Ultimate whispering gallery mode resonator and nontrivial relationship between spectrum and shape

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

Jet Propulsion Laboratory, California Institute of Technology, MS 298-100, 4800 Oak Grove Drive, Pasadena, CA 91109-8099

Andrey.Matsko@jpl.nasa.gov

Abstract: Using a similarity between morphologies of an optical planar waveguide and a whispering gallery resonator, we theoretically propose and experimentally demonstrate a one dimensional ring-like macroscopic object characterized with high finesse and small mode volume.

OCIS codes: (230.5750) Resonators

Currently, two general approaches exist for engineering the desired optical modes. In the most common approach, an optical waveguide provides an effective means for confinement and transport of 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 band-gap crystal (PBG) allows for confinement and guiding of photons using morphology of the system. This is achieved by placing defects in otherwise periodic arrays of a dielectric material.

We propose a new approach. It relies on the creation of an index contrast, as in the case of the optical fiber, but is obtained by shaping, similarly to the PBG case. The significance of this technique is that it allows for the designing single and multiply-coupled whispering gallery mode (WGM) resonators for a wide variety of applications ranging from nonlinear oscillators, high order filters, delay lines, and modulators, to devices for fundamental studies in quantum optics. As a demonstration of the power of this novel approach, we theoretically investigate an ideal, single mode, WGM resonator, and verify our findings with an experimental demonstration.

As a textbook example, an ideal optical resonator spectrum consists of a sequence of equidistant modes. Real optical resonators are typically quite different than their "ideal" prototypes. Instead of a single mode sequence, they have many, and instead of equidistant modes, they show a significant dispersion. WGM resonators are not an exception to this. Since early works with WGM resonators it was recognized that they have dense, geometry-dependent mode spectra. This feature generally hinders applications of WGM resonators in fundamental and applied physics.

Researchers working on optical waveguides faced a similar problem in designing a single mode fiber. The single mode fiber revolutionized the world of optics enabling long-distance telecommunications and multichannel television broadcast systems, functions that would be impossible with multimode fibers. 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. The ideal "single-mode" resonator would retain all the advantages of the single-mode fiber, so its development is quite significant.

A homogeneous dielectric waveguide becomes single-mode when the frequency of the propagating light is close to its cut-off frequency. This means that the thickness of the waveguide approaches the half-wavelength of light in the host material of the waveguide. It is quite complicated and impractical to fabricate a single-mode optical fiber by decreasing the fiber diameter. Instead, the 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 in the core, while the others fall into the cladding (Fig.1a). As a result, the core may have a reasonably large diameter. It is worth noting, however, that the core of a single-mode fiber is a multi-mode fiber, if the cladding is removed.

It is convenient to consider the WGM resonator (Fig.1b) as a multi-mode gradient waveguide. The resonator becomes an ideal single-mode-family resonator 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. There is another, nontrivial, approach to the problem, based on an analogy with the single-mode optical fiber, which resulted in the discovery reported in this paper. We here show that a WGM resonator of any size and made of any transparent material can be transformed into a single-mode resonator, if the appropriate *geometrical* "core" and "cladding" are developed.

To demonstrate the single-mode operation experimentally, we fabricated a monocrystal fluorite rod of $\sim$5 mm in

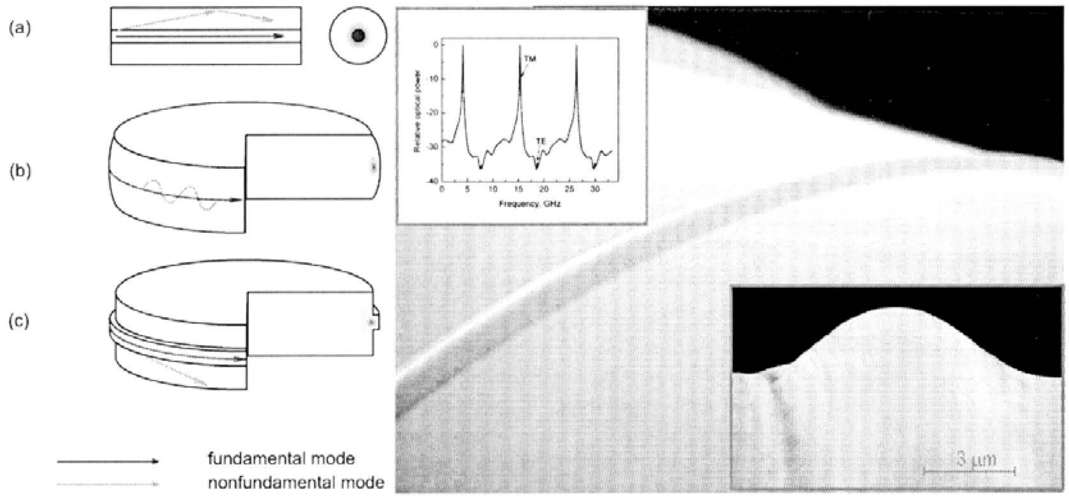

Fig. 1. Left: (a) A structure and mode localization in the optical fiber. Only one propagating mode survives in the core of the fiber, while others penetrate into the cladding and dissipate. (b) Mode localization in the whispering gallery mode resonator. The resonator corresponds to a multimode gradient fiber where 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. (c) Mode localization in a whispering gallery mode ring resonator. Only single mode family survives in the low-contrast axial system. Right: Scanning electron microscope image of the resonator. Insets: The image of the profile and spectrum of the resonator.

diameter. WGMs in such a rod have extremely dense spectra. After that we fabricated a small, nearly invisible, bump with dimensions of the order of several microns on the resonator surface and the spectrum of the resonator changed drastically (see Fig. 1). The resonator has a single TE and a single TM mode families. A single TM mode family was selected by the polarization of incoming light. We confirmed that this was a single mode resonator by i) making high-sensitivity logarithmic measurement of its spectrum, and ii) performing numerical simulation of its parameters. The residual surface roughness limited Q factors of both families of modes are on the order of 10^7.

With this approach, one could make an optical single-mode WGM resonator of the size of an apple, which is counter-intuitive and may be interesting as a fundamental research investigation. For practical applications, on the other hand, small resonators are of more interest. In this context, our approach leads to a novel means for engineering microcavities, manipulating their spectra, and even 3D packaging. Let us briefly describe some of the applications of the single-mode WGM resonator.

Several ideal WGM resonators can be fabricated on a single cylindrical rod. The resonators could be coupled through the evanescent fields inside the rod. We emphasize that the evanescent field range inside the dielectric is much larger than in the vacuum. The decay constant of the evanescent fields can then be easily manipulated by proper shaping of the resonators. The "intra-rod" coupling has a great advantage compared with the usual evanescent field coupling of WGM resonators because the former is much more stable with respect to the external environmental conditions such such as the temperature of the moisture in the air. The coupling only depends on the shape of the resonators and distance between them and is fixed unless the substrate geometry or optical properties are altered. Such an alteration can be implemented by changing the substrate temperature, or applying external pressure or voltage (in the case of ferroelectric materials). This provides the means for controlling the resonators properties (e.g., frequency) as well as their coupling.

Finally, the type of the dielectric media used for the proposed resonators is not important as long as it is solid and transparent. Generally, since the behavior of the system is defined only by geometry it is not even important for what kind of waves the structures represent a resonator. Microwave, acoustical or mechanical chains of resonators of this geometry have the same features and basis of design as these optical counterparts.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration and partial sponsorship from DARPA.