent circular mode-filtering cavity, tangent to an auxiliary nested structural element and nested structural elements on two adjacent sides, is formed between the auxiliary nested structural element and the nested structural elements on two adjacent sides.

2. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1, wherein the auxiliary nested structural element comprises one or more layers of nested glass tubes having different radii.

3. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein the nested glass tubes comprise an outer nested glass tube and an inner nested glass tube from outside to inside.

4. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein there are one or more auxiliary nested structural elements, each of which is located between two adjacent nested structural elements.

5. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein the auxiliary nested structural element is arranged symmetrically between two adjacent nested structural elements such that a geometric centerline of the auxiliary nested structural element coincides

with a geometric centerline of the two adjacent nested structural elements.

6. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein the inner cladding comprises three to five nested structural elements, and the auxiliary inner cladding correspondingly comprises three to five auxiliary nested structural elements.

7. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 6, wherein the nested structural elements are arranged at an interval circumferentially and uniformly along the internal surface of the outer cladding.

8. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein the nested structural element comprises three layers of nested glass tubes having different radii, comprising an outer nested glass tube, a first inner nested glass tube, and a second inner nested glass tube from outside to inside.

9. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein the outer cladding and the internal surface are both circular.

10. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein the nested glass tubes comprise circular nested glass tubes having different radii, respective circular nested glass tubes are tangent, and the outer nested glass tube is tangent to an inner cavity surface of the outer cladding.

11. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein the nested glass tubes comprise circular-arc nested glass tubes having different radii and circular nested glass tubes having different radii, wherein respective circular-arc nested glass tubes intersect with the internal surface of the outer cladding or intersect with adjacent nested glass tubes on the outside, and respective circular nested glass tubes are tangent to respective circular nested glass tubes or tangent to the internal surface of the outer cladding.

12. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein the nested glass tubes comprise circular-arc nested glass tubes having different radii, and respective circular-arc nested glass tubes intersect with the internal surface of the outer cladding.

13. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein a base material of the outer cladding, a base material of the inner cladding, and a base material of the auxiliary inner cladding are all pure silica glass.

14. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 3, wherein single-side wall thicknesses of the inner nested glass tubes and the outer nested glass tubes constituting the nested structure elements and the auxiliary nested structure elements are consistent or have a difference of less than 20%.

15. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 3, wherein single-side wall thicknesses of the inner nested glass tubes and the outer nested glass tubes constituting the nested structure elements and the auxiliary nested structure elements and a single-side wall thickness of the outer cladding are from 0.3 μm to 1.5 μm.

16. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 8, wherein the nested structure element comprises three layers of nested glass tubes having different radii, wherein the outer nested glass tube and the first inner nested glass tube are circular glass tubes having different radii, and a support pad is disposed at a connection between the outer nested glass tube and the first inner nested glass tube.

17. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 16, wherein there are one or more support pads distributed along a circumference; and a cross section of the support pad is approximately circular, oval, rhombic, or rectangular.

18. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein a ratio of a diameter of the equivalent circular fiber core cavity to a diameter of the equivalent circular mode-filtering cavity is 1:0.4 to 0.7.

19. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 3, wherein a ratio of a diameter of a circular fiber core to a diameter of the outer nested glass tube of the nested structural element is 1:1.2 to 1.5.

20. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 3, wherein a ratio of a diameter of the outer nested

glass tube of the nested structural element to a diameter of the first inner nested glass tube of the nested structural element is 1: 0.55 to 0.75.

21. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 3, wherein a ratio of a diameter of the first inner nested glass tube of the nested structural element to a diameter of the second inner nested glass tube of the nested structural element is 1: 0.4 to 0.7.

22. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein a fiber core cavity region and other cavity regions in the outer cladding are filled with a gas, and the gas is argon, nitrogen, helium, air or a mixture of multiple gases.

23. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein a loss of a fundamental mode of the optical fiber is less than 0.5 dB/km.

24. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 18, wherein a loss of a fundamental mode of the optical fiber is less than 0.1 dB/km.

25. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 1 or claim 2, wherein a loss of a higher-order mode of the optical fiber is greater than 6 dB/m.

26. The hollow-core anti-resonant optical fiber with a single-mode and an ultra-low loss according to claim 18, wherein an attenuation of a higher-order mode of the optical fiber is greater than 10 dB/m.