Tunability and synthetic lineshapes in high-Q optical whispering gallery modes

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ABSTRACT

We demonstrate novel techniques to manipulate spectral properties of high quality factor ($Q > 10^7$) whispering-gallery modes (WGM) in optical dielectric microresonators. These include permanent frequency trimming of WGM frequencies by means of UV photosensitivity of germanium doped silica resonators; electro-optical tuning of WGM in lithium niobate resonators, and cascading of microresonators for obtaining second-order filtering function. We present theoretical interpretation of experimental results, and application example of the techniques for photonic microwave filtering.

Keywords: Whispering Gallery Modes, Optical filters, Multiplexing Equipment, Optical communications, Optical fiber networks

1. INTRODUCTION

Optical solid state dielectric resonators with whispering-gallery modes (WGMs) possess a combination of unique features such as high Q-factors $10^8 - 10^{10}$, submillimeter size, and high mode stability.[1–4] Several effective approaches for coupling light into and out of WGMs have been devised, including a simple and efficient method of using angle polished fiber tips,[5] tapered fiber couplers,[6–8] and prism couplers.[9] All these makes the WGM dielectric cavities be attractive for usage in various fields of research and technology.

In many practical applications resonators with specific resonance frequencies are desired. This, however, is quite difficult to achieve, since the usual method for the fabrication of microresonators based on melting a fiber tip cannot produce a precise, predetermined geometry and, therefore, a desirable resonance frequency. Mechanical trimming of WGMs with applied strain[10–12] and temperature[13] tuning have been previously used for the controlled changing of the resonance frequency in WGM microresonators. Practical application of these methods is complicated and the size of the devices used for the guiding the mode frequency hinders the advantages of the small resonator size.

A technique of WGM resonance trimming utilizing a photosensitive coating was used with microring resonators. In that study, glass microrings were dipped in a polymer coating material and were exposed to UV light. This method produced resonators with relatively small Q (about 800) because of the polimer-induced absorption, but it still allowed large tunability of the optical resonance of the microring, enough for wavelength selective applications.[14]

In this paper we propose two method of tuning high-Q WGM spectra. One method allows permanent shifting of the WGM spectra of germanium doped silica microcavities. The other method allows for fast electro-optic tuning of the WGM spectrum of a cavity made of a crystal possessing a quadratic nonlinearity, such as $LiNbO_3$.

We report on an approach for trimming the frequency of microcavities by exploiting the photosensitivity of germanium-doped silica.[15–17] When exposed to UV light, this material undergoes a chemical change which alters index of refraction of the material.[15] This property is used in writing fiber Bragg gratings.[18] In our case, the change in the index of refraction results in a uniform translation of the resonant frequencies of a WGM microcavity.

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We have demonstrated a realization of a precise shift in the resonance frequency of high-Q (10^8) WGMs. Approximately 18 GHz permanent frequency shifts were obtained for modes of 1550 nm wavelength with application of 600 mW power 351 nm radiation from an *Ar*-ion laser. This is enough to tune a resonance over a full free spectral range of the WGM resonator.

The ability of permanent tuning of the WGM spectrum allowed us to construct a second-order optical filter. A single microresonator produces a Lorentzian-shaped filter function, and a flatter passband or a sharper rolloff cannot be achieved. It was shown that coupling the resonators in parallel or in series may result in a passband that is nearly flat.[19,20] In this paper we report on the demonstration of such a configuration using two tunable, coupled microcavities. By tuning the resonance frequency of one, germanium doped, cavity very close to the resonance of the second cavity, we succeeded in producing a two-cavity compound filter with a nearly top-hat shaped second order filter function.

Wavelength demultiplexing and channel sections in wavelength division multiplexing systems require tunable narrow-band optical filters that are compatible with single mode fibres. Desirable characteristics for the filters include fast tuning speed, small size, wide tuning range, low power consumption, and low cost. WGM cavities may be useful to construct such filters as well.

We report on a realization of a miniature resonant electro-optically tunable filter. Our filter is based on a micro-disc WGM cavity fabricated from a commercially available lithium niobate wafer. The filter operates at the 1550 nm wavelength regime.

Tunable resonance filters are characterized by the finesse (F) which is equal to the ratio of the filter free spectral range (FSR) and the filter bandwidth. Finesse indicates how many channels can fit in one span of the FSR. The repeatable value of finesse of the $LiNbO_3$ filter exceeds $F = 300$, but in some experiments we have achieved $F = 1000$. The tuning speed of the filter is approximately 10 ns, while the real spectrum shifting time is determined by filter's bandwidth and does not exceed 30 μs. We observed at least -20 dB suppression of the channel cross-talking rate for 50 MHz channel spacing. For comparison, a usual Fabry-Perot tunable filter may have a finesse of 100, 125 GHz bandwidth, and tuning speed in a millisecond range. The Fabry-Perot filters also meet -20 dB channel-to-channel isolation condition for 50 GHz channel spacing.[21,22]

In what follows we discuss properties of WGM-based filters in details.

2. UV-ASSISTED FREQUENCY TUNING OF OPTICAL WGM CAVITIES

The experiment involved microspheres made of germanium-doped silica. We fabricated spheres using two methods. In the first case, the silica sphere was fabricated in the way described in,[23] and was then covered by a small amount of germanium powder. The sphere was subsequently heated to a controlled temperature to melt the germanium, but not the silica sphere. As the germanium melted, it formed a thin coating over the surface of the sphere. A small amount of germanium also diffused below the surface of silica, creating a thin shell of photosensitive material. Repeating the powder-and-heat process many times, we produced germanium-coated/doped spheres of sufficient photosensitivity to use in the experiments.

The approach described above is time consuming. In the second case, for a better efficiency, we used a germanium-doped optical fiber with core material containing 19-20 molar percent of germanium. This shortened the fabrication process, and yielded microspheres with much greater maximum change in the index of refraction.

The setup for tuning frequency included an argon-ion laser to change the resonator frequency, a tunable 1550 nm diode laser to control the frequency shift, an erbium-doped fiber amplifier, a Fabry-Perot cavity as a frequency reference marker to stabilize the drift of the laser and to measure the spacing between the spectral lines. The probe light at 1550 nm from a tunable laser was sent into the microsphere with an angle-polished fiber.[5] The output light was collected and sent to a photodiode that produced a spectrum of the microsphere as laser frequency was swiped. The output light exits the microsphere at an angle of $5 - 15$ degrees from the direction of the incident light, so that the two beams are physically separated.[9] A second fiber with a convex tip focused the 600 mW UV output radiation from a 351 nm argon-ion laser onto the surface of the microsphere. This radiation changed the chemical structure of the microsphere material as well as caused the sphere heating. Both those effects resulted in frequency shift of WGMs. The temporal effect of heating was much stronger than

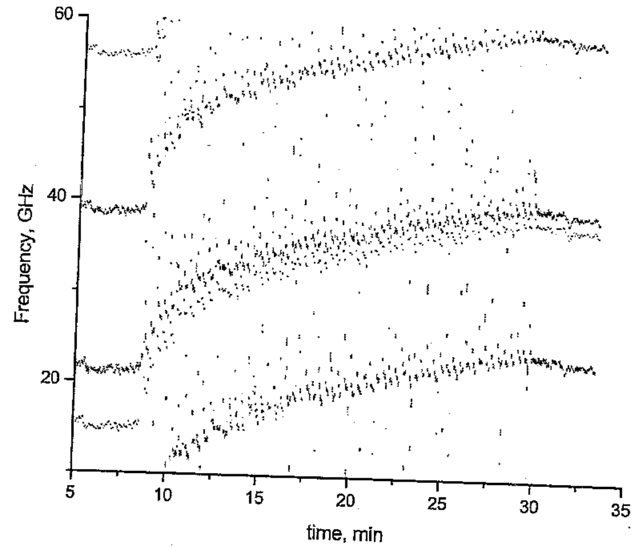

Figure 1. Resonance frequency shifts as a function of exposure by 600 mW 351 nm UV laser radiation

the effect due to UV-assisted permanent shift we are interested in. By alternately opening and closing a shutter at intervals of several seconds (simply allowing the sphere to cool down), we were able to separate the frequency shift caused by transient thermal effects from that were caused by a permanent chemical change.

Fig.1 shows the results from one of the experimental runs. In the germanium-coated spheres, we found the maximum resonant frequency shift of 8 GHz. In the germanium-doped spheres, we found a maximum shift of 18 GHz, which is more than one non-azimuthal (l-m) FSR in a large (> 100 μm diameter) sphere. This has a special significance, since shifting a spectrum by more than the FSR of the resonator provides us with the ability to engineer a resonance at any desired frequency.

3. SECOND ORDER FILTERS USING OPTICAL WGM CAVITIES

To produce second order filter based on two coupled WGM resonators we used essentially the same technic as was described in the previous Section. Our installation is shown on Fig.2. Namely, we modulated frequency of a 1550nm laser diode by modulating its current with a sawtooth signal. To increase the laser power, we use an erbium-doped fiber amplifier at the output of the laser. One half of this output passed through a Fabry-Perot cavity having FSR 20 GHz. The cavity served as a reference to correct for any laser frequency drift and to measure the spacing between resonance lines of our WGM cavity.

The other half of radiation from erbium-doped fiber amplifier was introduced into an angle-polished fiber which was used as the input coupler to the first, germanium doped, microcavity. We placed a second microcavity nearby the first one, and positioned it so that the equators of the cavities were coupled via evanescent field. A second angle-polished fiber served as an output coupler. Couplers and spheres were placed on miniature PZT translators so we can manage coupling between them. For the optimal tuning of the positions of the cavities the probe light passed through both spheres had less than 3 dB fiber-to-fiber losses. The light from the output coupler was sent to a photodiode, so that a plot of current versus time was obtained as the frequency spectrum of the combined system. Finally, the fiber with a convex tip focused the output of an UV argon-ion laser onto the surface of the first resonator that allowed permanent shift of the resonator modes.

The first resonator was constructed from germanium -doped silica, the core material from a germania-doped optical fiber. We used both spherical and toroidal resonators. Toroidal resonators are more difficult to fabricate, but those resonators have the advantage of a much sparser frequency spectrum.[24] This occurs because microtorus WGMs with trajectories localized far from the equatorial plane of the cavity have high losses and, therefore, are effectively removed from the resonator's spectrum.

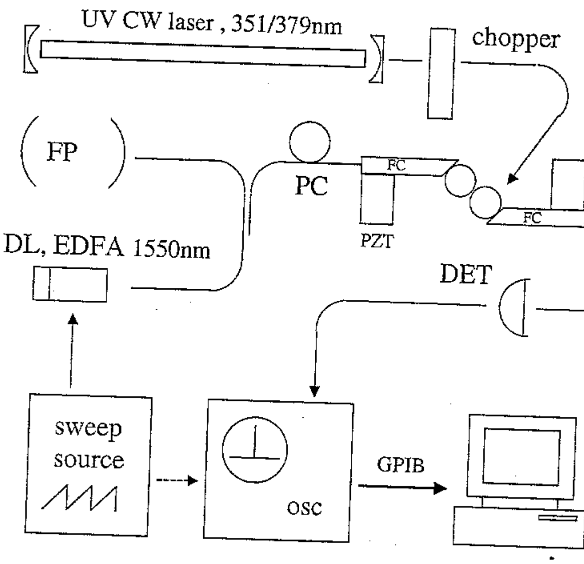

Figure 2. Installation to fabricate a second order filter

Microspheres made of pure silica were used as the second microcavity. They had approximately the same diameter as the first cavity. The mode structure of the second cavity remained unchanged throughout the experiment, despite of some exposure by small amounts of reflected and refracted UV light.

The differences in the size of the cavities is rather important. Our aim was to produce spectral lines of both resonators of similar width, to allow the realization of a complex spectral line structure. If resonances of two interacting cavities have differing widths, then as they are made to approach one another, the height of the narrower resonance will simply track the shape of the wider one, which is of no use for the filter application. The size of a cavity affects the quality of its resonance since cavities of similar size have similar quality factors.

Before starting the experiment, we first arranged for the maximum efficiency in the photochemical process to shorten the time of the experiment. The maximum efficiency occurs when the UV light is focused just inside the equator of a doped sphere (or a torus), at a point where the WG modes have a large field intensity. To achieve this, we first tuned the argon-ion laser to the 379 nm line. Laser radiation at this wavelength affects the chemistry of the material, but the process is relatively slow, so the overall effect can be made negligible if the exposure time is kept short. Nonetheless, the absorbed UV in the material results in thermal expansion, which produces a visible shift in the resonance frequencies. If the position of the UV fiber is adjusted such that the thermal shift in the frequency spectrum is a maximum, then the UV light is properly focused at the point of maximum efficiency.

After proper alignment, the UV laser was tuned to 351 nm, which is the most photochemically efficient wavelength generated by our argon laser. To be sure that the system is stable, several data points were first taken with the UV beam blocked. Subsequently, a strobe technique was used by alternately opening and closing a shutter at intervals of several seconds to track small changes of the WGM spectra. In this way, the frequency shift caused by the transient thermal effects can be separated from shifts caused by a permanent chemical change.

Fig.3 depicts the final spectrum obtained in the experiment with a germanium-doped microtorus and a pure-silica sphere. To highlight the filter performance we plotted also the Lorentzian fit of the curve. We see, that the two-cavity filter has much faster rolloff compared with the Lorentz line. On the other hand, the filter function does not look exactly like second order one because of small microcavities overcoupling.

4. TUNABLE FILTERS BASED ON OPTICAL WGM CAVITIES

In the previous sections we have discussed filters created due to UV assisted permanent tuning of the WGM spectra of a germanium doped silica microcavity. Let us now focus on a possibility of a controllable transient

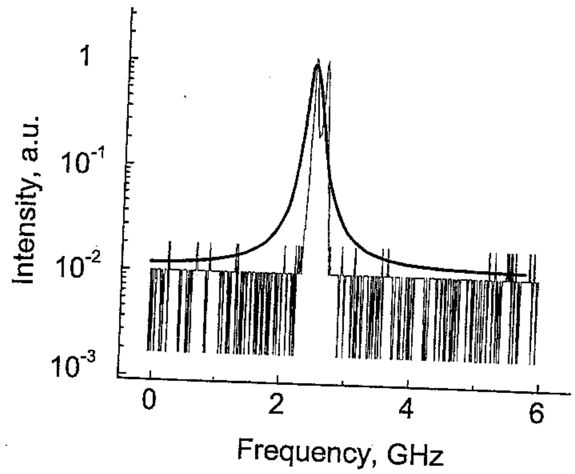

Figure 3. Filter spectrum. Thin line depicts experimental results, thick line - Lorentzian fit

tuning of the WGM spectra of a dielectric microresonator. This can be realized, for instance, with disk cavities fabricated from lithium niobate wafers.

A schematic diagram of the tunable filter configuration is shown in Fig.4. A Z-cut disk resonator has in $d = 4.8$ mm diameter and 170 μm in thickness.[25] The resonator perimeter edge was polished in the toroidal shape with 100 μm curvature radius. We studied several nearly identical disks. The repeatable value of the quality factor of the main sequence of the resonator modes was $Q = 5 \times 10^6$ (the observed maximum was $Q = 5 \times 10^7$), which corresponds to 30 MHz bandwidth of the mode.

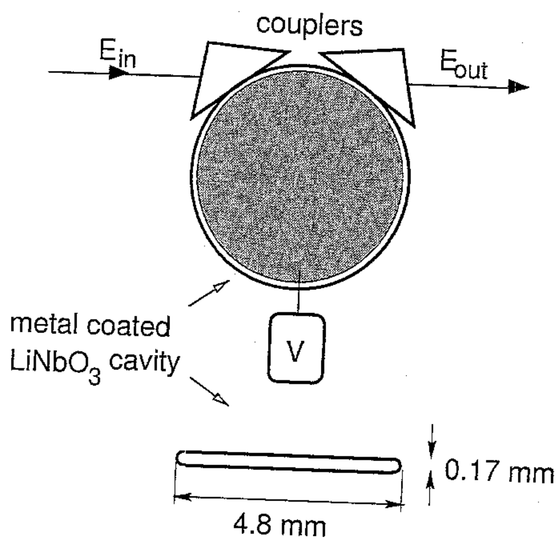

Figure 4. Filter setup. The cavity is coated with indium.

The light was sent into and retrieved out of the resonator via coupling diamond prisms. The repeatable value of fibre-to-fibre insertion loss was 20 dB (the minimum measured insertion loss was approximately 12 dB). The maximum transmission was achieved when light was resonant with the resonator modes. Tuning of the filter is achieved by applying voltage to the top and bottom disk surfaces coated with a conducting material. The coating is absent on the central part of the resonator perimeter edge where WGMs are localized.

The maximum frequency shift of the TE and TM mode may be found from[26]

$$\Delta\nu_{TE} = \nu_0 \frac{n_e^2}{2} r_{33} E_Z, \quad \Delta\nu_{TM} = \nu_0 \frac{n_o^2}{2} r_{13} E_Z, \tag{1}$$

where $\nu_0 = 2 \times 10^{14}$ Hz is the carrier frequency of the laser, $r_{33} = 31$ pm/V and $r_{13} = 10$ pm/V are the electro-optic constants, $n_e = 2.28$ and $n_o = 2.2$ are the refractive indexes of $LiNbO_3$, E_Z is the amplitude of the electric field applied along the cavity axis. We worked with TM modes because they reveal better quality factors than TE modes. If the quality factor is not very important, it is better to work with TE modes because their electro-optic shifts are three times as much as those of TM modes for the same values of applied voltage.

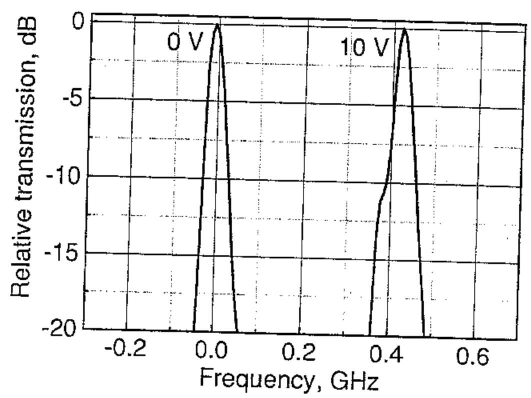

Figure 5. Transmission characteristics of the filter. The maximum transmission corresponds to 12 dB attenuation of the input signal.

Experimentally measured electro-optic tuning of filter spectral response and tuning of center wavelength with applied voltage is shown in Fig.5. Changing the tuning voltage from zero to 10 V shifted the spectrum of the filter by 0.42 GHz for TM polarization, in agreement with theoretical value. The filter exibits linear voltage dependence in ±150 V tuning range, i.e. the total tuning span exceeds the FSR of the resonator. It is interesting to note, that dependence $\Delta\nu(E_Z)$ had a hysteresis feature for large enough DC electric field ($E_Z > 2$MV/m), applied to the resonator. The applied voltage rapid varying results in an incomplete compensation of the mode shift, i.e. $\Delta\nu(E_Z = 0) \neq 0$. The resonance frequency returns to its initial position several seconds after the electric field is switched off. The maximum frequency tuning of the filter in the nonlinear regime was approximately 40 GHz. The physical origin of the hysteresis will be discussed elsewhere.

The insertion losses in our scheme occur primary due to inefficient coupling technique with the WGM. We believe that antireflection coating of the coupling prisms or usage of special grating placed on high-index fibres may reduce the losses significantly.

To demonstrate the filter performance we use it in an optical fibre line to transmit a video signal. Such transmission lines might be important for development of portable navigation and communication devices that can provide significantly higher capability to the space NASA missions, for example. The scheme of the transmission line used in the experiment is shown in Fig.6. Video signal with approximately 20 MHz FWHM bandwidth and zero carrier frequency was sent from a CCD camera to a mixer, where it is mixed with a 10 GHz microwave carrier. The resultant modulated microwave signal is filtered to suppress higher harmonics, amplified, and up-converted into light using a Mach-Zehnder electro-optic modulator. The modulated signal was then sent through our filter, heterodyned and detected with a fast photodiode. The microwave field from the photodiode output was mixed with a microwave carrier to restore the initial signal.

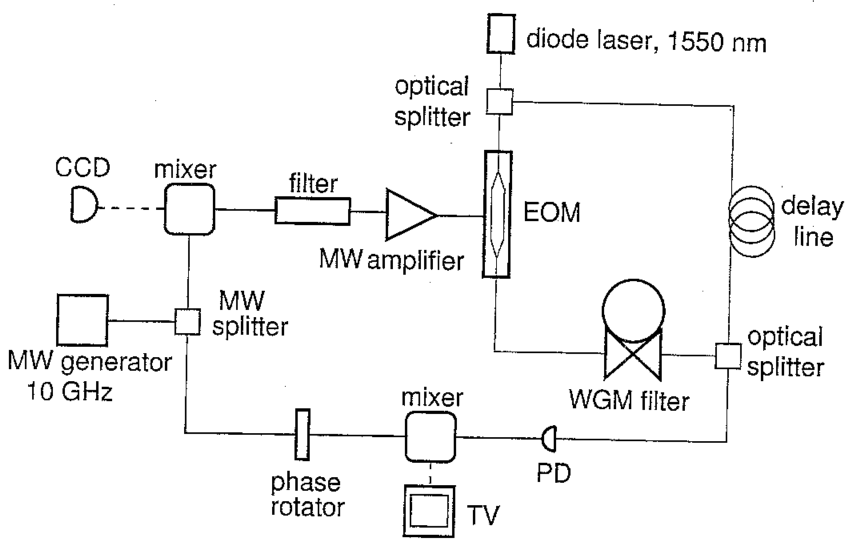

Figure 6. Schematic diagram of the video signal transmission experiment. Solid thin line corresponds to optical fibers, solid thick lines to microwave waveguides, and dashed lines - electric circuits.

It is important to note that to characterize the filtered signal and retrieve encoded information the filter output should be mixed with a monochromatic light and measured with a photodiode. The filter contains a high-Q cavity that introduces a group delay to the signal. If the laser used in the experiment has large linewidth, this group delay results in a frequency-to-amplitude laser noise conversion unless the scheme is balanced. To avoid this conversion we inserted the filter into a Mach-Zehnder configuration with a fiber delay line L_f to compensate for the group delay. Delay line length was equal to $L_f = n_o dF/2n_f = 1.2$ m , where $n_f \simeq 1.5$ is the refractive index of the fiber material and $F = 300$ is the cavity finesse. Such a compensation is not required if the laser linewidth is much smaller than the width of the cavity resonance. In our case optical characterization of the filter was achieved using semiconductor diode laser with a 30 MHz FWHM line, which is quite large. The laser power in the fiber was approximately 2.5 mW.

5. CONCLUSION

We have demonstrated several techniques of precise engineering the whispering gallery mode resonance frequencies of a dielectric microresonator. Depending on the dielectric nature we were able to produce permanent or temporal shifts of the whispering gallery mode spectrum. Our methods are important in applications where high-Q microresonators of specific resonance frequency are desired. On one hand, we have demonstrated a new technique for tuning the resonance of a germanium-doped silica microresonator to produce a coupled system of two microresonators. Such a system is basically a second order filter with a sharp rolloff. The technique may also be used to produce other complex filter functions with any desired line shapes. On the other hand, we realized tunable filter that uses high-Q whispering gallery modes excited in a disk-shaped lithium niobate resonator. The filter may be utilized for high-density telecommunication networks. Our experimental results are in an agreement with theory.

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