Microsphere integration in active and passive photonics devices

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ABSTRACT

As important step towards integration of microspheres in compact functional photonics devices, we demonstrate direct efficient coupling of light in and out of high-Q whispering-gallery (WG) modes in silica microspheres using angle-polished single mode fibers. Based on this principle, we present a 1-inch fiber-pigtailed microsphere module that can be used for fiber-optic applications, and a fiber-coupled erbium-doped microsphere laser at 1.55μm. In addition, we report preliminary data on the intensity modulation based on high-Q WG modes in a lithium niobate sphere. We also demonstrate a novel geometry WG-mode optical microcavity that combines $Q \sim 10^7$, typical for microspheres, with few-nanometer mode spacing earlier available in lower quality factor $Q \sim 10^4$ microfabricated planar rings.

Keywords: Microsphere, microcavity, photonics, microlaser, electrooptic modulator, erbium

1. INTRODUCTION

In the growing field of microcavity science and applications, microspheres [1-5] stand out as exceptional type of cavities with the dimensions compatible with microfabricated devices and the quality-factor normally obtained in large Fabry-Perot "supercavities". Despite numerous suggested applications – from compact filters, microlasers, diode laser stabilization, to microwave optoelectronic oscillators and sensors [6-12], - the roadpath towards miniaturized functional devices based on microspheres was blocked by the absence of compact and efficient couplers compatible with integrated and fiber optics. In this report, we describe in detail a new simple method for direct coupling from single-mode optical fibers to high-Q whispering-gallery (WG) modes in microspheres. In this method, the tip of the fiber is angle polished under the angle providing total internal reflection and synchronism of the evanescent wave in the truncated core area with the azimuthal propagation of WG modes in the microsphere. Based on this novel technique, we present a compact fiber-pigtailed optical filter module with a microsphere, and a fiber-coupled erbium-doped microsphere laser. By contrast to earlier microspehere laser demostrations, aimed at implementation of ultra-low threshold operation, our laser work focuses on obtaining significant output power, up to several microwatts, in the optical communication band 1.55μm.

The principle of angle-cut, or angle-folded dielectric waveguide can be utilized for obtaining similar phase-matched coupling of microsphere modes with planar integrated waveguides. Flexibility of this method allows efficient coupling between WG modes in low-refraction-index microspheres and guided modes in high-index (e.g. silicon) waveguides. This would pave the way to implementation of truly integrated narrow-line (sub-kHz) microsphere-stabilized semiconductor laser source and on-chip microwave optoelectronic oscillator.

As pointed out in many works, combination of strong field confinement and high quality-factor in whispering-gallery modes enables observation, at a low threshold, of various nonlinear optical effects. Beginning with extensive studies in liquid aerosol droplets (raman scattering, lasing in dye solution droplets), with further demonstrations of dispersive bistability in silica microspheres and low-threshold lasing in doped silica and ZBLAN spheres, nonlinear-optic studies with WG modes were focussed on isotropic, uniform materials that possessed the third-order nonlinear succeptibility. Meanwhile, novel applications will be possible if sphere is made of electro-optic, $\chi^{(2)}$ materials. Many of them are characterized by rather small optical losses so that quality-factors up to 10^7 can be expected if appropriate sphere fabrication and polishing technique is used for those crystalline materials. We present here observation of whispering-gallery modes in few-mm diameter lithium niobate spheres and demonstration, on their basis, of a prototype optical intensity modulator.

The final part of our report is devoted to the exploration of novel geometry for high-Q whispering-gallery mode microcavity. The goal is to reduce the cavity volume and the number of excited modes compared to microspheres and therefore create a miniature solid state cavity that would combine small size and very high Q with the type of spectrum one can expect in single-longitudinal-mode Fabry-Perot resonator. Applying an original new technique, we fabricated a dielectric

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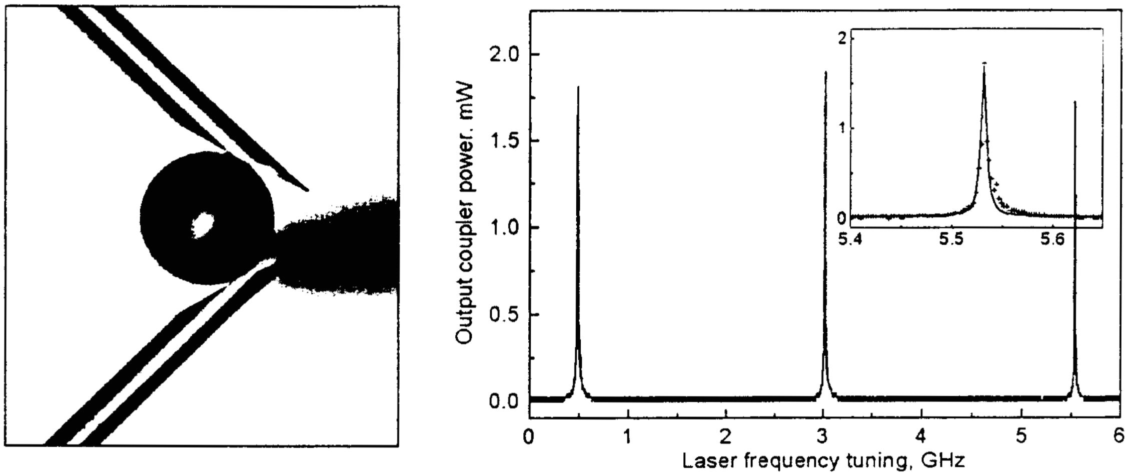
structure of quasi-toroidal, or highly-oblate spheroidal geometry in the area of desired WG mode lozalization. As confirmed by experiment, such a cavity does provide a drastic reduction in the number of excited WG modes (two within free spectral range of 383GHz corresponding to the cavity diameter 160μm at the wavelength 1.55μm), while maintaining the Q ~ 10^7.

2. SINGLE-MODE FIBER COUPLER FOR MICROSPHERES

At present moment, in addition to the well-known prism coupler with frustrated total internal reflection [1-9], few attempts have been reported to directly couple a sphere to an optical fiber. However these fiber couplers had either limited efficiency due to residual phase mismatch (side-polished bent fiber coupler [13]), or still appreciable size including fragile core-to-cladding transformers (tapered fiber coupler [14]). Recently, we have demonstrated a new and simple method of direct fiber coupling to high-Q WG modes, which in essense is a hybrid of waveguide and prism coupler. A close-up of the experimental setup with microsphere and two couplers is shown in Fig.1a. The tip of a single-mode fiber is angle-polished under steep angle. Upon incidence on the angled surface, the light propagating inside the fiber core undergoes total internal reflection and escapes the fiber. With the sphere positioned in the range of the evanescent field from the core area, the configuration provides efficient energy exchange in resonance between the waveguide mode of single-mode fiber and the whispering-gallery mode in the sphere. The angle of the polish is chosen to secure the phase matching requirement: $\Phi = arcsin(n_{sphere}/n_{fiber})$. Here n_{fiber} stands for the effective refraction index to describe the guided wave in the fiber core truncation area, and n_{sphere} stands for the effective refraction index to describe azimuthal propagation of WG modes (considered as closed waves undergoing total internal reflection in the sphere), see plot in Fig. 2. Since the linear dimensions of the angle- cut core area match well the area of evanescent field overlap, the



(a) (b)

Fig.1. Close-up view (a) and optical transmission characteristic (b) of a microsphere with two side-polished fiber couplers. Input power 7.5...8.3mW; maximum transmission at resonance ~23.5% (fiber-to-fiber loss 6.3dB); $Q_L > 3 \times 10^7$ at 1550nm; sphere diameter 405μm. Unloaded $Q_o \approx 1.2 \times 10^8$. Fiber: SMF-28, polished at ~76°.

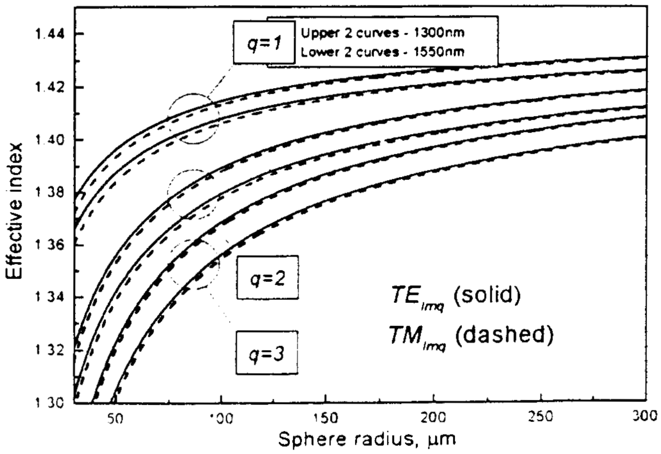


Fig.2. Effective index for WG mode azimuthal propagation (based on mode frequency approximation by C.C.Lam *et al* [15])

the new system is equivalent to a prism coupler with eliminated collimation/focusing optics. The effective refraction index to describe the azimuthal propagation of WG modes near the surface of the sphere can be calculated, for example, on the basis of asympthotic expressions [15] for WG mode frequencies ω_{lq}, where $n_{sphere} = 2cl / D\omega_{lq}$. Single coupler efficiency in our experiment was more than 60%, comparable with the best reported results for prism coupler (78%) and fiber taper (90%); total fiber-to-fiber transmission at resonance ~23% (insertion loss 6.3dB). The demonstrated simple "pigtailing" of the microspheres will lead to their wider use in fiber optics, enabling the realization of a whole class of new devices ranging from ultra-compact narrow band filters and spectrum analyzers and high-sensitivity modulators and sensors, to compact laser frequency stabilization schemes and opto-electronic microwave oscillators.

Fig.3 presents a prototype packaged microsphere-based fiber-optic filter module with in-line positioned angle polished input and output couplers, insertion loss ~12 dB and the loaded Q factor 3×10^7 at 1550nm.

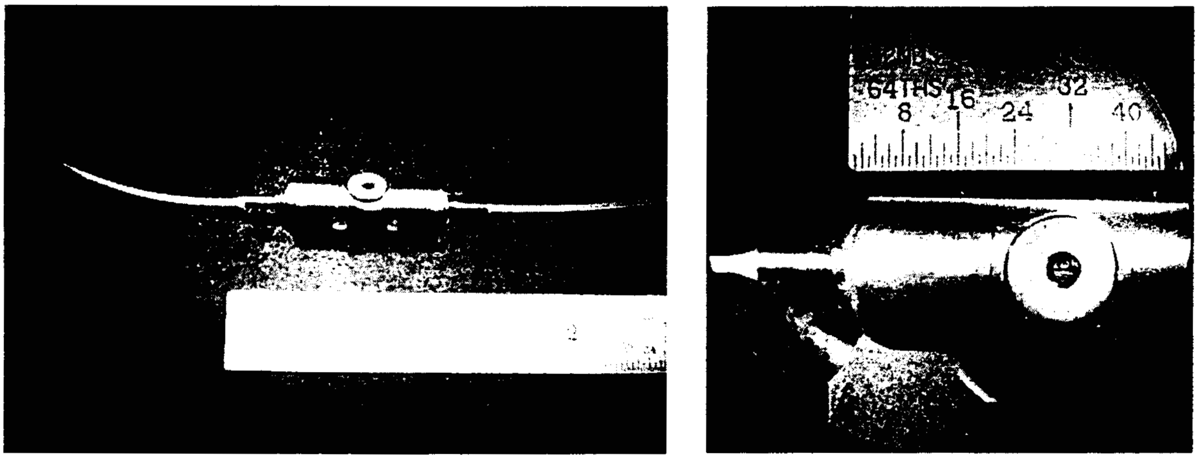


Fig.3. A prototype fiber pigtailed microsphere package. Insertion loss ~12dB; loaded Q~3×10^7 at 1550nm

Apart from "discrete element" fiber optics applications, microspheres present further challenge for true integration with planar optics devices. Very high $Q \geq 10^8 \ldots 10^9$, uncommon for existing planar microcavities, would open way for sub-kHz-linewidth integrated laser sources [11] and single-chip microwave optoelectronic oscillators [12]. The ultimate goal is the replacement of laboratory hand preparation of spheres (fusion of silica preforms in ox-hydric flame or CO_2 laser beam) by appropriate microfabrication technology. It is worth to note here that such a task may not be extraordinary difficult, given the progress in planar silica waveguides and succesful demonstrations of thermal treatment techniques for formation of smooth curvilinear integrated optics elements. The other part of the integration is the development of appropriate waveguide coupler elements. This task can possibly be solved along three routes: a)precise tailoring of propagation constant in the waveguide to match that of the sphere [16]; b)truncation, or "reflection" of the waveguide from vertical cleave, by analogy with the above-described fiber coupler.

2. FIBER-COUPLED ERBIUM-DOPED MICROSPHERE LASER

Early reports on microsphere lasing demonstrated the stimulated emission in dye-doped polysterene spheres with relatively low-Q of $\sim10^4$ and free-beam excitation [17]. Reports of high-Q microspheres acting as laser cavities were focused on the possibility to achieve extremely low threshold [7] of laser operation with Nd ions. Preliminary data on 1.55μm lasing in Er-doped ZBLAN spheres have been reported [18] with pumping and outcoupling of laser radiation obtained by means of bulky prism coupler. Our miniature design utilizes the earlier disclosed angle-polished single-mode fiber coupler for both delivering pump power into the sphere and the pickup of laser radiation. The schematic of experiment is presented in Fig.4, with the inset photograph showing the lasing sphere next to the fiber coupler. The circular lasing area is visualized by upconversion-pumped fluorescence at 525-545nm. The pumping radiation is provided by the multimode diode laser E-Tek LDPM7000 BBA10, stabilized by external fiber grating at the wavelength 977.6nm. Through polarization controller and wavelength division multiplexer, the pumping radiation reaches the angle-polished fiber coupler and excites the WG modes in the microspheres. The modes are excited in a travelling-wave regime, (counterclockwise direction in Fig.4). Quality-factor of microsphere modes at pumping wavelength was $1.5\cdot10^8$ in loaded regime (zero microsphere-coupler gap) and (0.7...1)×10^6 in the undercoupled regime. Relatively low undercoupled Q of the sphere, compared to projected Q_P = 2 × 10^7 from the reported pump attenuation 2.8dB/m of the material, may be explained by scattering losses produced by residual optical inhomogeneities (refraction index variations) in the spheres. The spheres were produced from the 0.6mm rods of core material extracted from fiber preforms (INO 502 O1). Main part of the silica cladding was removed by machining, subsequently the remaining cladding was etched in hydrofluoric acid. Since the core of the preform (produced by CVD technique) contained alternating layers with varying concentration of components and refraction index, prior to formation of a sphere, the material was fused several times and mixed for homogenization.

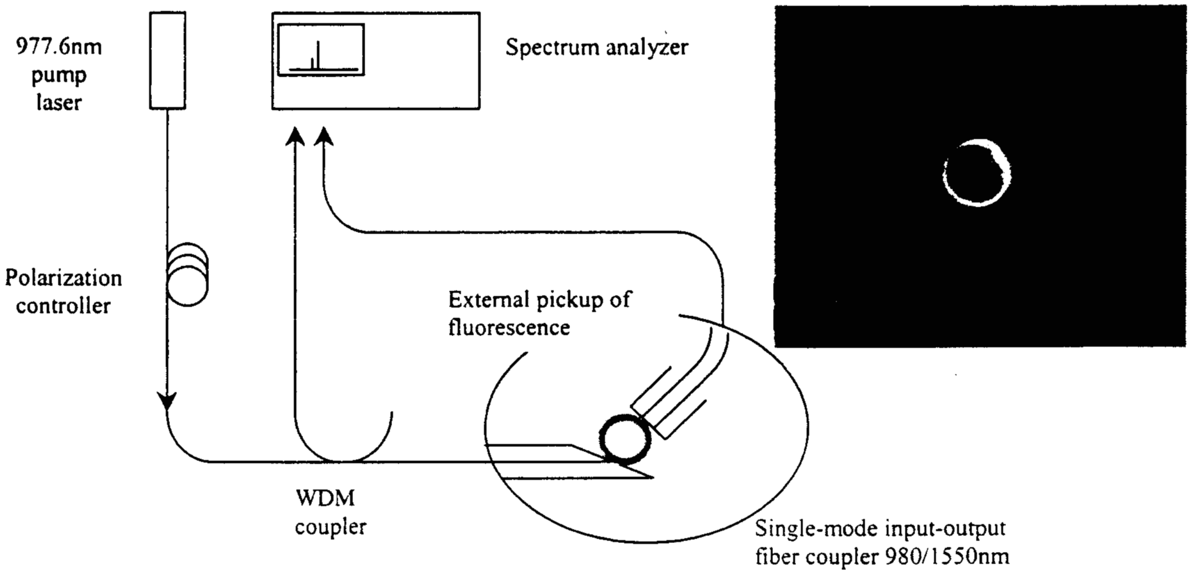


Fig. 4. Schematic of the laser experiment and a close-up of the microsphere with single-mode fiber coupler.

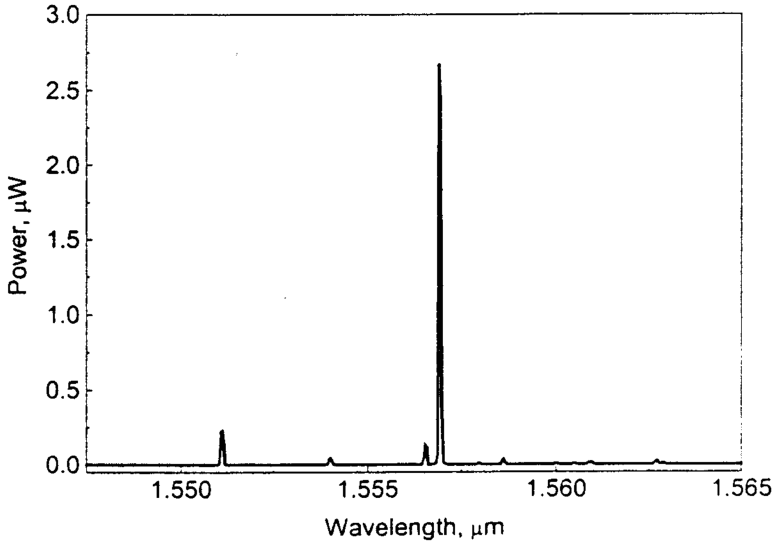


Fig.5 Typical oscillation spectrum of the fiber-coupled erbium-doped microsphere laser

After that, the sphere of diameter 50 to 150 micron was formed by microtorch fusion technique described elsewhere [4]. The laser radiation was outcoupled in the direction opposite to the pump (clockwise in Fig.4), split out by the WDM coupler and send to the optical spectrum analyzer (Advantest Q8383). Depending on the alignment of the coupler, the lasing could be obtained throughout the most of luminescence band of Er^{3+} ion - between 1530nm and 1560nm. Fig.5 presents a typical spectrum of oscillation of Er-doped sphere. Maximum obtained power in our preliminary experiment was ~3μW in the output fiber.

3. TUNABLE WHISPERING-GALLERY MODES IN LITHIUM NIOBATE SPHERE

Efficient recycling of light in WG modes of spherical cavities calls for variety of applications that may be suggested if a sphere is built of nonlinear material. In this case, responsivity of the device would increase compared to conventional single-path, or low-finesse interferometer configurations, because of the high-Q of WG mode resonances. As a first step towards nonlinear devices based on spherical cavities, we present here observation of WG modes in few-mm diameter lithium niobate spheres and demonstration, on their basis, of a prototype optical intensity modulator.

Lithium niobate, one of the most common nonlinear-optic material, is an electrooptic crystal with low losses $\alpha \leq 0.02$ cm^{-1}, allowing the quality-factor $Q=2\pi n/\alpha\lambda \sim 10^7$ of whispering-galery modes. By contrast to amorphous materials, high-quality spheres may not be obtained by fusion of crystalline materials. Spontaneously forming boundaries between misoriented crystalline grains, or blocks, create significant optical inhomogeneities through the bulk of the sphere and on the surface, thus increasing the scattering losses beyond the acceptable level. (Self organized spheres of cubic (non-birefringent) crystalline material were reported in [6]. Because of their sub-grain few-micron size, they supported WG modes of reasonable $Q \sim 10^4$-10^5.) To obtain high-surface quality spheres of birefringent crystalline materials, one has to necessarily machine and polish them using conventional optical methods. On flat or low-curvature substrates, modern metods allow to obtain angstrom size residual inhomogeneities – compatible to the roughness of fire-polished silica and therefore allowing ultimate $Q>10^9$. These methods, however, have never been adapted for very small radii of curvature. In one of the early works [2], WG modes with quality-factor of about 1×10^8 were observed in a 3.8cm diameter mechanically for the Gravity Probe B experiment. In the meantime, with a given size of surface inhomogeneity, limitation of Q by scattering losses is in direct proportion to the sphere diameter.

In our preliminary experiments, we used a lithium niobate sphere of diameter D = 4.8mm, custom fabricated and polished out of commercially obtained $LiNbO_3$ specimen (from Casix Inc). Because evanescent wave coupling could be provided by a prism of refraction index higher than that of the material (n_o = 2.220; n_e = 2.146), we used a miniature diamond prism (n = 2.4). Spectral measurements were done using the E-Tek DFB laser at about 1550nm, frequency-scannable via current modulation. As seen from results presented in Fig.6, the employed prism coupling technique provided about 50% energy coupling efficiency in the loaded regime. The observed free spectral range FSR ~ 8.3GHz corresponded to the sequence of successive principal mode numbers l for TE-type WG modes excited in the plane perpendicular to the crystal

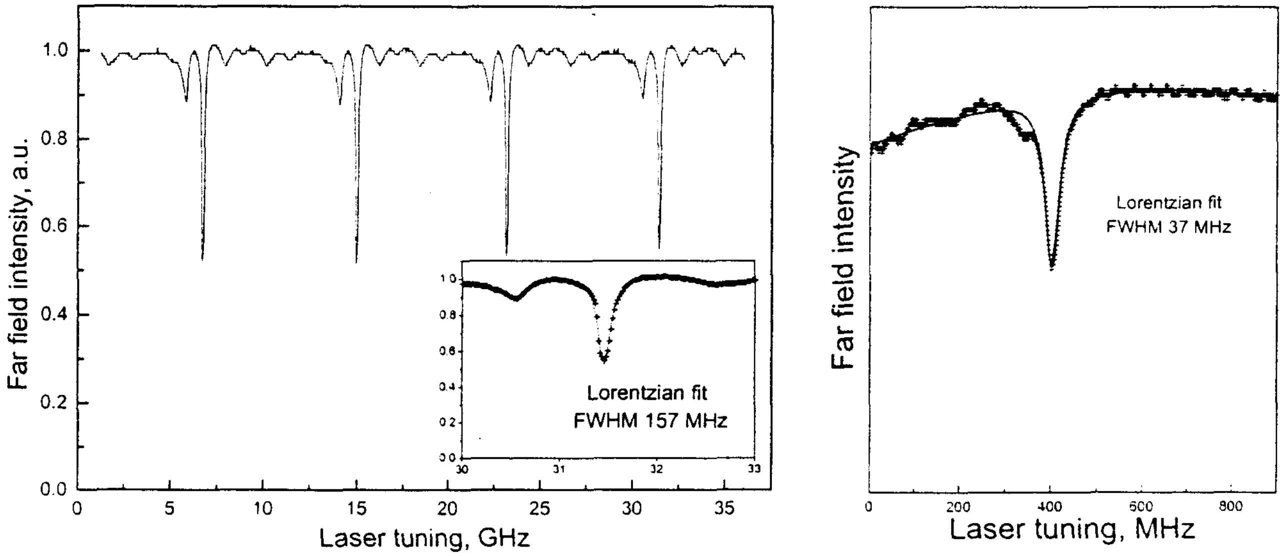


Fig.6. Whispering-gallery mode spectrum in a 4.8mm diameter $LiNbO_3$ sphere, at 1550nm: a)35GHz scan revealing the FSR=8.3GHz of TE mode sequence, excitation in normal plane to the crystal axis; b)closeup of an individual mode; resonance bandwidth 37MHz corresponding to the quality factor $Q > 5\times10^6$

axis. The estimated loaded quality-factor of the modes in Fig.6a is about 1.2×10^6, and the non-Lorentzian shape of the observed resonance dips suggested that they corresponded to clusters of slightly non-degenerate modes. Let us note that the character of the observed spectrum critically depended on the orientation of the sphere. With the excitation off the perpenducular plane to the crystal axis, the observed spectrum became dense, revealing a sequence of closely spaced modes with Q-factors up to 5×10^6 (see Fig.6b). Thise preliminary result confirms that inexpensive fabrication and polishing techniques allow to achieve the Q factor in the spheres of crystalline lithium niobate that is close to the limits defined by material attenuation.

With the far off symmetry plane orientation of the input beam, the observed frequency response in the far field represented a continuous sequence of fringes produced by partially overlapping modes (see Fig.7).

The electrooptical effect in the spheres of lithium niobate is in the simplest way manifested via the tuning of WG modes by applied electrical field. To demonstrate this, we applied RF electrodes near the poles of the sphere and observed the displacement of the mode spectrum in the frequency domain by the applied voltage U at the rate 0.5MHz /Volt. This electrical tunability is in satisfactory agreement with the crude estimate $|\Delta\nu/U| = \frac{1}{2}\, n^2 \gamma_{13} / D \approx 0.8$ MHz/V, where $\nu = 194$THz -- is the lightwave frequency; $\gamma_{13} = 10$pm/V -- is the electrooptical constant; and $D = 4.8$mm, diameter of the sphere, is used as electrode spacing.

Presented in Fig.7 is the demonstration of the low-frequency electrooptical intensity modulation by the lithium niobate sphere. During continous monitoring of WG mode spectrum in the sphere by means of frequency-tuned laser, a 100kHz rf voltage with $U_{eff} = 40$V (~125V peak-to-valley) was applied to electrodes, resulting in amplitude modulation maximal near the slopes of individual cavity resonances.

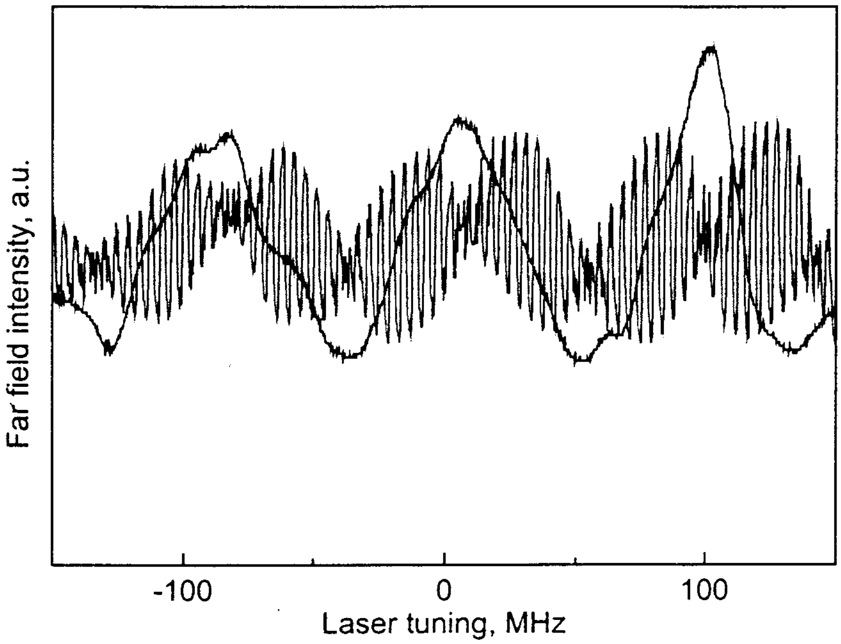


Fig.7. Demostration of low frequency electrooptical intensity modulation by the lithium niobate sphere: effect of radiofrequency (100kHz) voltage (U_{eff}=40V)

By definition, an electrooptical modulator, based on a cavity, may not be a wide-band device. It may however be suitable for a number of applications where optical carrier is fixed, and the cavity spectrum can be trimmed to have optical modes at the carrier frequency and the modulation sidebands. With development of appropriate fabrication techniques and reduction of the sphere size (at least 100 fold reduction is possible without compromising the optical Q), this inconvenience will be compensated by two serious advantages over existing modulators. First, the controlling voltage (analog of V_π) can be reduced into milliVolt domain. Second, tiny capacity of electrooptic microspheres will simplify application of microwave fields, compared to both plane-wave bulk electrooptical modulators and integrated Mach-Zender interferometer modulators.

4. HIGHLY OBLATE SPHEROIDAL MICROCAVITY: FREE SPECTRAL RANGE OF FEW NANOMETERS AND FINESSE ~10^4

Despite their small dimensions, because of high symmetry microspheres exhibit relatively dense spectrum of high-Q whispering-gallery modes. Even with the optimized near-field coupler devices [13,14,19], the typical spectrum consists of *overlapping* groups of $TE\ (TM)_{lmq}$ modes spaced by "large" free spectral range (FSR). By "large" FSR we denote here, roughly, the interval in the sequence of *fundamental* resonances corresponding to successive number l of wavelengths packed along the "equatorial" circumference of the sphere. It is easy to estimate that with the silica sphere diameter between 150-400 micron, the "large" FSR should be 670...165GHz, or in the wavelength scale, 5.4...1.3nm, near the center wavelength 1550nm. Although degenerate in ideal spheres, modes with different *transverse* structure (mode index m defining the field extent in the "latitudinal" domain) are split in slightly eccentrical cavity. As a result, average mode spacing is between 1 and 10GHz, in typical microspheres of 150-400micron diameter and ~1% eccentricity obtained by microtorch (or CO_2-laser assisted) fusion of silica preforms.

For some of applications such as spectral analysis and laser stabilization, such a dense spectrum precludes simple technical solutions and calls for using intermediate filtering etc. To overcome this problem, the ultimate solution would be to create a single mode waveguide ring shaped by planar technology methods or somehow spliced out of a section of straight guide. The first option is implemented in planar ring cavities [20], but the quality-factor in this case is limited to $Q \leq 10^4 \ldots 10^5$ by fundamental scattering losses at flat boundaries. Technically, direct splicing of small single mode fiber rings is not out of question, however because of bending losses the low-contrast core does not effectively confine radiation unless the radius is more than few millimeters. In our experiment, we approached the "single-mode" operation in high-Q WG mode microcavity by shaping the dielectric, in the area of WG mode localization, into geometry of highly eccentric ellipsoid of rotation. A pre-determined amount of low-loss silica glass, preshaped as a sphere, was heated and squeezed between flat cleaved tips of optical fiber.

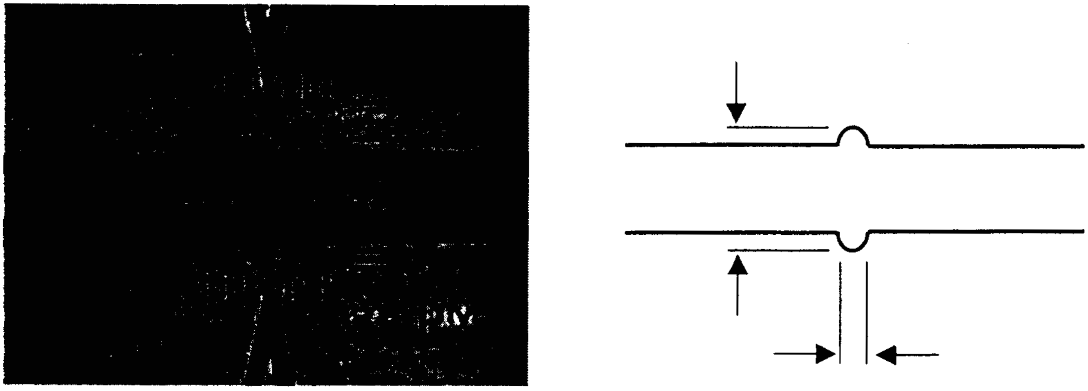


Fig.8. Microphotograph and the cross section of a novel geometry high-finesse dielectric microcavity with whispering gallery modes

As a result, the action of surface tension forces under axial compression resulted in desired geometry (see typical microcavity in Fig.8). One of the fiber "stems" was then cut, the whole structure installed in proper alignment next to a standard prism coupler, and the whispering-gallery mode spectrum observed using the frequency-tunable DFB semiconductor laser near the wavelength of 1550nm. The laser could be continuously frequency-scanned, by modulation the current, within the range of ~80GHz. To obtain high-resolution spectrum of WG modes over a wide range, we have combined 15 individual scans with ~60GHz frequency shifts between them. The frequency reference for "stitching" the spectral fragments was provided by simultaneous recording of the fringes of high-finesse (F~120) passively stabilized Fabry-Perot ethalon (FSR=30GHz). Additional frequency marks were obtained a system of sidebands resulting from 3.75GHz amplitude modulation of the laser signal before sending it into the Fabry-Perot interferometer. Total drift of the FP fringes was less than 400MHz over the total measurement time ~15min. After recording the individual scans, the combined spectrum was complilated on computer. Results are presented in Fig.9. As seen in Fig.9, only two whispering-gallery modes of selected polarization are excited within the free spectral range of the cavity FSR = 383GHz, or 3.06nm in the wavelength domain. The transmission of "parasitic" modes is at least 6dB smaller than that of principal ones. With individual mode bandwidth 23MHz, the finesse $F = 1.7 \times 10^4$ is therefore demonstrated.

Presented here are preliminary experimental data on the novel, highly oblate spheroidal dielectric cavity with WG modes. They demonstrate that, because of the increased curvature of the cavity in transverse direction with respect to azimuthal circulation of light, the multiple "transverse" modes are effectively decoupled from the input/output device. Rigorous analysis of the transmission characteristic of the new cavity requires 1)electrodynamic analysis (solution of the Helmholtz equation in spheroid) and 2)calculation, on the basis of obtained eigenfunctions for the WG modes, of the input/output coefficients with evanescent wave coupler devices. Conventional solution for boundary problem for a spheroid is non-existent. Apart from numerical methods, the mode structure and frequencies may possibly be obtained using the eikonal methods previously applied to microspheres [21]. With the field configuration known, calculation of evanescent coupling coefficients can be done within the guidelines described in [22].

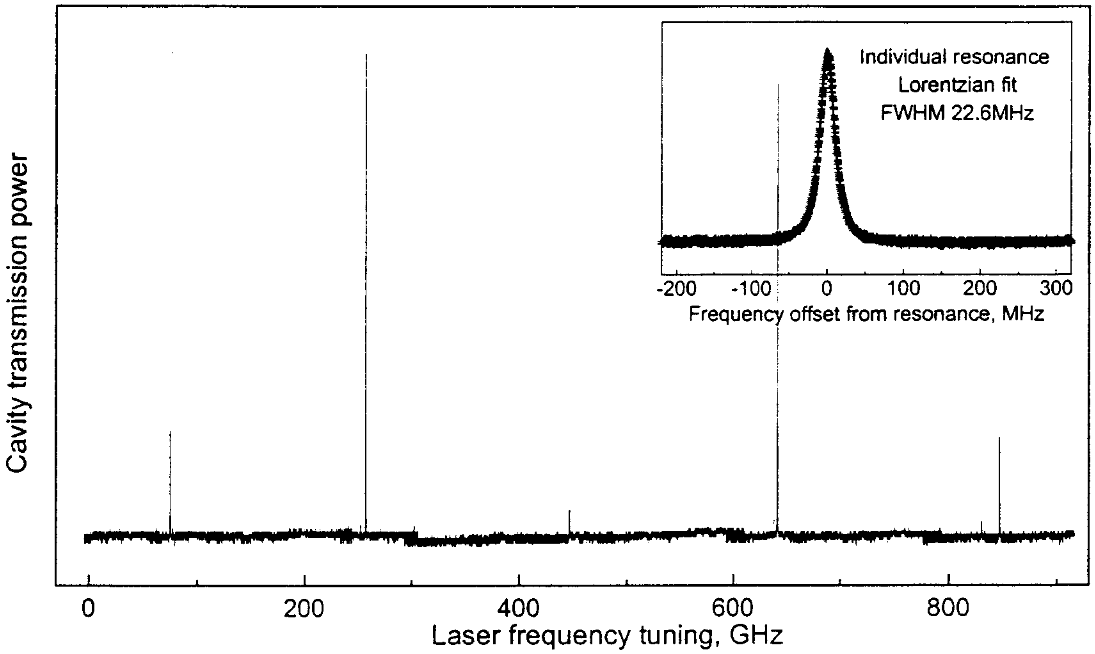


Fig.9. Spectrum of whispering-gallery modes in spheroidal dielectric microcavity (D = 160μm; d = 35μm). Free spectral range 383GHz (3.06nm) near central wavelength 1550nm. Individual resonance bandwidth 23MHz (loaded Q = 8.5×10^6). Finesse $F = 1.7\times10^4$

Strong reduction of the number of effectively excited modes increases the applicability of the new microcavity compared to microspheres. In simple diode laser frequency locking schemes [11], robust single mode operation should be possible because WG mode spacing is now compatible with the gain bandwidth of the laser diode proper. In spectral analysis applications, the as yet unprecedented resolution becomes available with a truly miniature device. For an optoelectronic oscillator, the new cavity provides convenient reference for sub-millimeter-wave to teraHertz frequency sidebands, provided that appropriate detector and modulator are developed to complement such a very-high-frequency OEO.

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