A system of coupling optical energy in a waveguide mode, into a resonator that operates in a whispering gallery mode. A first part of the operation uses a fiber in its waveguide mode to couple information into a resonator e.g. a microsphere. The fiber is cleaved at an angle $\Phi$ which causes total internal reflection within the fiber. The energy in the fiber then forms an evanescent field and a microsphere is placed in the area of the evanescent field. If the microsphere resonance is resonant with energy in the fiber, then the information in the fiber is effectively transferred to the microsphere.

4 Claims, 7 Drawing Sheets
FIG. 1

REFLECTING SURFACE NORMAL

FIG. 2

Effective index

q=2

Upper 2 curves - 1300nm

Lower 2 curves - 1550nm

Sphere radius, μm

TE_{lmq} (solid)

TM_{lmq} (dashed)
FIG. 6A

CASE

SPHERE

602

600

610

FIBERS

FIG. 6B

FIG. 6C

OPTICAL WAVEGUIDE
FIG. 7

ELECTRO-ABSORPTION MODULATOR SECTION

GAIN SECTION

RF OUTPUT

OPTICAL OUTPUT

PHOTODETECTOR (REVERSELY BIASED ELECTRO-ABSORPTION MODULATOR)

FIG. 8

OUTPUT FROM PRISM

MICROSPHERE WITH SURFACE GRATING

OUTPUT FROM GRATINGS

DFB LASER
COUPLING SYSTEM TO A MICROSHERE CAVITY

CROSS-REFERENCE TO RELATED APPLICATIONS


STATEMENT AS TO FEDERALLY-SPONSORED RESEARCH

The invention described herein was made in the performance of work under a NASA 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.

A first way of doing this is by operating using a direct fiber coupling to a resonator, e.g. a microsphere using a hybrid of a waveguide and prism coupler formed on the fiber itself. Another aspect of the disclosure describes using a surface field to allow input and output coupling.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other aspects will now be described in detail with respect to the accompanying drawings, wherein:

FIG. 1 shows an angle polished fiber coupler system for coupling to a microsphere;

FIG. 2 shows a model of sphere radius versus fiber characteristic;

FIGS. 3A and 3B show single mode fibers and a resonator;

FIGS. 4A and 4B show an embodiment using this waveguide to whispering mode technique for coupling between different waveguides;

FIGS. 5A–5D show an embodiment for forming the waveguides on a chip and forming a resonator near the waveguides;

FIGS. 6A–6C show details of a system for doing this using optical waveguides;

FIG. 7 shows an embodiment of carrying out electro-optical absorption on a chip;

FIG. 8 shows an embodiment which couples light into a resonator using a surface grating; and

FIGS. 9A–9C show steps of formation of a improved 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 111 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 angle 114 forms an angle 2=180°–P with the direction of the axis of the fiber, as shown. The angle 2 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 101 is selected to satisfy a phase matching requirement. The angle is selected according to the relationship $P=\arcsin(n_{\text{sphere}}/n_{\text{fiber}})$. $n_{\text{sphere}}$ represents the effective refractive index that describes the guided wave in the fiber core truncation area 110. $n_{\text{fiber}}$ represents the effective refraction 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.

More specifically, the effective index to describe the azimuthal propagation of the WG modes can be calculated as $n_{\text{fiber}}=c/\omega_0\epsilon$, on the basis of asymptotic expressions for WG mode "positions" as follows:

$$\omega_0=\frac{m\pi}{\epsilon} + \frac{2^{2/3}a_0^{1/3}}{(n^2-1)^{2/3}} + \frac{P}{(n^2-1)^{2/3}} + \left(\frac{2}{10} \frac{a_0^{2/3}}{\epsilon} \frac{2^{2/3}a_0^{1/3}}{(n^2-1)^{2/3}} \frac{a_0^{2/3}}{\epsilon} + O(\epsilon^{-1})\right)$$

Again, $l$, q are azimuthal and radial mode indexes respectively; $\epsilon$ is the sphere radius; $c$ is the speed of light; $n$ is the refractive index of the sphere material ($n=1.4440 (1.4469)$ for silica at the wavelength $\lambda=1550$ nm (1300 nm)); $P=\Pi/n$ for TE modes and $P=1/n$ for TM modes; $V=1+\epsilon_0$; and $\epsilon_0$ is the $q$-th root of the Airy function, $Ai(-\epsilon)$, equal to 2.338, 4.088, 5.521 for $q=1, 2, 3$ respectively. Results of calculation of $n_{\text{fiber}}$ (at both wavelengths 1550 nm and 1300 nm) for silica spheres of different radii are given in FIG. 2. The calculation is made for three lowest radial order modes TE (TM) _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_0=1.4505; the material index of the cladding n_clad=1.4453 at the wavelength λ=1550 nm, and correspondingly n_0=1.4535 and n_clad=1.4483 at λ=1300 nm (Corning Inc Product Information sheet P1036, 1998). As known from the theory of step-index fibers (see e.g. L. B. Jeunhomme, *Single-Mode Fiber Optics* (Marcel Dekker, N.Y., 1983)), propagation constant k̄ for the core-guided mode can be approximated as follows:

\[ k̄ = k_0 \left[ 1 + \frac{\Delta}{2} \left( \frac{\lambda}{\lambda_0} \right)^2 \right] \]

where k =2π/λ— the free-space wave vector; \( \Delta = (n_0 - n_{clad})/n_0 \)— the relative index difference; \( \lambda \) — the wavelength in vacuum. Using standard solution \( V(V) \) for the fundamental LP_01 mode of the fiber and the parameters of our fiber, the effective index relevant to the phase-matching condition is n_eff = 1.4476 at 1550 nm and n_eff = 1.4509 at 1300 nm. The 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 n_eff becomes difficult. This value is assumed to be equal to the effective index n_guide of the guided 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 \( \Phi = 77.9^\circ \) and \( 76^\circ \). A fused silica rod 320 supports the microsphere 322 at a microwave optoelectronic oscillator, OEO (X.S. Yao, L. Maleki, Opt. Lett., Vol. 22, No. 24, pp. 1867–9, 1997).

For example, if InP waveguides having an n=3.17 are on an InGaAsP supporting layer (n=3.50) over an InP substrate, the effective index for 3 μm×3 μm cross section will be n_effective,3.30. The optical index of InP waveguides \( n_{waveguide} \) can be approximated as follows:

\[ n_{waveguide} = n_{core} \times \left( \frac{h}{w} \right) \]

where \( n_{core} \) is the material index of the core material, \( h \) is the height of the waveguide, and \( w \) is the width of the waveguide. For example, if the material index of the core material is 3.5 and \( h/w = 1/3 \), then the effective index of the waveguide is approximately 3.4.

In any of FIGS. 5A-5C, the sphere 504 is arranged on a chip 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 etching 512 that will house a microcavity 504 as shown in FIG. 5C.

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 FIG. 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 etching 512 that will house a microcavity 504 as shown in FIG. 5C.

Optics is the science of light, and it is concerned with the properties of light, and with the physical processes by which light interacts with matter. The field of optics is divided into two main branches: geometrical optics and wave optics. Geometrical optics deals with the behavior of light as rays, while wave optics deals with the behavior of light as waves.

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 substrate as shown in FIG. 4A. The throughput configuration, which is the analog of FIG. 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 etching 512 that will house a microcavity 504 as shown in FIG. 5C.
upper electroabsorption modulator is coated with a high-reflectivity coating to induce pulse colliding in the modulator and thus enhance the mode locking capability. At the lower section 702, the gap 710 between the electroabsorption modulator and the waveguide is etched deeper to induce optical separation. The gap interface acts as a partial mirror to reflect light back to the lower guide and form a laser cavity together with high-Q microsphere and the upper waveguide terminated by a high reflectivity mirror. The lower electroabsorption modulator is reverse biased so that it acts as a photodetector. The output from the photodetector and the E/A modulator and thus enhance the mode locking capability. At the Silica microspheres can support whispering gallery modes, is also disclosed. This device can be used with any of the embodiments described previously.

The system herein forms a whispering gallery mode in a dielectric body having axial symmetry e.g. a sphere, ellipsoid disk, ring or the like. The microspheres that are described herein can actually be any of these shapes, or can be any other shaped resonator. This system can be modeled by closed waves undergoing continuous total internal reflection. The resonances described herein correspond to completion of an integer number of wavelengths packed along the closed trajectory.

The fabrication is shown with reference to FIGS. 9A-9C. A cylindrical cavity preform of silica is formed with vertical walls as shown in FIG. 9A. In this example, the walls have a 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 ellipsoidal 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 RFA laser treatment, ultraviolet treatment and infrared treatment can also be used.

Other modifications are contemplated. What is claimed is:

1. A method comprising:
   forming a cylindrical cavity preform with vertical walls;
   re-shaping said vertical walls in a way that removes a mode field from flat boundaries of the vertical walls;
   treating the resulting shape to form an ellipsoidal geometry;
   rounding and smoothing edges of the ellipsoidal geometry to reduce radiation loss and to form a dielectric resonator body.

2. A method as in claim 1 wherein said cylindrical cavity preform has walls with a diameter of 100 to 200 μm, and a thickness of 20 to 40 μm.

3. A method as in claim 1 wherein said treatment comprises one of wet/dry etching, ion milling techniques, RTA laser treatment, ultraviolet treatment or infrared treatment.

4. A method as in claim 1 wherein said preform is formed on a relatively flat substrate.