Flexible coupling of high-Q goblet resonators for formation of tunable photonic molecules

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Abstract: We report on a method for a highly flexible arrangement of polymeric high-Q whispering gallery mode resonators. Parallel on-chip fabricated goblet resonators are detached from the substrate by bonding a gold wire to the field-free center of their polymeric cavity. This enables the precise control of the resonator's spatial position. The modal spectrum of the detached resonator reveals preservation of its high optical quality. Manipulation of the resonators' position allows for designing coupled resonators geometries and tuning the coupling properties dynamically after batch fabrication. The properties of the modal spectrum evidence the successful optical coupling.

OCIS codes: (140.3945) Microcavities; (140.4780) Optical resonators; (160.5470) Polymers; (230.4555) Coupled resonators; (220.4000) Microstructure fabrication.

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1. Introduction

Whispering gallery mode (WGM) resonators confine light within small volumes and for long storage times. Both, fundamental research [1,2] and applications have taken advantage of this outstanding ability. Photonic devices on the micrometer scale have been conceived for use as optical filters [3], lasers [4], or nanoparticle [5] and molecule detectors [6,7]. This versatility of WGM resonators results from their ultra-high Q factors which are typically achieved by a thermal treatment at the end of the fabrication process leading to extra-smooth surfaces [8, 9]. Coupling of multiple WGM resonators further enlarges their application scope and can significantly enhance selected device properties. In quantum optics arrays of coupled microcavities are expected to serve as simulators of quantum many-body physics [10]. For sensors based on coupled resonators improved detection sensitivity is predicted [11]. In optical filtering the line-shape tuning of WGM-resonators can be exploited [12] and unique dispersion characteristics are utilized in so-called coupled resonator optical waveguides (CROW) [13]. In lasing devices the angular emission profile can be tailored and low-threshold single-mode emission is feasible [14].

Even more desirable is the possibility to flexibly arrange and dynamically control the individual cavities. In particular the adjustability of the coupling gap between two resonators and therefore the determination of the inter-cavity photon tunneling rate adds an important additional degree of freedom. In photonic applications this could be used for tuning of the lasing characteristics of active resonant systems during operation or for the realization of adjustable filtering devices.

But a couple of obstacles have to be overcome to achieve efficient resonator coupling. Such systems are typically defined by lithographic processing [15–17] and are therefore inherently inflexible. After fabrication the system is fixed and tuning of the coupling conditions or changes in geometry are not feasible. Furthermore, the coupling of two or more WGM resonators requires a spatial separation of the resonators in the order of the wavelength. However, a thermal treatment of the resonators will result in shrinkage of each single resonator. Thus the gap between two resonators would enlarge and coupling is annihilated. As a consequence a thermal surface modification, which is required to reduce surface-scattering losses and to improve optical qualities, may not be applied to the coupled structures after lithography.

One possibility to couple on-chip resonators is to approach one substrate to another one, where the resonators on both substrates are fabricated at the edge. This is technically demanding and restricted to coupling of only two resonators [18]. In an alternative method the resonators are detached with a microfork and placed at the desired location. In this case the control of the resonator gets lost once the resonators are positioned [19]. So, dynamic manipulation of the coupling conditions is not possible.

We report here on a novel method to realize post-fabrication tunable photonic molecules based on thermally treated, high-Q polymeric resonators fabricated parallel on-chip. By a subsequent detachment and mounting procedure we are able to controllably position detached

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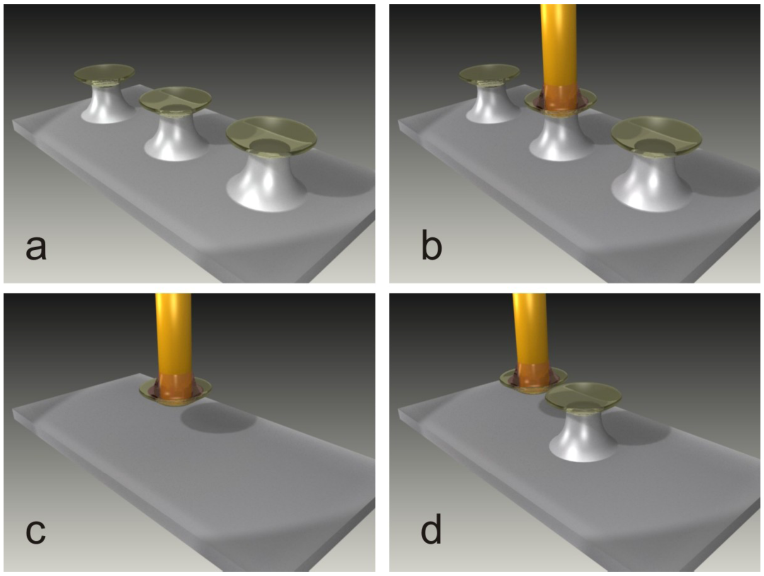

Fig. 1. Schematic of resonator detaching method: Starting with parallel on-chip fabricated polymeric goblet resonators on silicon pedestals (a). A gold wire is approached to the center of a resonator and bonded with UV-curing adhesive (b). By XeF_2 etching the silicon pedestal is removed and the polymer resonator is detached (c), freely movable and can be coupled to another resonator on a different substrate (d).

resonators with nanometer resolution with respect to substrate-bound cavities. Optical coupling of such resonator pairs is demonstrated by the modifications of the modal properties.

2. Fabrication

In order to realize an adjustable system of resonators, polymeric goblet-resonators with a diameter of 90 µm are fabricated using lithography, isotropic etching and a subsequent thermal reflow-step. The process parameters are provided in [20]. Such WGM resonators made out of PMMA on silicon pedestals are depicted schematically in Fig. 1(a). This type of goblet resonator shows a Q-factor in the order of 10^6 in the near infra-red band (1300-1400 nm). Large numbers of these resonators can be processed in parallel on one substrate.

In order to detach a single microgoblet, one end of a 50 µm thick gold wire is mounted in a manual wire bonder (F&K Devoltec Semiconductor GmbH Bonder 53XX - Ball Deep Access), dipped in UV-curing adhesive (Norland Optical Adhesive NOA63) and eventually approached to the center of a single polymeric goblet-resonator. For curing of the adhesive the setup is exposed with a UV-diode laser (375 nm), mechanically connecting the end of the gold wire to the resonator (Fig. 1(b)). The upper part of the gold wire is glued to a copper support frame made of a 0.5 mm diameter copper wire that is affixed to the substrate next to the array of resonators. Subsequently the gold wire is cut above this second adhesive joint. Afterwards the entire sample is etched with XeF_2, resulting in the complete removal of the pedestal. The polymeric resonator thus is detached from its substrate and solely attached to the copper frame via the gold wire (Fig. 1(c)). In a final step the gold wire with the bonded WGM-resonator is removed from the supporting copper frame and the gold wire is mounted to an arm of a translation stage with piezo-actuators. The length of the gold wire is kept short (about 0.5 mm) to ensure mechanical stability and to prevent mechanical oscillations. Now, this freely movable WGM-resonator can be precisely positioned with a resolution of 20 nm relative to fixed resonators fabricated on a further substrate or to other detached resonators (Fig. 1(d)). This fabrication method is adaptable to other types of WGM-resonators fabricated on silicon (disks, toroids) and is not limited to the PMMA microgoblets presented here.

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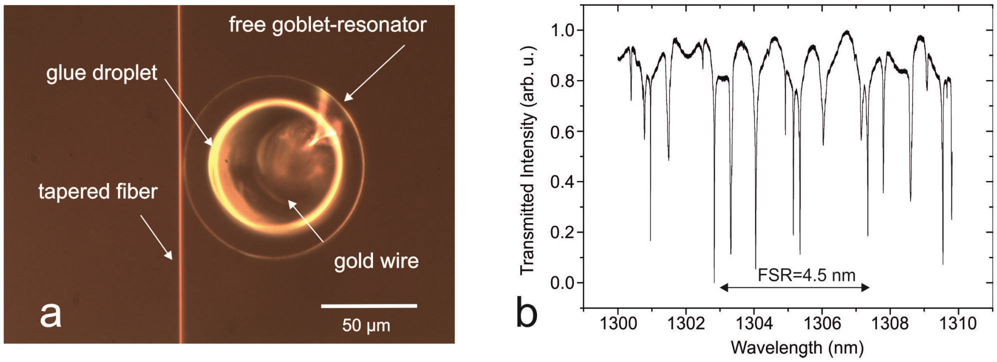

Fig. 2. (a) Microscope image (top view) of a detached polymeric goblet-resonator coupled to a tapered fiber. The 90 µm diameter resonator is carried by a 50 µm gold wire bonded with UV-curing adhesive to the center of the resonator. (b) Transmission spectrum of a tapered fiber coupled to a detached polymeric goblet-resonator. The high-Q whispering-gallery modes located in the rim are not affected by the gold wire serving as a mechanical support. The free spectral range is 4.5 nm corresponding to a 90 µm diameter resonator.

3. Optical characterization of portable polymer resonators

To prove this approach being suitable for high-Q coupled resonator experiments, the optical properties of individual detached goblet resonators were investigated in a first step. The optical characterization of the detached resonators was performed with a tapered fiber setup in the 1300 nm wavelength region. The light of a tunable external cavity diode laser (linewidth 200 kHz) is coupled into a tapered fiber (SMF-28). Transmission through the fiber is monitored with a photodiode. When the resonator-fiber gap is adjusted properly, whispering gallery modes are efficiently excited in the polymeric goblet resonator. Two microscope objectives enable observation of the samples from above and from the side. The relative position of the fiber and the WGM resonator can be aligned by translation stages with piezo-actuators. For determining the absolute wavelength information, part of the signal is guided through a HF-gas reference-cell.

Figure 2(a) shows a microscope image of a detached polymeric goblet resonator with a diameter of 90 µm aligned to a tapered fiber optical waveguide. The resonator is carried by a gold wire with a diameter of 50 µm. The diameter of the glue droplet is typically about 65 µm. The transmission spectrum of this resonator is presented in Fig. 2(b). The Q-factor of the modes is determined by measuring the linewidth of the Lorentzian-shaped dips. Measurements before and after the detaching process yield quality-factors both in the order of 10^5, demonstrating that the resonator still supports high-Q whispering gallery mode resonances. Therefore, the optical properties of the resonators are not affected significantly by the gold wire. Spatial separation of the gluing point and the guided light avoids losses that would be caused by the gold wire when in too close proximity to the guided mode. The free spectral range (FSR) was determined to be 4.5 nm corresponding to the 90 µm diameter of the WGM-resonator. Careful handling after detaching and working in low dust environment ensure that more than 80% of the processed resonators preserve their good optical properties.

The high positioning precision of the resonator in combination with a high Q-factor of the modes make this approach highly promising for the realization of coupled whispering gallery mode resonators.

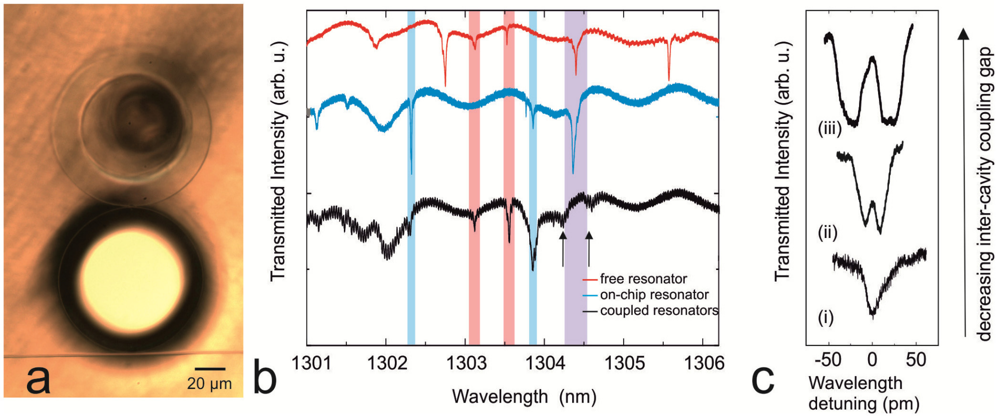

Fig. 3. (a) Microscope picture of two evanescently coupled resonators: The lower resonator is fixed to the substrate, the upper one is freely movable. The tapered fiber optical waveguide is aligned to the on-chip resonator. (b) Tapered fiber transmission: The red and the blue curve represent the spectra of the individual resonators, the black line shows the coupled system. Evanescently coupled modes are highlighted in red and blue. In violet the vanishing of single modes due to destructive inference is marked.(c) Transmission spectra for different inter cavity coupling gaps. From (i) to (ii) the gap size was reduced by 250 nm. For spectrum (iii) the air gap is further decreased by 500 nm. If the air gap is sufficiently small mode splitting occurs. With decreasing gap width the spectral separation of the modes increases.

4. Realization of coupled-resonator systems

Because of the high degree of flexibility, various coupling schemes, in terms of number of resonators and geometry, are conceivable. In the setup shown in Fig. 3(a) a double-cavity geometry, often referred to as photonic molecule, is built from a detached and a substrate-bound resonator. The tapered fiber is placed in the vicinity the on-chip resonator. The detached resonator is then approached to the substrate bound resonator in the configuration shown in Fig. 3(a). When the gap and the resonator planes are well aligned coupling of the resonators can be observed.

To investigate the photonic molecule, the spectra of the individual resonators are compared to the spectrum of the coupled system. In Fig. 3(b) the spectrum of the substrate bound resonator (blue) as well as the spectrum of the detached resonator (red) is depicted. In both spectra resonances with Q-factors in the order of 10^5 can be observed. The spectrum of the double-cavity is shown in black. In this spectrum modes of the on-chip resonator can be found. In addition, modes of the detached resonator appear. The wavelength of a mode localized on one of the resonators is slightly red-shifted in presence of the second resonator, compared to its spectral position in the isolated cavity. This is caused by the increased optical path length, due to the change of the dielectric environment, induced by the presence of the second resonator. Because the critical coupling gap-size is different for each individual mode, the Q-factors of some modes are reduced. When interacting resonances overlap spectrally, splitting of the cavity eigenstates occurs [21]. In the violet highlighted spectral region, a mode in both isolated resonators is visible. However, in the coupled system this mode vanishes. The two new minima that appear aside (black arrows in Fig. 3(b)) suggest a splitting of about 320 pm. By variation of the air gap width between the resonators, the splitting of the super-modes can be controlled (Fig. 3(c)). These observations clearly demonstrate that the presented coupling method is suitable for the formation of photonic molecules.

5. Conclusion and outlook

In conclusion, we introduced a novel method for dynamic spatial control of high-Q polymeric whispering gallery mode resonators. On-chip produced goblet-resonators were bonded to a gold wire and detached from the substrate by the use of an additional XeF_2-etching step. Since the mechanical holder does not disturb the field distribution of the high-Q modes, the optical properties of the resonator can be preserved. The dynamic control of high-Q resonators with small mode volumes is well suited for coupled-resonators experiments. Applicability was shown by coupling of a resonator-pair built from a detached and a substrate-bound resonator.

The presented method is adaptable to other on-chip produced resonators like disks or toroids.

Even geometries with more than two resonators are feasible. By the combination of several on-chip resonators with one or more detached resonators more complex adjustable photonic molecules can be built. One further advantage is the production of the coupled resonators on different substrates. A composition of resonators that are pretreated with different processes, for example bio-functionalization or dye-doping, may add further functionalities. Coupling of photon emitters to optical modes of tunable photonic molecules enables cavity quantum electro-dynamic experiments and applications in quantum information processing.

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