

OPTICAL FIBER, LIGHTING APPARATUS HAVING THE SAME, AND
METHOD FOR FORMING THE SAME

Cross-Reference To Related Application

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[0001] This application claims the benefit of priority of Singapore patent application No. 10201908040X, filed 30 August 2019, the content of it being hereby incorporated by reference in its entirety for all purposes.

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Technical Field

[0002] Various embodiments relate to an optical fiber, a lighting apparatus having the optical fiber and a method for forming the optical fiber.

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Background

[0003] FIG. 1 shows a light diffusing fiber 190 of the prior art. The light diffusing fiber 190 includes a solid core 192 (e.g., silica or doped silica), a scattering core 194, and another solid core 196 (e.g., silica or doped silica). The light diffusing fiber 190 utilises small scatterers (e.g. voids) 195 to extract out guided light from the fiber 190. The scatterers 195 are generated during a preform fabrication step based on a chemical vapour deposition process. The preform containing the scatterers 195 is drawn to the light diffusing fiber 190 with a coating layer (or jacket) 198 (e.g., low index polymer or glass) to provide physical strength and light guidance (for clarity, the jacket 198 is not shown in the side view). Hence, the chemical vapour deposition process is essential to create the scattering mechanism and realise the diffusing fiber 190. However, such chemical vapour deposition process is expensive and complicated.

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Summary

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[0004] The invention is defined in the independent claims. Further embodiments of the invention are defined in the dependent claims.

[0005] According to an embodiment, an optical fiber is provided. The optical fiber may include a core region having a scattering structure defined therein, the scattering structure being twisted about a longitudinal axis of the core region, wherein the scattering structure is configured to scatter light propagating in the optical fiber out of the optical fiber.

5 [0006] According to an embodiment, a lighting apparatus is provided. The lighting apparatus may include a light source configured to provide a light, and an optical fiber as described herein, the optical fiber being configured for receiving the light for propagation in the optical fiber.

[0007] According to an embodiment, a method for forming an optical fiber is provided. The
10 method may include twisting a scattering structure in a core region of the optical fiber about a longitudinal axis of the core region, wherein the scattering structure is configured to scatter light propagating in the optical fiber out of the optical fiber.

Brief Description of the Drawings

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[0008] In the drawings, like reference characters generally refer to like parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

20 [0009] FIG. 1 shows a schematic diagram of a light diffusing fiber of the prior art.

[0010] FIG. 2A shows a schematic side view of an optical fiber, according to various embodiments.

[0011] FIG. 2B shows a schematic view of a lighting apparatus, according to various embodiments.

25 [0012] FIG. 2C shows a method for forming an optical fiber, according to various embodiments.

[0013] FIG. 3A shows a schematic diagram of a fiber with a twisted structure, according to various embodiments.

30 [0014] FIG. 3B shows a schematic diagram of a fiber with a twisted scattering structure having a variable pitch, according to various embodiments.

[0015] FIG. 3C shows a schematic diagram of a fiber with a twisted scattering structure and scattering agents, according to various embodiments.

[0016] FIG. 3D shows a schematic diagram of a fiber with a twisted scattering structure and spectral modifying agents, according to various embodiments.

5 [0017] FIG. 3E shows a schematic diagram of a fiber with an external twist, according to various embodiments.

[0018] FIGS. 4A to 4J show cross-sectional views of various structures that fulfill transverse refractive index and/or geometrical features for defining a fiber with a twisted scattering structure.

10 [0019] FIG. 5 shows a schematic diagram illustrating the scattering angle distribution of a fiber according to various embodiments.

[0020] FIGS. 6A and 6B show schematic diagrams illustrating a fabrication process to fabricate a radiating fiber having cross-sectional features twisted along the fiber axis, according to various embodiments.

15 [0021] FIG. 7 shows a microscopy image of a fabricated fiber. The scale represents 20 μm .

[0022] FIG. 8A shows a schematic diagram illustrating a setup for fiber illumination while FIG. 8B shows a photo of an illuminated fiber of various embodiments.

Detailed Description

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[0023] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various

25 embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0024] Embodiments described in the context of one of the methods or devices are analogously valid for the other methods or devices. Similarly, embodiments described in the context of a

30 method are analogously valid for a device, and vice versa.

[0025] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0026] In the context of various embodiments, the phrase “at least substantially” may include “exactly” and a reasonable variance.

[0027] In the context of various embodiments, the term “about” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0028] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0029] As used herein, the phrase of the form of “at least one of A or B” may include A or B or both A and B. Correspondingly, the phrase of the form of “at least one of A or B or C”, or including further listed items, may include any and all combinations of one or more of the associated listed items.

[0030] Various embodiments may provide a twisted optical fiber possessing a twisted or helical path for out-scattering light.

[0031] Various embodiments may provide design and fabrication methods of a radiating fiber. A radiating fiber may find interesting applications in decorations and lightings of small areas such as consumer electronics, automotive, architectural and medical industry, to name just a few, where bulky light fixtures cannot be deployed. The techniques disclosed herein may provide a method to obtain one or more light radiating fibers, which offer easy manipulation of light scattering strength over a distance. The radiating fiber may be realised via simple and low-cost fabrication routes and may also allow post-fabrication control of scattering strength.

[0032] In contrast to known fibers, such as the light diffusing fiber 190 (FIG. 1), the techniques disclosed herein do not involve the expensive and complicated chemical vapour deposition process. The techniques disclosed herein may provide a fiber having a radiating mechanism that utilises a twisted structure. In various embodiments, the twisted structure or the light guiding pipe structure may have a cross-sectional geometric and/or refractive index features such that when viewed transversely, permit the twist to be observed. The light guiding structure (or fiber)

may have a core of transparent material and a surrounding cladding of lower refractive index material which when twisted about its axis scatters light.

[0033] FIG. 2A shows a schematic side view of an optical fiber 200, according to various embodiments. The optical fiber 200 includes a core region 202 having a scattering structure 204 defined therein, the scattering structure 204 being twisted about a longitudinal axis 205 of the core region 202, wherein the scattering structure 204 is configured to scatter light (represented by solid arrow 222) propagating in the optical fiber 200 out of the optical fiber 200 (the out-scattered light is represented by open arrows 223).

[0034] In other words, an optical fiber 200 that may provide out-scattered light 223 may be provided. Such an optical fiber 200 may provide illumination to the surroundings. The optical fiber 200 may include a (optical) core region (for light propagation or transmission) having a scattering structure 204 defined therein. The scattering structure 204 may be twisted (or wounded), e.g., helically twisted, about a longitudinal axis 205 of the core region 202. Therefore, the scattering structure 204 may extend longitudinally (or lengthwise or in the direction of or along the length of the core region 202). The longitudinal axis 205 may include or may mean any axis extending longitudinally, including, for example, the central axis of the core region 202. The scattering structure 204 may scatter (or emit) light 222 propagating in (or through) the optical fiber 200 out of the optical fiber to provide out-scattered light 223. In some embodiments, the twisted scattering structure 204 may have a plurality of loops along the length of the core region 202.

[0035] The core region 202 may be configured to transmit light. The light 222 may propagate in the core region 202 and may then be out-scattered (as light 223) as the propagating light 222 encounters the scattering structure 204. For example, the light 222 may be scattered as the light 222 encounters the interface between the core region 202 and the scattering structure 204.

[0036] In various embodiments, the light 222 may not propagate in the scattering structure 204, e.g., when the scattering structure 204 includes air or may be an airy scattering structure 204, or when the refractive index of the scattering structure 204 is lower than that of the core region 202. This may mean that the scattering structure 204 may not be adapted to guide light therewithin, or the scattering structure 204 may not be a light-transmitting structure. In other embodiments, the light 222 may propagate in the scattering structure 204 with a higher refractive index than the core region 202. This may mean that the scattering structure 204 may

guide light therewithin and the scattering structure 204 may scatter out light due to the twisting nature of the scattering structure 204.

[0037] The core region 202 may be solid, for example, completely solid. The core region 202 may include a high (refractive) index material. As non-limiting examples, the core region 202
5 may include a glass or a polymer.

[0038] In various embodiments, the scattering structure 204 may be provided within the core region 202, or may be integrated with the core region 202, or may be part of the core region 202. There is therefore provided a twisted scattering structure 204 within the core region 202 for out-scattering the light 222.

10 [0039] The direction of the twist of the scattering structure 204 may be along the longitudinal direction of the core region 202. The scattering structure 204 may follow a twisted (e.g., helical) path that is curved or a curved-shaped spiral path. However, it should be appreciated that other shapes may be possible, for example, the scattering structure 204 may follow a twisted (e.g., helical) path that is a square-shaped spiral path.

15 [0040] The optical fiber 200 may be a radiating fiber, meaning that light 222 propagating in the fiber 200 may be emitted out of the fiber 200, in the form of the out-scattered light 223.

[0041] It should be appreciated that more than one scattering structure 204 may be defined in the core region 202. In other words, the core region 202 may include a plurality of scattering structures 204 defined therein, each scattering structure 204 extending longitudinally and being
20 twisted about the longitudinal axis 205 of the core region 202, and configured to scatter the light 222 propagating in the optical fiber 200 out of the optical fiber 200. Each scattering structure 204 may be spaced apart from another scattering structure 204.

[0042] In various embodiments, the scattering structure 204 may have a refractive index that is different from a refractive index of the core region 202. The scattering structure 204 may be a
25 higher index or a lower index structure, compared to the core region 202.

[0043] The scattering structure 204 may include a solid material.

[0044] In various embodiments, a void region may be defined in the core region 202, the void region defining the scattering structure 204. In other words, the scattering structure 204 may include or may be a void region. In this way, the optical fiber 200 may include a void region or
30 space in the core region 202 to define the scattering structure 204. The void region may be a hollow channel, e.g., having air within. The void region may be an air region or an air channel.

[0045] The optical fiber 200 may further include a material filled within the void region so that a refractive index of the scattering structure 204 may be different from a refractive index of the core region 202. The material may be a solid material or a fluid (e.g., an index fluid), for example, a high index material or a low index material. As a result, the refractive index of the scattering structure 204 may be higher or lower than the refractive index of the core region 202.

[0046] In various embodiments, the scattering structure 204 may be transversely offset from a central axis (or centre) of the core region 202. As would be appreciated, the central axis may be aligned to a central point or central region of the core region 202. The transverse direction of the core region 202 may be perpendicular to the longitudinal direction of the core region 202. The scattering structure 204 may be offset from the central axis in a radial direction of the core region 202.

[0047] In various embodiments, the scattering structure 204 may be twisted (e.g., helically twisted) about the longitudinal axis 205 with a transverse offset (T) that is at least substantially constant (throughout the length of the core region 202, or along a length portion of the core region 202). This may mean that, at any point along the length of the core region 202, the transverse offset or spacing between the scattering structure 204 and the central axis of the core region 202 may be substantially constant or remains substantially the same. In other words, each point on the scattering structure 204 may be equi-distant to the central axis of the core region 202. Therefore, the scattering structure 204 may extend longitudinally with a constant transverse offset (T).

[0048] In various embodiments, the scattering structure 204 may be twisted (e.g., helically twisted) about the longitudinal axis 205 with a transverse offset (T) that is variable (throughout the length of the core region 202, or along a length portion of the core region 202). This means that the transverse offset (T) of the scattering structure 204 relative to the central axis of the core region 202 changes along a longitudinal direction of the core region 202.

[0049] In various embodiments, the scattering structure 204 may be twisted (e.g., helically twisted) about the longitudinal axis 205 with a twist period (or pitch, P) that is at least substantially constant (throughout the length of the core region 202). Therefore, the scattering structure 204 may extend longitudinally with a constant twist period.

[0050] In various embodiments, the scattering structure 204 may be twisted (e.g., helically twisted) about the longitudinal axis 205 with a twist period (or pitch, P) that is variable.

Therefore, the scattering structure 204 may extend longitudinally with a variable twist period. This may mean that there may be a higher number of loops of the twisted scattering structure 204 at one section of the optical fiber 200 compared to another section of the optical fiber 200. The twist period may, for example, decrease, along a length portion of the core region 202, in a longitudinal direction away from at least one input region of the optical fiber 200. A decrease in the twist period over a section of the optical fiber 200 leads to an increase in the number of loops of the scattering structure 204 over the section of the optical fiber 200. By having the twist period decrease, along a length portion of the core region 202, a more uniform illumination may be provided over the length of the fiber 200. An input region of the optical fiber 200 may mean a region through which the light 222 may be provided or launched into the optical fiber 200 for propagation. The input region of the optical fiber 200 may include an end region or end facet of the optical fiber 200. As a non-limiting example, the twist period may decrease, in the longitudinal direction, towards a central region or portion of the optical fiber 200, or towards an output region of the optical fiber 200.

[0051] In various embodiments, a size (e.g., a cross-sectional dimension) of the scattering structure 204 may be variable (throughout the length of the core region 202, or along a length portion of the core region 202). This means that the size of the scattering structure 204 changes along a longitudinal direction of the core region 202.

[0052] In various embodiments, a perimeter (or outer surface) of the core region 202 may have a non-circular (cross-sectional) shape that may be (helically) twisted about the longitudinal axis 205 to define the scattering structure 204. This may mean that the non-circular shape may be twisted longitudinally, along the length of the core region 202, about the longitudinal axis 205. In the context of various embodiments, a non-circular shape may mean a shape that is not a complete circle. The perimeter may have one or more portions that may be curved or may resemble parts of a circle, but the perimeter, as a whole, is not a complete circle. The perimeter may have one or more portions that may be curved, and one or more portions that may be linear or straight. The perimeter may have, but not limited to, an elliptical shape, an oval shape, a rectangular shape or a triangular shape.

[0053] In various embodiments, the optical fiber 200 may include a (longitudinal) structure defined in the core region 202, wherein a perimeter of the structure may have a non-circular shape that may be (helically) twisted about the longitudinal axis 205 to define the scattering

structure 204. The (longitudinal) structure may be defined centrally in the core region 202, or may be defined in an off-central position. The (longitudinal) structure may or may not be a light-transmitting structure, depending on its refractive index compared to that of the core region.

5 [0054] In various embodiments, at least a portion of the optical fiber 200 may be externally (helically) twisted. This may mean that the entire portion of the optical fiber 200 may itself be arranged in the form of or define a (helical) twist. The external twist of the optical fiber 200 may be temporarily or permanently induced or generated. In various embodiments, the entire optical fiber 200 may be externally (helically) twisted, meaning that the entire optical fiber 200
10 may be arranged, bent or curled in a (helical) twist.

[0055] The optical fiber 200 may further include a (outer) cladding (or cladding region or jacket) arranged to surround the core region 202. The cladding may include a low index material, or at least the refractive index of the cladding may be lower than the refractive index of the core region 202. As non-limiting examples, the cladding may include a glass or a
15 polymer.

[0056] The optical fiber 200 may further include a plurality of scattering agents configured to scatter the light 222 propagating in the optical fiber 200 out of the optical fiber 200. This may mean that the scattering agents may interact with the light 222 and scatter the light 222 out of the fiber 200 as the out-scattered light 223. The scattering agents may be used to adjust the
20 scattering intensity of the optical fiber 200. The scattering agents may be provided in the core region 202 and/or the cladding of the optical fiber 200.

[0057] The optical fiber 200 may further include a plurality of spectral modifying agents configured to, in response to interaction with the light 222 propagating in the optical fiber 200, emit a resultant light of a different wavelength. This means that the resultant light and the
25 light 222 have different wavelengths (or colours or colour spectra). The resultant light may be emitted out of the optical fiber 200 as the out-scattered light 223. For example, the spectral modifying agents may absorb the light 222, and, in response to the absorption, generate a resultant light of a different wavelength compared to the wavelength of the propagating light 222. In this way, the spectral modifying agents may change a wavelength (or spectrum) of
30 light that is scattered out of the optical fiber 200. The spectral modifying agents may include

phosphors and/or (optical) absorbers. The spectral modifying agents may be provided in the core region 202 and/or the cladding of the optical fiber 200.

[0058] In the context of various embodiments, it should be appreciated that the terms “twist” or “twisted” may include any twisted structure or path, including but not limited to, a twist with a constant pitch, a twist with a variable pitch, a forward direction of twist, a reversing direction of twist, a clockwise directional twist, an anti-clockwise directional twist or any combinations thereof. As a non-limiting example, a section of the twist may be of a constant pitch while another section of the twist may be of a different constant pitch or a variable pitch. As a further non-limiting example, a section of the structure may be twisted in the forward direction while another section of the structure may be twisted in the reverse direction (or having a clockwise directional twist and an anti-clockwise directional twist). The change in the direction may occur a plurality of times. The change in the direction may occur periodically or randomly.

[0059] In the context of various embodiments, the term “twist” may include a reference to a “helical twist”. This may mean, for example, that the scattering structure 204 may be helically twisted about the longitudinal axis 205 of the core region 202.

[0060] FIG. 2B shows a schematic view of a lighting apparatus 220, according to various embodiments. The lighting apparatus 220 includes a light source 221 configured to provide a light (represented by arrow 222b), and an optical fiber 200b, the optical fiber 200b being configured for receiving the light 222b for propagation in (or through) the optical fiber 200b. The optical fiber 200b may be optically coupled to the light source 221. The optical fiber 200b may be configured to receive the light 222b. The optical fiber 200b may be as described in the context of the optical fiber 200 of FIG. 2A. In various embodiments, the light source 221 may be a laser, for example, a laser diode.

[0061] FIG. 2C shows a method 230 for forming an optical fiber, according to various embodiments. In the method, a scattering structure is twisted in a core region of the optical fiber about a longitudinal axis of the core region, wherein the scattering structure is configured to scatter light propagating in the optical fiber out of the optical fiber.

[0062] It should be appreciated that descriptions in the context of the optical fiber 200 may correspondingly be applicable in relation to the method 230 for forming an optical fiber.

[0063] Various embodiments or techniques will now be further described in detail.

[0064] As a non-limiting example, a glass rod or preform with an off-centred scattering structure or core (e.g., an air hole) may be used to create a cross-sectional geometric and/or refractive index feature. Such a rod may be drawn into an optical fiber having a scattering structure or core that is twisted along the axis of the optical fiber to form a twisted structure that is visible transversely. FIG. 3A shows a schematic diagram of a fiber 300 with a twisted scattering structure (or helical scattering core) 304 (e.g., an air channel), according to various embodiments. The fiber 300 may include a solid core 302 (e.g., glass or polymer) within which may be defined the twisted scattering structure 304 with refractive index and/or geometrical feature across the cross-section of the fiber 300. It should be appreciated that a “twist” may mean any rotation of an element about its axis (e.g., its longitudinal axis when in an untwisted state) or longitudinal axis of the structure within which the twisted element is defined, including but not limited to, a variable twist, a reversing direction of twist, or a random combination of various forms of twist. The fiber 300 may further include a coating layer (or jacket) 306 (e.g., low index polymer or glass). For clarity, the jacket 306 is not shown in the side view.

[0065] Parameters related to the helical structure 304 may include the pitch (or twist period), P , and the transverse offset, T . The pitch, P , may refer to the distance between two successive points on the helical structure 304 that are aligned to each other along an axis that is parallel to a longitudinal axis of the fiber 300. The transverse offset, T , may refer to the distance of the helical structure 304 to the centre or central axis of the fiber 300 in a perpendicular direction. The pitch, P , may be constant or variable along the length of the fiber 300. The transverse offset, T , may be constant along the length of the fiber 300. FIG. 3B shows a schematic diagram of a fiber 300b with a twisted scattering structure 304b having a variable pitch. As may be observed, the period of the twisted structure 304b decreases from P_1 to P_2 as the structure 304b extends longitudinally within the core region 302b. It should be appreciated that the fiber 300b may have an outer cladding or jacket.

[0066] FIG. 3C shows a schematic diagram of a fiber 300c with a twisted scattering structure 304c defined in the core region 302c of the fiber 300c. The fiber 300c may further include a plurality of scattering agents (represented by solid circles 340c) to scatter the light in the fiber 300c out of the fiber 300c. It should be appreciated that the fiber 300c may have an outer cladding or jacket. Additionally or alternatively, scattering agents may be provided in the outer cladding.

[0067] FIG. 3D shows a schematic diagram of a fiber 300d with a twisted scattering structure 304d defined in the core region 302d of the fiber 300d. The fiber 300d may further include a plurality of spectral modifying agents (represented by open circles 340d) to modify the spectrum of the out-scattered light. The spectral modifying agents 340d may include phosphors and/or (optical) absorbers. It should be appreciated that the fiber 300d may have an outer cladding or jacket. Additionally or alternatively, spectral modifying agents may be provided in the outer cladding.

[0068] A non-limiting example of the scattering manipulation will now be described with reference to the fiber 300 of FIG. 3A. When a suitable preform is drawn into a fibre with spinning, the introduced off-centred helical structure 304 may be a low or high index area that fulfils the required cross-sectional feature of refractive index and/or geometry that may produce the observable twist. As a non-limiting example, the helical structure 304 may be an air channel or a channel with filled-in low or high index material or fluid. Its scattering strength may vary depending on at least one of a size, position (or offset, T), twisting pitch (P), or the number of introduced scattering structures (e.g., scattering agents). In the context of various embodiments, the size of the helical structure 304 may be between about 1/50 and about 1/2 of the fiber diameter, the offset may be between about 1/100 and about 1/2 of the fiber diameter, the pitch may be between about 1 mm and about 100 mm, while the number of scattering structures may be between about 1 and about 100. For example, a larger transverse offset, T , and/or a shorter pitch, P , may induce stronger scattering. Twist with a variable pitch may be practical to build or be defined along the fiber, which may be used to create a fiber with one or more higher or lower scattering regions at will. For instance, the introduced variable pitch along the fibre length may control the longitudinal degree of scattering, for example, to compensate for the natural decay of the light intensity along the length. In this way, a more uniform illumination may be provided over the entire fiber. As a non-limiting example, stronger scattering regions (e.g., with shorter pitch, P) may be defined towards light out-coupling end regions for the fiber, and weaker scattering regions (e.g., with longer pitch, P) may be defined in a longitudinal direction away from the light out-coupling end regions, for example, towards the light incident end of the fiber. A variable pitch may be implemented by controlling the spinning speed at the fiber drawing stage as will be described further below.

[0069] It should be appreciated that as well as the in-built twisted path of the cross sectional feature, as described above, that may be introduced during the fibre drawing process, additional twist may be introduced in the fiber post fabrication process to tune the degree of scattering. Thus, the radiating fiber of various embodiments may allow for a post-treatment such as external twisting to modify or moderate the scattering angle and/or scattering strength. The post-treatment may be applied over the entire fiber length or at desired local sections. It should also be appreciated that a permanent twist may be imparted to the fiber by means of local heating, for example, at a particular location of the fiber, to the point where viscous flow of the fiber material may occur, with the application of a twist at the same time, such that the twist may be frozen in once heating is removed and the fiber material cools. FIG. 3E shows a schematic diagram of a fiber 300e with an external twist, which may be temporarily or permanently induced as described above. The fiber 300e may include a core region 302e that may be (helically) twisted about an axis 342 (e.g., longitudinal axis of the fiber 300e when in an untwisted state). Each point on the fiber 300e may be equi-distant to the axis 342. For ease of understanding, the twisted scattering structure defined in the core region 302e is not shown. It should be appreciated that the fiber 300e may have an outer cladding or jacket.

[0070] It should be appreciated that two or more of the embodiments shown in FIGS. 3A to 3E may be combined together in any manner.

[0071] More non-limiting examples of structures with cross-sectional geometric and/or refractive index features are shown in FIGS. 4A to 4J. As may be appreciated, when preforms having the illustrated cross-sectional geometric and/or refractive index features are drawn into respective fibers, e.g., with spinning, these structures may form, within the corresponding fiber, a recognisable or observable twist along the fiber axis, when viewed transversely. It should be appreciated that the designs shown in FIGS. 4A to 4J may not be mutually exclusive to each other.

[0072] Referring to FIGS. 4A to 4C and 4I to 4J, the dark areas 454a, 454b, 454c, 454i, 454j represent regions or structures having a different refractive index (e.g., higher or lower refractive index) compared to that of the surrounding material 450a, 450b, 450c, 450i, 450j that defines the core region material of the fibers when drawn. The structures 454a, 454b, 454c, 454i, 454j may be respective air holes and/or include an index material to provide the desired refractive index.

[0073] Structures with non-circular cross-sectional shapes may be provided. For example, the structure 454a may be a straight line (or a rectangle) extending in a radial direction, but any lines that may extend in any directions and/or of any suitable shapes may be suitably employed, for example, a zig zag line, a curved line, etc. The structure 454i may have a cross-sectional square shape while the structure 454j may have a cross-sectional elliptical or oval shape. However, other non-circular shapes, e.g., a rectangle, a triangle, or any suitable (polygonal) shapes may be provided. While the structures 454i, 454j are shown positioned centrally of the respective surrounding material 450i, 450j, it should be appreciated that the structures 454i, 454j may be positioned at any off-central positions.

[0074] The structures 454b, 454c have circular shapes but any suitable (polygonal) shapes may be employed. The structures 454b may be coaxially aligned and opposite to each other. The structures 454c may be aligned symmetrically or asymmetrically to each other.

[0075] When spun into fibers, the structures 454a, 454b, 454c, 454i, 454j define the scattering structures. When spun into fibers, the structures 454a, 454b, 454c, are twisted longitudinally along the fabricated fibers to define the scattering structures. When spun into fibers, the perimeters of the structures 454i, 454j having a non-circular shape are twisted longitudinally along the fabricated fibers to define the scattering structures. In the fabricated fibers, light may propagate in the cores having the materials 450a, 450b, 450c, 450i, 450j and may be scattered as the light encounters the twisted structures defined by the structures 454a, 454b, 454c, 454i, 454j.

[0076] Preforms having perimeters of non-circular shapes may be used, as shown by the non-limiting examples of FIGS. 4D to 4H. Preforms having a structure or shape where the circular symmetry is broken, for example, as illustrated in FIGS. 4D and 4E, may be used. Non-circular shapes may also be used, for example, an ellipse as shown in FIG. 4F or an oval, a rectangle as shown in FIG. 4G, and a triangle as shown in FIG. 4H. However, it should be appreciated that any suitable (polygonal) shapes may be provided. In the fibers spun from the preforms having the structures illustrated in FIGS. 4D to 4H, light may propagate in the cores having the materials 450d, 450e, 450f, 450g, 450h and may be scattered as the light encounters the fiber-air or fiber-polymer jacket interfaces, for example, coinciding with twisted structure of the fibers.

[0077] The preform material 450a, 450b, 450c, 450d, 450e, 450f, 450g, 450h, 450i, 450j may include any transparent glass or polymer material that may be drawn into an optical fiber. The drawn fibers may be jacketed by an additional external layer to serve as a cladding so as to construct a core and cladding structure for guiding light (or to fulfil a waveguide structure). The external layer may not be necessary if the structure is made of a flexible polymer material and exposed to air directly.

[0078] It should be appreciated that two or more of the embodiments shown in FIGS. 3A to 3E and FIGS. 4A to 4J may be combined together in any manner.

[0079] In addition to the scattering intensity, various embodiments may allow for modification of the scattering angle distribution. For example, referring to FIG. 5 illustrating the scattering angle distribution of a fiber 500 with a helical scattering structure 504, with the incident light 530 provided to the fiber 500, the scattering may be stronger in a forward direction with a larger forward scattering angle, θ_f , as compared to the backward scattering angle, θ_b . The forward scattering angle, θ_f , may be modified or moderated by adjusting one or more design parameters such as pitch, P , and/or offset, T . For example, a short pitch and a large offset may increase θ_b .

[0080] The radiating fiber of various embodiments may be fabricated without including the use of an expensive and complicated chemical vapour deposition process. An exemplary fabrication method for such a fiber will now be described. Referring to FIG. 6A, a glass rod 650 may be drilled to make or define a hole or void 654 along the rod 650. The introduced hole 650 may provide the transversal geometric and/or refractive index feature. An additional high or low index material may be inserted or introduced into the hole 654. The prepared preform 656 may be drawn into a fiber in a drawing tower by heating in a furnace until the material becomes viscous. During the drawing process, referring to FIG. 6B, the preform 656 may be rotated (in a spinning motion represented by the arrow 658) at a desired rate to produce a fiber 600 with a twisted scattering structure defined by the void structure 654. The spinning rate and/or the drawing speed may determine the pitch, P , of the twisted structure. A higher spinning rate may produce a shorter pitch and, therefore, stronger scattering, while, a lower spinning speed may result in a longer pitch and, therefore, weaker scattering. If the spinning rate is varied during the fiber drawing process, the resulting fiber 600 may possess a variable pitch along the length of the fiber 600. As a result, the scattering intensity becomes variable, which may help to realise a

more uniform luminance along the fiber 600. During the drawing process, a pressure control (represented by the arrow 659) may be applied to build positive pressure in the air hole 654 to prevent the hole 654 from closing under the action of surface tension. As a non-limiting example, as a form of pressure control, air may be supplied into the hole 654 to keep the
5 hole 654 from closing or collapsing.

[0081] During optical fiber drawing, a low-index polymer coating, such as UV curable fluorinated acrylate or thermally curable silicone, may be applied to provide light guidance and physical strength to the fiber. Additionally, scatterers or scattering agents may be incorporated in the polymer resin used to form the cladding layer (or outer jacket) to adjust the scattering
10 intensity. It may also be possible to provide for colour adjustment, where phosphors or absorbers may be included that may modify the spectrum of the scattered light. The phosphors or absorbers may, for example, be provided in the (polymer) cladding layer.

[0082] It should be appreciated that preforms having the structures or features as shown in FIGS. 4A to 4J may be subjected to spinning during fiber drawing to produce optical fibers
15 having twisted (e.g., helically twisted) scattering structures.

[0083] An alternative to the drilling process described above is to use a stack-and-draw technique to build the cross-sectional geometric and/or refractive index feature. Capillary tubes or doped silica rods with index decreasing or raising elements may be stacked together with silica rods to form the structure, as a bundle. The stack may be inserted into a jacketing tube to
20 retain the structure during fiber drawing, to form the preform. The preform may be spun during drawing to form a radiating fiber with a twisted scattering path defined by the capillary tubes or doped silica rods index decreasing or raising elements.

[0084] A radiating fiber made from silica incorporating a twisted air hole or channel, thus, fulfilling the above-described cross-sectional feature twisted along the fiber axis, is fabricated
25 via the fabrication process described in relation to FIGS. 6A and 6B. A low index acrylate polymer coating is applied during the drawing process, which may provide a nominal 0.45 numerical aperture (NA) for light injected into one end and guided along the length of the fiber. A microscope image of the cross-section of the fabricated fiber 700 is shown in FIG. 7. The fabricated radiating fibre 700 has a core region 702 with an air hole 704 that is off-centred and
30 offset from the centre of the fiber 700 by about 29 μm . Along the length of the fiber 500, the air hole 704 follows a twisted path with a 1 cm pitch along the fiber 700 in order to scatter out light

from the fiber 700. As shown in FIG. 7, the diameter of the fiber 700 is measured to be about 220 μm , and the size of the hole 704 is about 33 μm .

[0085] To demonstrate the scattering characteristics, a fabricated fiber may be illuminated, for example, using a blue laser diode (LD). Referring to FIG. 8A showing a schematic diagram of a setup 870 for fiber illumination, illustrating an illuminating apparatus with a light source (e.g., blue LD 872) and a radiating fiber 800, the blue LD 872 may be butt-coupled to the fiber 800. The blue light coupled into the fiber 800 propagates along the length and may be scattered by the twisted scattering structure within the fiber 800. The output end of the fiber 800 may be connected to another LD or a mirror (M) 874 to send light back towards the input end, thereby making illumination more uniform and enhancing the radiating intensity. FIG. 8B shows a photo of a blue-illuminated fiber 800b, using a 18-m long radiating fiber.

[0086] If required, the scattering intensity may be adjustable, meaning made stronger or weaker, by applying an external twist to the fiber 800 by means of, for example, gripping the fiber by an external apparatus and rotating the grips relative to each other. Additionally or alternatively, a permanent twist may be imparted to the fiber 700 by means of local heating to the point where viscous flow may occur together with the application of a twist such that the twist is frozen in. Hence, the scattering intensity may become tunable at any desired position along the fiber 800.

[0087] The design, fabrication and demonstration of a radiating fiber having a twisted scattering structure of a non-cylindrical symmetry (e.g., in the form of a helical structure) are described herein. The techniques disclosed herein may provide a way to scatter light from optical fibers according to one or more of the following.

[0088] (i) A light guiding structure (or fiber) having a core of transparent material and a surrounding cladding of lower refractive index material which when twisted about its axis scatters light.

[0089] (ii) A twisted light guiding fiber having one or more of the following:

- a fiber with cross-sectional geometric and/or refractive index feature such that when viewed transversely permit a twist to be observed;
- herein, twist may be understood to mean any rotation of the fiber about its axis, including a variable twist, a reversing direction of twist, or a random combination of various forms of twist;

- twist with a variable pitch may be used to create a fiber with higher or lower regions of scatter at will;
- light guiding fiber may mean a light guiding pipe whose length substantially exceeds its width;
- 5 • the fiber may include one or more transparent materials, such as silica, compound glass or polymers;
- the fiber may include core and cladding areas to form a waveguide;
- the fiber may include mixed low and high index areas;
- 10 • or a single transparent material with a non-cylindrical symmetry cross-section wherein the feature that creates the non-cylindrical symmetry is a gas such as air, or vacuum, or a solid such as one or more transparent materials;
- it should be appreciated that the fiber(s) of various embodiments may be used with other forms of scattering or spectral modifiers, such as might be embedded in glass regions within the fiber or in coatings of low or high index polymers wherein the
- 15 glass or polymer may contain at least one of scatterers, phosphors or absorbers to modify the scattering intensity and/or change the colour of the scattered light.

[0090] (iii) A device for distributed illumination based on a light source and a radiating fiber, having one or more of the following:

- the illumination strength and distribution may be controllable by varying the
- 20 twisting pitch permanently introduced during fabrication;
- the illumination strength and angular distribution may be adjustable by external twisting of the fiber after fabrication;
- a permanent twist may be imparted to the fiber by means of local heating to the
- 25 point where viscous flow may occur together with the application of a twist such that the twist is frozen in.

[0091] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the

30 appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.