A vertically-coupled whispering gallery mode (WGM) resonator optical waveguide, a method of reducing a group velocity of light, and a method of making a waveguide are provided. The vertically-coupled WGM waveguide comprises a cylindrical rod portion having a round cross-section and an outer surface. First and second ring-shaped resonators are formed on the outer surface of the cylindrical rod portion and are spaced from each other along a longitudinal direction of the cylindrical rod. The first and second ring-shaped resonators are capable of being coupled to each other by an evanescent field formed in an interior of the cylindrical rod portion.
The present teachings disclose a vertically-coupled WGM resonator optical waveguide device and methods related thereto, that are capable of delaying, storing, and buffering of optical pulses. The optical waveguide includes a cylindrical rod portion having a round cross-section and an outer surface. First and second ring-shaped resonators are formed on the outer surface of the cylindrical rod portion and are spaced from each other along a longitudinal direction of the cylindrical rod. The first and second ring-shaped resonators are capable of being coupled to each other by way an evanescent field formed in an interior of the cylindrical portion.

According to the present teachings, a method of reducing a group velocity of light is provided. The method includes providing an optical waveguide that includes a cylindrical portion and a chain of whispering gallery mode resonators formed on the cylindrical portion, the chain including a plurality of ring-shaped resonators each being spaced from each other along a longitudinal direction of the waveguide. The method further includes coupling light to a mode of one of the ring-shaped resonators by directing light into an optical coupler arranged in the vicinity of the one ring-shaped resonator. The method also includes forming an evanescent field in an interior of the cylindrical portion and sequentially coupling each of the ring-shaped resonators in the chain in order to reduce the group velocity of light that is coupled into the waveguide.

According to the present teachings, a method of making an optical waveguide is provided. The method includes providing a cylindrical rod made of an optically transparent material, turning the cylindrical rod, and removing material from the cylindrical rod at pre-set distances along a longitudinal direction thereof to thereby form a chain of ring-shaped resonators along the cylindrical rod.

Additional features and advantages of various embodiments will be set forth, in part, in the description that follows, and in part, will be apparent from the description, or may be learned by practice of various embodiments. The objectives and other advantages of various embodiments will be realized and attained by means of the elements and combinations particularly pointed out in the description herein.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a vertically-coupled WGM resonator optical waveguide according to various embodiments;

FIG. 2(a) shows the distribution of an evanescent field formed in an optical waveguide having the structure shown in FIG. 2(b);

FIG. 2(b) shows a simplified view of the waveguide of the present teachings including light being coupled into a single ring-shaped resonator by way of an optical coupler; and

FIG. 3 is a cross-sectional side view of the vertically-coupled WGM resonator optical waveguide according to various embodiments.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only, and are intended to provide an explanation of various embodiments of the present teachings.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present teachings are directed to a vertically-coupled whispering gallery mode (WGM) resonator optical waveguide, a method of reducing a group velocity of light...
the size of this evanescent field in FIG. 10, the ring-shaped resonators can be used as a narrowband waveguide teachings. In an exemplary composite (LiNbO₃), each of the neighboring ring-shaped resonators is dependent upon the separation distance between them. According to various embodiments, the separation distance, X, between each of the ring-shaped resonators can be as small about 1 µm to about 30 µm, for example. In the optical waveguide 10 of the present teachings, it has been found that as the separation distance between the resonators is increased, the group velocity of light in the waveguide 10 decreases exponentially. For example, the group velocity of light in the optical waveguide 10 of the present teachings is much smaller when the separation distance between the resonators is about 30 µm compared to the group velocity when the separation distance is about 1 µm. It has been found that the optical waveguide 10 of the present teachings is capable of reducing the group velocity by as much as a factor of 10³.

The intra-rod, coupling achieved by way of the structure of the optical waveguide 10 of the present teachings provides various additional advantages. For example, by coupling the ring-shaped resonators through a cylindrical rod and not through air, as is done in known resonator waveguides, the evanescent field formed in the cylindrical rod is much more stable with respect to external conditions. External conditions can include the properties of ambient air, such as, for example, humidity. In addition, the size of the evanescent field is much larger than an evanescent field that would be formed in air or in a vacuum. Moreover, it has been found that the decay constant of the evanescent field can be readily manipulated by altering the size and shape of the ring-shaped resonators 32 of the waveguide 10 of the present teachings.

Furthermore, in the optical waveguide 10 of the present teachings, the coupling characteristics can be substantially fixed once the following structural parameters are set: the size and shape of the ring-shaped resonators, the distance between the ring-shaped resonators, and the size and shape of the cylindrical rod. Accordingly, the coupling characteristics can be altered by changing the geometry of the optical waveguide 10 (i.e., the size, shape, or separation distance between the ring-shaped resonators and/or the size and shape of the cylindrical rod) or its optical properties. With respect to the optical properties of the waveguide 10, these can be changed by varying the temperature of the waveguide 10 or by applying an external pressure or voltage, as in the case when the waveguide 10 is made from a ferroelectric material.

Referring to FIG. 3, the dimensions of the structural features of the vertically-coupled WGM resonator optical waveguide 10 of the present teachings will be described. While various dimensions are described for each structural feature, final dimensions can be dependent upon the environment of use, manufacturing constraints, and the desired light altering characteristics to be achieved.

FIG. 3 shows a cross-section through a longitudinal axis of the waveguide 10. The cylindrical rod 20 can have a round cross-section that is substantially circular and defined by a diameter, D. The diameter, D, can range from about 100
μm to about 1 cm. According to an exemplary embodiment, the diameter, D, can be about 3 mm. It is also contemplated that the cylindrical rod 20 can have a cross-section that is round but non-circular. For example, the cross-section of the cylindrical rod 20 could be oval or elliptical in shape, whereby the major and minor axes are in the ranges as set forth above.

As shown in FIG. 3, a cross-section through the ring of the ring-shaped resonators 32 can include a cross-section that is square whereby the height, H, and the thickness, T, are equal. According to an exemplary embodiment, the height, H, and the thickness, T, of such a cross-section can be about 5 μm. However, it is contemplated that the ring-shaped resonators 32 can have various cross-sections. For example, a cross-section through a ring could have a height and thickness that are unequal whereby the cross-section would be rectangular in shape. Accordingly to various embodiments, the cross-sections of the ring-shaped resonators 32 are constant through the circumferential direction, that is, around the diameter of the resonators 32. Moreover, if the cylindrical rod 20 has a cross-section that is substantially circular and defined by a diameter, D, then the outer diameter D' of the ring-shaped resonators 32 can also be circular, whereby D' is larger than D. Notwithstanding the cross-sectional shape of the ring-shaped resonators 32, the resonators 32 can be formed so as to support a plurality of modes. In a preferred embodiment, each of the ring-shaped resonators 32 can be designed to support a single mode.

Still referring to FIG. 3 and as discussed above, each of the ring-shaped resonators 32 that make-up the chain of WGM resonators 30 can be separated from a neighboring resonator 32 by a separation distance, X. The size of the separation distance, X, can depend upon the type and quality of material used to fabricate the waveguide 10 of the present teachings, as well as the potential environment of use of the waveguide 10. According to various embodiments, the separation distance, X, can range from about 1 μm about 30 μm.

According to various embodiments, a method of reducing a group velocity of light can be achieved through the use of the optical waveguide 10 of the present teachings. The method includes coupling light into a mode of one of the ring-shaped resonators 32. This is achieved by directing light into an optical coupler 49 arranged in the vicinity of the ring-shaped resonator 32 and then forming an evanescent field 50 in an interior of the cylindrical rod portion 20, as shown in FIGS. 2(a) and 2(b). The method further includes sequentially coupling each of the ring-shaped resonators 32 in the chain 30 to reduce the group velocity of light that was coupled into the waveguide 10.

The optical waveguide 10 of the present teachings can be made utilizing various machining technologies. For example, the optical waveguide 10 can be made by securing a cylindrical rod 20 onto a machining machine in order to turn the rod 20 around its longitudinal axis. A cutting tool can then be used to remove material from the cylindrical rod 20 at pre-determined distances to thereby form the chain of ring-shaped resonators 30 along the cylindrical rod 20. According to various embodiments, the cutting tool could be a diamond tipped cutter. While the rod 20 is still being turned, a polishing can be used to polish the surface of the finished surface of the waveguide 10.

The intra-rod coupling achieved by way of the design of the vertically-coupled WGM resonator optical waveguide 10 of the present teachings provides great advantages compared to evanescent field coupling in known resonators. Being less susceptible to external conditions, the optical waveguide 10 of the present teachings is capable of reducing the group velocity of light by as much as a factor of 10⁶.

Accordingly, the waveguide of the present teachings can be used to efficiently route and switch optical pulses in fiber optical communication networks. More particularly, the waveguide 10 of the present teachings can be used as an efficient optical delay line in photonic devices such as those used in spaces exploration applications.

What is claimed is:

1. An optical waveguide comprising:
   a cylindrical rod portion having a round cross-section and an outer surface and having a diameter comprising a constant value across the cylindrical rod; and
   a first ring-shaped resonator and a second ring-shaped resonator formed on the outer surface of the cylindrical rod portion and being spaced from each other along a longitudinal direction of the cylindrical rod;
   wherein the first ring-shaped resonator and the second ring-shaped resonator are capable of being coupled to each other via an evanescent field formed in an interior of the cylindrical rod portion.

2. The optical waveguide of claim 1, wherein the waveguide is an integral, one-piece structure.

3. The optical waveguide of claim 1, wherein each of the first and second ring-shaped resonators define a second circular outer diameter, whereby the second circular outer diameter comprises a length of 5 micrometers greater than the diameter of the cylindrical rod.

4. The optical waveguide of claim 1, further comprising a chain of three or more ring-shaped resonators spaced along the longitudinal direction of the cylindrical rod portion, whereby each resonator in the chain is capable of being optically coupled to a neighboring resonator.

5. The optical waveguide of claim 4, wherein each resonator in the chain of ring-shaped resonators is equidistantly spaced from a neighboring resonator along the longitudinal direction of the cylindrical rod portion.

6. The optical waveguide of claim 1, wherein a cross-section through a ring of each ring-shaped resonator defines a rectangle.

7. The optical waveguide of claim 6, wherein the rectangular cross-sections of each ring-shaped resonator define a square.

8. The optical waveguide of claim 1, wherein the cylindrical rod portion and the first and second ring-shaped resonators are made of an optically transparent material.

9. The optical waveguide of claim 8, wherein the optically transparent material is calcium fluoride (CaF₂).

10. An optical waveguide comprising:
    a cylindrical portion having a diameter comprising a constant value across the cylindrical portion; and
    a chain of whispering gallery mode resonators formed on the cylindrical portion, the chain comprising a plurality of ring-shaped resonators each being spaced from each other along a longitudinal direction of the waveguide; wherein the cylindrical rod portion and the chain of whispering gallery mode resonators form a unitary, one-piece waveguide structure.

11. The optical waveguide of claim 10, wherein the chain of whispering gallery mode resonators are equidistantly spaced along the longitudinal direction of the waveguide.

12. The optical waveguide of claim 10, wherein at least one of the ring-shaped resonators is arranged such that an evanescent field is formed in an interior of the cylindrical portion when light is coupled to a mode of the least one ring-shaped resonator.
13. The optical waveguide of claim 12, wherein each ring-shaped resonator in the chain of whispering gallery mode resonators is capable of being optically coupled to a neighboring resonator via the evanescent field formed in the interior of the cylindrical portion.

14. The optical waveguide of claim 10, wherein the cylindrical portion and the chain of whispering gallery resonators are made of an optically transparent material.

15. The optical waveguide of claim 14, wherein the optically transparent material is calcium fluoride (CaF₂).

16. A method of reducing a group velocity of light comprising:
providing an optical waveguide comprising a cylindrical portion having a diameter comprising a constant value across the cylindrical portion and a chain of whispering gallery mode resonators formed on the cylindrical portion, the chain comprising a plurality ring-shaped resonators each being spaced from each other along a longitudinal direction of the waveguide,
coupling light to a mode of one of the ring-shaped resonators by directing light into an optical coupler arranged in the vicinity of the one ring-shaped resonator;
forming an evanescent field in an interior of the cylindrical portion; and
sequentially coupling each of the ring-shaped resonators in the chain to reduce the group velocity of light that is coupled into the waveguide.

17. A method of making an optical waveguide comprising:
providing a cylindrical rod made of an optically transparent material;
turning the cylindrical rod; and
removing material from the cylindrical rod at predetermined locations along a longitudinal direction thereof to thereby form a chain of ring-shaped resonators along the cylindrical rod and provide a constant rod diameter across the cylindrical rod.

18. The method of claim 17, further comprising polishing a surface of the waveguide.

19. The method of claim 17, wherein the step of removing material from the cylindrical rod includes placing a diamond cutter into contact with the turning cylindrical rod.

20. A vertically coupled whispering gallery mode optical waveguide capable of reducing the group velocity of light traveling in a communication network comprising the features of claim 1.