# Morphology-dependent photonic circuit elements

**Anatoliy A. Savchenkov, Ivan S. Grudinin, Andrey B. Matsko, Dmitry Strekalov, Makan Mohageg, Vladimir S. Ilchenko, and Lute Maleki**

*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109-8099*

Received November 8, 2005; revised January 11, 2006; accepted January 16, 2006; posted February 8, 2006 (Doc. ID 65874)

We theoretically propose and experimentally demonstrate the design of a novel one-dimensional ringlike macroscopic optical circuit element. The similarity between morphologies of an optical planar waveguide and a whispering-gallery axially symmetric solid-state resonator is used. © 2006 Optical Society of America

*OCIS codes:* 230.5750, 220.4830.

There are two general approaches for engineering optical modes. The most common approach is to use optical waveguides to confine and guide light. The waveguide is based on the refractive-index contrast between its material and the surroundings to support light confinement and guiding. In the other approach, a photonic bandgap crystal[1] provides confinement and guiding of photons by use of the morphology of the structure. One achieves this by placing defects in otherwise periodic arrays of a dielectric material. In this Letter we propose a new approach that relies on generating an effective refractive-index contrast produced by shaping the geometry of a whispering-gallery mode (WGM) resonator. With this technique, single and multiply-coupled WGM resonators can be designed for a wide variety of applications.

The utility of WGM-based devices and the efficiency of nonlinear optical interactions of WGMs depend on accurate engineering of the cavity mode structure. Specifically, this means producing cavities with extremely rarified (single-mode-family) spectra. Achieving the required level of control over the mode spectrum has eluded scientists working on WGM resonators. Thus WGM resonators have as yet neither entered the mainstream of photonic device engineering nor been embraced by the mainstream of optical physics.

Researchers working on optical waveguides faced a similar set of problems in designing the single-mode fiber. Single-mode fiber has revolutionized the world of optics by enabling long-distance telecommunications and multichannel television broadcast systems that would be impossible with multimode fibers. This is so because a single-mode fiber can retain the fidelity of a light pulse over long distances. It exhibits no dispersion caused by multiple modes and is characterized by lower attenuation than a multimode fiber.

A homogeneous dielectric waveguide becomes single mode when the frequency of the propagating light is close to its cutoff frequency. This means that the thickness of the waveguide approaches the half-wavelength of light in the host material of the waveguide. It is impractical to fabricate a single-mode optical fiber by decreasing the fiber's diameter. Instead, single-mode operation is ensured by the specially selected radial profile of the refractive index of the fiber material. The core of the fiber has a larger index of refraction than the cladding material that surrounds it. The difference of the indices is small, so only one mode propagates inside the core, while the others decay into the cladding [Fig. 1(a)]. For instance, the condition for single-mode operation of a planar waveguide is[2]

$$d_{co} < \frac{\lambda}{2\sqrt{\Delta\epsilon}}, \qquad (1)$$

where $d_{co}$ is thickness of the core, $\lambda$ is the wavelength of light in vacuum, and $\Delta\epsilon$ is the difference between the susceptibilities of the core and the cladding materials. As a result, the core may have a reasonably large diameter. Note that the core of a single-mode fiber is a multimode fiber if the cladding is removed.

Let us consider the WGM resonator as a multimode gradient waveguide [Fig. 1(b)].[3] The resonator becomes an ideal single-mode-family resonator only if the waveguide is thin enough. Following this trivial approach, the WGM resonator should be designed as an approximately half-wavelength-thick torus to support a single-mode family. Recent experiments con-

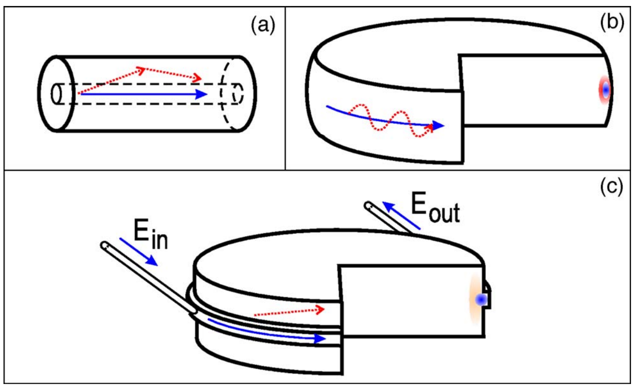


Fig. 1. (Color online) (a) Structure and mode localization in the optical fiber. Only one propagating mode, shown by the solid arrow, survives in the core of the fiber, while others (dotted arrows) penetrate into the cladding and dissipate. (b) Mode localization in the WGM resonator. The resonator corresponds to a multimode gradient fiber for which the index of refraction is set by the resonator shape, not by the change of the refractive index of the resonator host material, which is constant. Both the fundamental and the auxiliary modes survive. (c) Mode localization in a low-contrast WGM resonator. Only a single-mode family survives. The other modes penetrate into the cylinder rod and dissipate. The coupling to the single-mode family is achieved with, e.g., a cleaved fiber coupler.

0146-9592/06/091313-3/$15.00 

firmed this conclusion, and nearly single-mode resonators have been demonstrated.[4]

There is another, nontrivial, approach for engineering optical modes based on an analogy with single-mode optical fiber, which is the major point reported in this Letter. We show here that a WGM resonator made of any transparent material of any size can be transformed into a single-mode resonator if the appropriate geometrically defined core and cladding are developed [Fig. 1(c)].

To show that WGM modes can be described by use of a waveguide formalism, we start with the usual wave equation:

$$\nabla \times (\nabla \times \mathbf{E}) - k^2 \epsilon(\mathbf{r}) \mathbf{E} = 0, \qquad (2)$$

where $k=\omega/c$ is the wave number, $\epsilon(\mathbf{r})$ is the coordinate-dependent dielectric susceptibility, $\mathbf{E}$ is the electric field of the mode, and $\mathbf{r}$ is the radius vector.

Higher-order WGMs (i.e., those with the wavelength much smaller than the resonator size) of both TE and TM kinds are localized in the vicinity of the equator of the resonator. Here cylindrical coordinates can be conveniently used. Applying the technique of separation of variables, and assuming that the resonator's radius changes as $R=R_0+L(z)$ $[R_0 \gg |L(z)|]$ in the vicinity of the equator, we transform Eq. (2), for the TE mode family, to

$$\frac{\partial^2 E}{\partial r^2} + \frac{\partial^2 E}{\partial z^2} + \left\{ k^2 \epsilon \left[ 1 + 2\frac{L(z)}{R_0} \right] - \frac{\nu^2}{r^2} \right\} E = 0, \qquad (3)$$

where $\nu$ is the angular momentum number of the mode (we assume that $\nu \gg 1$), $E(r,z)$ is the scalar field amplitude, and $\epsilon$ is the susceptibility of the resonator material. Equation (3) is similar to the gradient waveguide equation. It is easy to see that, for instance, modes of a spherical WGM resonator coincide with modes of a gradient waveguide with parabolic distribution of the refractive index in the $z$ direction. Hence it is the geometry of the surface that should be modified to produce an ideal single-mode WGM resonator. A core for the WGM waveguide can be obtained by proper design of the resonator's surface in the vicinity of the equator. The rest of the resonator body acts as the cladding [Fig. 1(c)].

Consider a resonator consisting of a cylindrical drum and a small, ringlike protrusion, $L(z)=L_0$ for $d \geq z \geq 0$, on its surface. The drum's effective susceptibility does not depend on the $z$ coordinate and is equal to $\epsilon$. The effective susceptibility of the ring, $\epsilon(1+2L_0/R_0)$ [see Eq. (3)], is slightly larger. Therefore the ring is the core that confines the light in the $z$ direction, while the drum is the cladding. The condition for single-mode operation of the resonator by use of inequality (1) is

$$1 > \frac{d}{\lambda}\sqrt{\frac{2L_0\epsilon}{R_0}} > \frac{1}{2}. \qquad (4)$$

Condition (4) stays valid for a resonator with an arbitrarily large radius. Both the width and the height of the ring can be much larger than the wavelength of light. The ratio $L_0/R_0$ acts in the same way as the ratio $\Delta\epsilon/\epsilon$ in an optical fiber.

To demonstrate the single-mode operation experimentally, we built such a resonator by using a two-step fabrication process that we developed in-house. The first step is a diamond turning process, which employs computer control of a precision lathe. In our diamond turning setup we use an air bearing to achieve the required stiffness and repeatability of workpiece rotations. A commercial brushless motor and a magnetic clutch were used to rotate the bearing. The structures obtained at this step are engineered to ~40 nm precision and have optical $Q$ factors of as much as $10^7$. If higher $Q$ factors are needed, additional optical polishing must be performed. This polishing step leads to the modification of the structure initially obtained by the diamond turning.

The optical polishing is performed by application of a polycrystalline diamond slurry. The optimal size and type of the grains as well as the speed of rotation depend on the material being polished. The optical $Q$ factor of the resonators after the second fabrication step can be limited by contributions from bulk losses, radiation leakage, and surface losses. We have shown that bulk losses are the main restriction on the quality factor. Ultimately, $CaF_2$ resonators could have $Q$ factors of the order of $10^{14}$; practically, $Q=2\times 10^{10}$ was achieved.[5]

We fabricated a monocrystalline fluorite rod of 5 mm diameter. WGMs in such a rod have extremely dense spectra. Then we fabricated a small ring with dimensions of the order of several micrometers on the surface (Fig. 2). The resonator spectrum changed drastically [see Fig. 3(a)]. The resonator has a single TE and a single TM mode family. A single TM mode family was selected by the polarization of incoming light. We confirmed that this was a single-mode resonator by making high-sensitivity logarithmic measurements of its spectrum and by performing numerical simulation of its parameters, which clearly demonstrated that only the fundamental modes survive. Loaded $Q$ factors of both families of modes shown in Fig. 3(a) are equal to $8\times 10^6$. The particular resonator's $Q$-factor was limited by residual surface roughness. It is worth noting that the surface rough-

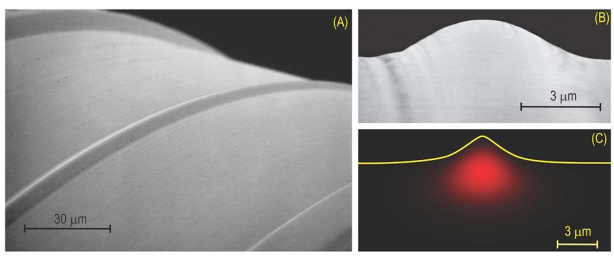


Fig. 2. (Color online) (A) Scanning electron microscope images of the resonator whose spectrum is shown in Fig. 3. The resonator has a nearly Gaussian shape, with 2.5 $\mu$m height and 5 $\mu$m full width at half-maximum. (b) Image of the profile of the resonator shown in (A). (C) Intensity map of the field in the resonator shown in (A) simulated by numerical solution of Eq. (3).

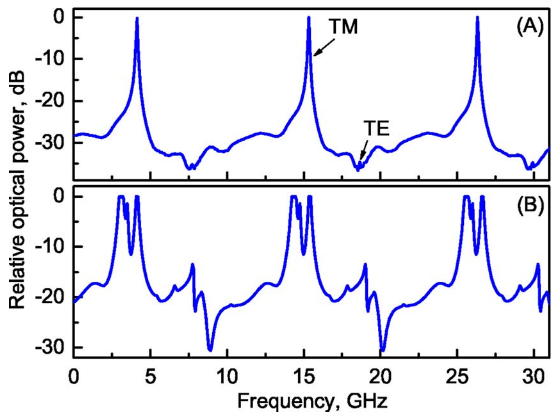


Fig. 3. (Color online) (A) Spectrum of a nearly ideal single-mode resonator obtained by use of a 980 nm laser as well as cleaved fiber couplers [Fig. 1(c)]. The mode number is approximately $\nu = 3 \times 10^4$. The low-$Q$ modes on the spectrum background belong to the drum. (b) Spectrum of the multimode resonator made on the same drum (2.5 $\mu$m height and 15 $\mu$m width) and detected with the same coupling technique. The resonator is partially visible in the lower right-hand corner of Fig. 2(a).

ness that is necessary for achieving $Q = 10^{14}$ for the conditions of our experiment is approximately 1 nm,[6] which is achievable in principle.

We used an angle-polished fiber to couple light into the resonators.[7] Here we also present the spectrum of a multimode resonator made by the same technique on the same drum [Fig. 3(b)] to demonstrate that the coupling does not affect the observed mode structure. With this approach, one can make a single-mode optical WGM resonator of any size. A resonator the size of an apple requires a ring with a dimension of tens of micrometers for single-mode propagation of 1 $\mu$m wavelength light. This is counterintuitive because the size of the single-mode channel is much larger than the wavelength. This type of experiment may be interesting in fundamental research investigations. For practical applications, small resonators are of more interest. In this context, our approach leads to a novel means for engineering of microcavity spectra.

In conclusion, the high mode density of spherical and cylindrical WGM resonators has limited the usefulness of these devices in optical science and technology. Light sent into these cavities occupies a large multiplicity of overlapping and possibly interacting modes, thus complicating device performance and limiting the accuracy of physical measurements. We have demonstrated an experimental single-mode-family resonator that, by design, avoids this pitfall. By engineering the photonic density of states to minimize interaction between the modes and force all input energy into one eigenstate, we have provided science with a new tool with which to study the threshold dynamics of nonlinear and quantum optical processes and for sensing chemical concentrations and fluid flow. It also creates a new class of photonic circuit elements that could expand the capabilities of communications technology.

The type of the dielectric medium used for the proposed resonators is not important as long as it is solid and transparent. Generally, as the behavior of the system is defined only by the system's geometry, it is not even important for what kinds of wave the structure is a resonator. Microwave, acoustical, or mechanical chains of resonators of this type have the same features and basis of design as these optical counterparts.

The research described in this Letter was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA and with support from the Defense Advanced Research Projects Analog Optical Signal Processing. Fabrication and testing of single-mode WGM resonators is a component of a Ph.D. degree project of I. S. Grudinin. A. Matsko's e-mail address is andrey.matsko@jpl.nasa.gov.

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