ABSTRACT

At technique for holding a resonator relative to an optical fiber at a specified distance. Structures including a rectangular indentation may be formed in the end of the optical fiber. The resonator may be placed against edges of the structures, to hold a different portion of the resonator spaced from an area where the waveguide modes will emanate.

25 Claims, 11 Drawing Sheets
FIG. 1

FIG. 2

Sphere radius, \( \mu M \)

Effective index

q=2

Upper 2 curves - 1300nm

Lower 2 curves - 1550nm

TE_{lmq} (solid)

TM_{lmq} (dashed)
ELECTRO-ABSORPTION MODULATOR SECTION

A GAP TO INDUCE REFLECTION

PHOTODETECTOR (REVERSELY BIASED ELECTRO-ABSORPTION MODULATOR)

FIG. 7

DFB LASER

MICROSPHERE WITH SURFACE GRATING

OUTPUT FROM GRATING

FIG. 8
COUPLING SYSTEM TO A MICROSPHERE CAVITY

STATEMENT AS TO FEDERALLY-SPONSORED RESEARCH

The invention described herein was made in the performance of work under a NASA 7-1407 contract, and is subject to the provisions of Public Law 96-517 (U.S.C. 202) in which the Contractor has elected to retain title.

BACKGROUND

Microsphere resonators have certain desirable characteristics including exceptionally high quality ("Q") factors, and small dimensions. Optical systems often use microsphere resonators as a building block for fiber optic systems. However, it is often necessary to couple optical energy from an optical fiber into the microsphere cavity. The existing couplers often suffer from certain drawbacks.

SUMMARY

This application teaches new ways of launching energy into a resonator device such as a microsphere resonator.

DETAILED DESCRIPTION

FIG. 1 shows the basic schematic embodiment of a first fiber coupler system. A single mode fiber 100 has an end 110 which will be used to couple propagating light 112 into a resonator 120 which can be a microsphere resonator. The single mode fiber 100 is formed with its end area 110 having an angled portion 114. The angled portion 114 forms an angle \( \omega = 180 - \Phi \) with the direction of the axis of the fiber, as shown. The angle \( \omega \) is controlled as described herein.

The light is coupled in the direction 112 and incident on the angled surface. Upon incidence, the light propagating inside the core comes into contact with the angled region 114. The light undergoes total internal reflection and then forms an evanescent field around the fiber end 110. Effectively, the light escapes the fiber in this way. The microsphere 120 is placed in the area of the evanescent field. The energy from the evanescent field is efficiently exchanged in a resonant mode of the microsphere. Effectively, therefore, the information is resonantly transitioned between the "waveguide" mode of the single mode fiber and the whispering gallery mode in the microsphere.

The angle \( \Phi \) is selected to satisfy a phase matching requirement. The angle is selected according to the relationship \( \Phi = \arcsin(n_{\text{sphere}}/n_{\text{fiber}}) \). \( n_{\text{sphere}} \) represents the effective refractive index that describes the guided wave in the fiber core truncation area 110. \( n_{\text{fiber}} \) represents the effective refractive index that describes the azimuthal propagation of waveguide modes. These can be considered as closed waves, undergoing total internal reflection in the microsphere.

The linear dimensions of the angle-cut core area can match to the area of evanescent field overlap. This allows the system to operate similarly to a prism coupler with illuminated collimation focusing objects.

The effective refractive index can be used to define the azimuthal propagation of the waveguide modes near the surface of the sphere. This can be calculated based on asymptotic expressions for waveguide mode frequencies \( \omega_{TM,\omega} \) where \( n_{\text{sphere}} = \frac{c}{a} \), \( L \) and \( q \) are respectively azimuthal and radial mode indexes, \( a \) is the radius of the sphere and \( c \) is the speed of light. Different indices can be calculated and used to form a model.

More specifically, the effective index to describe the azimuthal propagation of the WG modes can be calculated as \( n_{\text{eff}} = \frac{c}{a} \omega_{TM,\omega} \) on the basis of asymptotic expressions for WG mode "positions" as follows:

\[
\omega_{q, \omega} = \frac{mc}{a} \left[ 1 + \frac{1}{2} \frac{a q^2}{1} - \frac{P}{(a^2 - 1)^{1/2}} + \left( 1 + \frac{2}{10} q^2 - \frac{2}{1} \frac{a q^2}{(a^2 - 1)^{1/2}} - \frac{2}{1} \frac{a q^2}{(a^2 - 1)^{1/2}} - \frac{a q^2}{(a^2 - 1)^{1/2}} + a q^2 \right) \right]^{-1}\]

Again, \( L, q \) are azimuthal and radial mode indexes respectively; \( a \) is the sphere radius; \( c \) is the speed of light; \( \omega \) is the refraction index of the sphere material \( \left( n=1.4440 \right) \) for silica at the wavelength \( \lambda=1550 \text{ nm} \) (1300 nm); \( P, m \) for TE \( \omega \) modes and \( P=1/2 \) for TM \( \omega \) modes; \( v=1+\lambda \) and \( a_{\lambda} \) is the \( q \)-th root of the Airy function, \( A_1(-\lambda) \), equal to 2.338, 4.088, 5.521 for \( q=1,2,3 \) respectively. Results of calculation of \( n_{\text{eff}} \) (at both wavelengths 1550 nm and 1300 nm) for silica spheres of different radii are given in FIG. 2. The calculation is made for the three lowest radial order modes TE \( (TM)_{\omega, q=1,2,3} \).

Since the guided wave in the core no longer exists after reflection, precise calculation of \( n_{\text{fiber}} \) is a non-trivial task implying the explicit computation of the evanescent field in the truncation area. However, as confirmed by the experiments below, a consistent recipe for a functional coupler can be based on a straightforward approximation that assumes \( n_{\text{fiber}} \) equal to the effective mode index in a regular fiber.
In a specific embodiment, the standard Corning SMF-28 fiber is used with the germanium-doped core of diameter 2a=8.3 μm and index difference of 0.36%. The material index of the core was n_c=1.4505; the material index of the cladding n_l=1.4453 at the wavelength λ=1550 nm, and correspondingly n_c=1.4535 and n_l=1.4483 at λ=1300 nm (Corning Inc Product Information sheet PI1036, 1998). As known from the theory of step-index fibers (see e.g. L. B. Jeanchomme, Single-Mode Fiber Optics (Marcel Dekker, N.Y., 1983)), propagation constant Δ for the core-guided mode can be approximated as follows:

\[ \beta = k_{0} n_{c} + Δ \left( \frac{1}{n_{c}} - \frac{1}{n_{l}} \right) \]

where k=2π/λ—is the free-space wave vector; Δ=0(n_c−n_l)/n_c—the relative index difference; ν is the normalized transverse decay constant; V=n_c (2Δ)^1/2—the normalized frequency. Using standard solution ν(V) for the fundamental LP01 mode of the fiber and the parameters of our fiber, the effective index relevant to the phase-matching condition is

\[ n_{eff} = \beta k_{0} n_{c} + Δ \left( \frac{1}{n_{c}} - \frac{1}{n_{l}} \right) \]

One exemplary model is shown in FIG. 2. In this model, different results of calculations are presented for different q values, at the frequency and for different resonators of different characteristics.

Another issue comes from the way in which the fiber and the modes operate after reflection from the truncation plane. After this reflection, the guided wave in the fiber no longer exists. Precise calculation of the effective index becomes difficult. This value is assumed to be equal to the effective index of the n_{guide} wave and the regular fiber, although the precise value may be difficult to obtain.

The specific way in which the system is used is shown in FIGS. 3A and 3B. A close up view of the assembly has two fiber couplers 300, 310, each with cleaved ends as described herein. The polishing angles of the fibers are about 12.1 degrees and 13.3 degrees respectively or @=77.9° and 7.6°. A fused silica rod 320 supports the microsphere 322 at a radius 235 μm between two angled conical fiber couplers. The optical information can be updated between the fibers, via the sphere.

The above has described one way of coupling optical energy into such a microsphere. Since evanescent waves are used for the energy coupling, this is effectively near-field coupling.

The principle implemented in the above description of a single mode optical fiber coupler can also be extended to use integrated optic waveguides.

FIG. 4A shows a total internal reflection mirror on a channel waveguide that provides a phase-matched excitation coupler for WG modes. The cutting angle Φ is defined, as previously, from the effective index of the guide and the effective index of azimuthal propagation of WG mode in particular sphere. Because of the high index available with planar semiconductor waveguides (n_{guide}≈3.0–3.5), optimal coupling can be achieved with wide variety of cavity materials, by adjusting the angle Φ in accordance with the relation Φ=arcsin (n_{spher}/n_{guide}).

For example, if InP waveguides having n=3.17 are on an InGaAsP supporting layer (n=3.50) over an InP substrate, the effective index for 3 μm x3 μm cross section will be n_{guide}=3.30. The optimal angle for excitation of TE_{00} whispering gallery modes in 200 μm diameter fused silica sphere Φ=25°, all near the wavelength 1550 nm. The configuration depicted in FIG. 6 can be fabricated by CVD (chemical vapor deposition) methods, lithography, wet etching, and subsequent cleaving of the wafer to provide a flat mirror surface at the reflection plane. More consistent results may be obtained with ion-assisted etching, or "IAE".

If only input coupling is required, the waveguide may be simply truncated as shown in FIG. 4B at the cleave. No folded mirror is necessary, even though that could further simplify the fabrication. Although configuration of the optical field may be disturbed because of mode transformation in the truncation area, the phase-matched coupling can still be achieved, with adjustment or experimental trimming of the truncation angle.

A corner reflector, or truncated guide can be formed on the edge of a substrate as shown in FIG. 4A. The throughput configuration, which is the analog of Figure 3B, can be achieved by assembling two chips at 500, 502. The sides of a microsphere 504 can be arranged as shown in FIGS. 5A and 5B. Alternatively, the couplers can be formed in the central part of the chip 510, next to a through hole or a micromachined depression 512 that will house a microcavity 504 as shown in FIG. 5C.

In any of FIGS. 5A–5C, the sphere 504 is arranged relative to the chip 500 as shown in FIG. 5D. Preferably the central diameter line of the sphere 500 is at or around the chip surface. This can facilitate holding the chip into place.

FIG. 5 shows the embodiments incorporating a microsphere cavity. The described method of coupling is applicable to all types of waveguide mode cavities (including disks, rings etc.). It also provides a tool to achieve efficient coupling between integrated optics components of different materials and substrates.

FIG. 6 shows a filter element including a waveguide microcavity within a case collinear input and output fibers/ waveguides 605, 610 using a sphere for filtering non-resonant paths.

FIG. 7 shows an embodiment of device integration of a novel waveguide coupler element for waveguide modes in microspheres. A coupled optoelectronic oscillator (COEO) is based on a high-Q microsphere. COEO is a variant of a microwave optoelectronic oscillator, OEO (X. S. Yao, L. Maleki, JOSAB, Vol.13, no.8, pp.1725–35, 1996), which is a microwave oscillator that uses optical energy storage elements to achieve high spectral purity signals at frequencies ranging from hundreds of MHz to above 100 GHz. These devices, normally have a laser, optical modulator, detector, microwave amplifier and fiber-optic delay, optoelectronic oscillator. Each of these devices can be implemented on a single chip except for the relatively bulky delay element. By using a miniature optical cavity such as a microsphere, the entire device can be placed on a chip.

The waveguide coupling element described herein facilitates the incorporation of a microsphere in the OEO-on-chip, thereby simplifying the setup. To operate with an optical cavity, the laser in the OEO requires locking to one of the modes of the cavity. Oscillation will occur as the microwave modulation sidebands to adjacent cavity modes.

To eliminate the need for independent laser locking to cavity modes, the high-Q cavity can be incorporated into the laser resonator. An additional modulation feedback loop will ensure microwave oscillation. This is described in, “coupled OEO,” (X. Yao, L. Maleki, Opt.Lett., Vol.22, No.24, pp.1867–9, 1997).

The embodiment of COEO-on-chip, is shown in FIG. 7. When activated by a current source, the active waveguides 700, 702 provide gain for the laser system. Electro-absorption modulators 705 are fabricated at the ends of waveguides by etching out the insulating gap to separate electrodes of gain sections from modulator sections. The
upper electroabsorption modulator is coated with a high-
reflectivity coating to induce pulse colliding in the modu-
lator and thus enhance the mode locking capability. At the
lowers based on their precise shaping and undercutting.

A cylindrical cavity preform of silica is formed with vertical
walls as shown in FIG. 9A. In this example, the walls have
diameter 100 to 200 μm, a thickness of 20 to 40 μm, and
are on a relatively flat substrate.

The vertical surface of the vertical walls is next re-shaped
to provide removal of the mode field from the flat boundaries
as shown in FIG. 9B. This is done by removing the edge
portions 900 forming a complex shape shown in FIG. 9B.

After that, further thermal and mechanical treatment is used
to approach elliptical geometry. The edges, e.g. 510, are
rounded and smoothed to minimize surface roughness and
reduce radiation loss. By rounding these surfaces, curvature
confinement and fire polish grade surface can be obtained,
obtaining a Q approaching 10^6.

The cylindrical preform described in FIG. 9A can be
produced by wet/dry etch as well as ion milling techniques
using appropriate crystal orientation. Other techniques such
as RTA laser treatment, ultraviolet treatment and infrared
treatment can also be used.

The above has described a fiber/waveguide coupling
method for high Q optical microsphere cavities operating in
whispering gallery modes. The techniques as disclosed
above operated by angle polishing the fiber waveguide tip to
shape synchronize between the waveguide modes and the
evanescent wave in the area of total internal reflection of
the waveguide mode. This technique may enable compact pack-
aging solutions for various devices. The devices may be
based on microspheres and other whispering gallery mode
micro cavities. For example, the whispering gallery mode
micro cavities may include the recently discovered highly
oblate spheroidal cavities also called micro toruses.

For maximum efficiency in the energy exchange between
the fiber/waveguide and the micro cavity, a number of
conditions should coincide. First, the fiber/waveguide
should be positioned with its core section area at the
epicenter of proximity with the microsphere. The axis of the
fiber should also will exist in the symmetry plane of the
waveguide mode localization. An air gap is often maintained
between the core section of the fiber and the microsphere.
This airgap should be maintained stable within the range of
the evanescent wave, typically in the range between 500 and
1500 nm.

The following embodiment discloses a modification of
the fiber coupler that enables self alignment of the fiber core
with respect to the micro cavity, and may stabilize the
airgap, accordingly. The present system configuration of the
coupler is shown in FIG. 10. The fiber waveguide 1000 is
fabricated with a rectangular groove 1010 in the angled end
portion 1002 of the fiber. The fiber core 999 passes through
the bottom surface 1003 of this groove 1010. The width
1004 of the groove should be much less than the diameter of
the microsphere, for example ½ to ½ the diameter of the
microsphere. FIG. 11 shows the microsphere 1100 being
brought into mechanical contact with the walls 1012, 1014
of the trench 1010. This contact will not substantially affect
the performance of the Micro cavity because of the way the
system is configured. The waveguide modes emanating from
the core 999, and are localized according to a “belt of light”
which surrounds the sphere in the area of the core. The belt
of light is shown as 1110 in FIG. 11. In fact, the shape of this
belt of light is only truly relevant in the area of the contacts,
and the belt of light may diverge in other areas. This belt of
light is fully accommodated between the walls of the trench,
and hence nowhere within this belt of light does the micro-
sphere element actually contact the trench. The width 1004
of the trench can be calculated for any particular diameter of
sphere 1100 in order to accommodate the area of the
waveguide mode. The depth 1006 of the trench may be
Accordingly, this may moderately contribute to the insertion within the surface. A soft metal such as gold, for example, be two or 3.

while observing waveguide mode resonance. This technique 40 conducting light within an optical fiber to an edge portion while the above describes the resonators as being spheres, it spaced from second surfaces of said optical fiber, said surface portion when pressed against said first and second corresponding curved surfaces formed on an end of said optical fiber.

6o resonator, having a curved outer surface, which is pressed against both said first and second opposing edges. 65

An apparatus as in claim 6, wherein said specified amount of said specified amount is at an area where said core portion is located.

5. An apparatus as in claim 3, wherein a minimum amount of said specified amount is at an area where said core portion is located.

6. An apparatus as in claim 1, further comprising a second curved surface, forming holding areas outside of said first and second opposing edges.

7. An apparatus as in claim 6, wherein said second curved surface is substantially round, and is centered around an area of said core.

8. An apparatus as in claim 6, wherein said indentation portion extends by only a specified amount over a surface on said fiber, where said specified amount is less than a distance from 1 outer edge of the fiber to the other outer edge of the fiber.

9. An apparatus as in claim 6, further comprising a resonator element with a curved outer wall, coupled to be held between surfaces of said curved outer surface.

10. An apparatus as in claim 1, wherein said indentation portion has substantially vertical sidewalls, and a substantially flattened bottom.

11. An apparatus as in claim 10, wherein said core is in a central portion between said substantially vertical sidewalls.

12. An apparatus as in claim 1, wherein said end portion of said fiber is a cleaved end portion which is cleaved at a specified angle which is non 180 degrees relative to an axis of the fiber.

13. An apparatus as in claim 12, wherein said specified angle is 45 degrees.

14. An apparatus as in claim 12, wherein said specified amount is less than a distance from one outer edge of the fiber to the other outer edge of the fiber.

15. An apparatus as in claim 1, wherein said indentation portion extends substantially from one outer edge of the fiber to the other outer edge of the fiber.

16. An apparatus as in claim 1, wherein said indentation portion extends by a specified amount on a surface of said fiber, said specified amount being less than a distance from one outer edge of the fiber to the other outer edge of the fiber.

17. An apparatus as in claim 1, further comprising a resonator element, coupled to surfaces of said fiber.

18. A method, comprising: conducting light within an optical fiber to an edge portion of the optical fiber, and placing a resonator within a proximity of said edge portion of said optical fiber in a way such that a portion of said resonator is pressed against first surfaces of said optical fiber, and another portion or said resonator is spaced from second surfaces of said optical fiber, said second surfaces of said optical fiber including surfaces including a core of said fiber.

19. A method as in claim 18, wherein said edge portion of said optical fiber comprises edge portions defining a notch in the portion of the optical fiber.

20. A method as in claim 19, wherein said end portion of said optical fiber is a cleaved end portion.

21. A method as in claim 20, wherein said notch is formed by a rectangular indentation in the end of the optical fiber.

22. A method as in claim 21, further comprising conducting light to a location within said rectangular indentation.

23. A method as in claim 21, wherein said placing comprises pressing curved surfaces of said resonator against edges of said resonator against each other.

24. A method as in claim 23, wherein said curved surface of said resonator are spherical surfaces.

25. A method as in claim 18, wherein said placing comprises placing curved surfaces of a resonator against corresponding curved surfaces formed on an end of said optical fiber.