Wafer-level fabrication of vacuum-gap Fabry-Pérot resonators with quality factors exceeding one billion

Naijun Jin[1,*], Yifan Liu[2,3], Dahyeon Lee[2,3], Haotian Cheng[1], Charles A. McLemore[2,3], Samuel Halladay[1], Yizhi Luo[1], David Mason[1], Scott A. Diddams[3,4], Franklyn Quinlan[2,3] and Peter Rakich[1]

[1] *Department of Applied Physics, Yale University, New Haven, CT 06520, USA*
[2] *National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA*
[3] *Department of Physics, University of Colorado Boulder, 440 UCB Boulder, CO 80309, USA*
[4] *Electrical, Computer and Energy Engineering, 425 UCB Boulder, CO 80309, USA*

[*] *naijun.jin@yale.edu*

Abstract: We present a wafer-level fabrication method for high-Q, compact vacuum-gap Fabry-Pérot resonators. With quality factors surpassing one billion at 1560 nm, these resonators are well-suited in a range of applications as frequency references.

1. Introduction

Optical resonators with high quality factors have found various applications in laser, sensing, clock and microwave-photonics systems, and among them, Fabry-Pérot resonators consisting of high-reflectivity mirrors are widely used due to their straightforward construction and record-high stability. The simplest form of Fabry-Pérot resonators has one flat and one concave mirror bonded to a spacer with low thermal expansion. Using this type of resonator as frequency references, people have demonstrated stabilized lasers with sub-10 mHz fundamental linewidth [1] and optical phase detection-based fiber sensing systems with superb sensitivity [2–4]. However, several technical and practical challenges must be addressed before these Fabry-Pérot resonators can be widely deployed outside laboratories. First, the most stable Fabry-Pérot resonators are often bulky, and they need to operate at the cryogenic temperature. To address this, people recently have demonstrated compact resonators with frequency stability better than 1 Hz operating at the room temperature [5]. But second, these resonators need to operate in vacuum to reach thermal noise limit, and the size of the vacuum system can limit their access to field applications. Finally, from manufacturing point of view, the fabrication of high-reflectivity mirrors relies on mechanical polishing of individual substrates [6], and the construction of resonators relies on optical contact bonding, both of which often hinder production at scale.

In this work, we report a wafer-level method for creating vacuum-gap Fabry-Pérot resonators with quality factors exceeding one billion. We first use a reflow-based technique to fabricate an array of micro-mirrors on a single wafer, and then bond this wafer to a spacer along with another flat mirror under vacuum to form an array of vacuum-gap resonators. As the last step, we dice this array into individual resonator cubes. The diced resonators have a size that is smaller than $(10\text{ mm})^3$ and operate at the room temperature without any vacuum system.

2. Resonator Fabrication and Characterization

The process of resonator fabrication comprises curved mirror patterning, wafer bonding and resonator array dicing. First to create curved mirrors, we use a reflow-based technique (Fig. 1a), which allows for tailored radii of curvature and achieves sub-Angstrom roughness [7]. The process starts with patterning photoresist disks on a super-polished ultra-low-expansion (ULE) glass substrate by two-step photolithography (Fig. 1a (i)). When placed in a solvent vapor environment at elevated temperature, the photoresist disks absorb the vapor, undergoes reflow and gradually form near-parabolic surfaces around the disk centers (Fig. 1a (ii)). We then transfer the reflowed pattern down into the substrate with reactive ion etch. In this step, we set the etch time so that thinner disk patterns are completely transferred, while the thicker ones are only partially etched and the underlying surface is kept pristine for the later bonding process (Fig. 1a (iii)). After stripping the remaining resist, we add a highly reflective dielectric coating with a designed reflectivity $> 99.999\%$ (Fig. 1a (iv)) [8].

The reflow technique accomplishes two primary goals: it molds the desired mirror shape and smooths the surface of the photoresist. Following reflow, we have optimized the subsequent etch step that maintains the surface quality

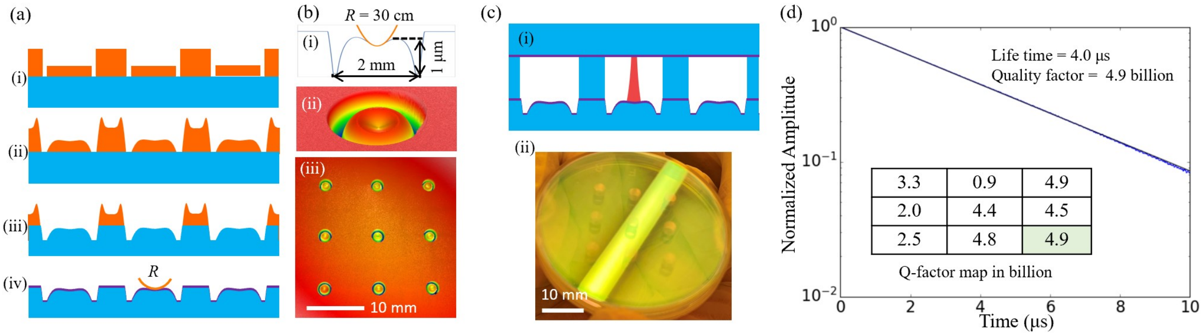

Fig. 1. (a) Illustration of the first step in our fabrication process: creating an array of curved mirrors. (b) Surface profiles of a curved mirror: (i) linecut and fitting of radius of curvature, (ii) corresponding 3D profile and (iii) 3D profile of a mirror array. (c) Illustration and photo of the bonded resonator array. (d) Results of quality factor measurement at 1560 nm. The inset is the quality factor map of the array, and the ring-down curve corresponds to the measurement for the shaded device.

of both photoresist and substrate, essential for maintaining low surface scattering. To confirm the surface shape and quality, we measure the profile of the mirrors with a white-light interferometric microscope. Fig. 1b shows a linecut of a curved mirror in (i), the corresponding 3D profile in (ii) and an array of such mirrors in (iii). These mirrors here have a diameter of 2 mm and radius of curvature of 30 cm. Under higher magnification, the surface RMS roughness is determined to be better than 1 Å.

Upon completion of the curved mirror array fabrication, the subsequent process involves the bonding of a structurally robust resonator array. Optical contact bonding is an established method for joining ultra-flat and smooth glass parts, relying on intermolecular forces once the parts are brought into contact [9]. First, to ensure all the bonding surfaces are particle-free and hydrophilic, we have the patterned mirror substrate, a pre-machined and polished spacer with nine holes and a coated flat substrate undergo thorough sonication cleaning and chemical treatment. During bonding, we first manually align the patterned mirror substrate to the spacer holes and apply finger pressure to the point where we see the interference pattern between the substrate interface totally disappears. We then positioned this partially bonded two-piece assembly along with the flat mirror substrate within a custom wafer bonder. After pumping out this setup to a vacuum level of 10^{-5} Torr, the flat mirror substrate is clamped onto the two-part assembly [10]. This way we obtain a fully bonded array of vacuum-gap resonators. Fig. 1c (ii) is a photo of the fully bonded assembly.

To assess the quality of the resonators after the bonding step, we measure their optical lifetime, equivalently optical quality factor, with the ring-down technique. By monitoring the decay of the transmitted light through the resonators after the input light being switched off on resonance, we are able to extract the lifetime of resonant modes τ, as shown in Fig. 1d, and equivalently their linewidth $\delta\nu$. We can then calculate the optical quality factor to be $\nu_0/\delta\nu$, where ν_0 is the frequency of 1560 nm light. The inset of Fig. 1d shows the quality factor map of all 9 resonators, of which 8 devices have it larger than 2 billion and the highest is nearly 5 billion. At the same time, the high yield of these high-Q resonators marks the scalability of this technique.

As the last step of the whole process, we dice the bonded resonator array into individual cubes with a wafer dicing saw, as illustrated in Fig. 2. Here, the bonding between the interfaces in the assembly has to be strong enough to withstand the relatively violent mechanical grinding and also to avoid any potential vacuum leak. Following the best practice, we have bonded another resonator array assembly under vacuum with the mirrors from the same coating run, and without further due, directly placed it into an oven and annealed it for extended time, which can enhance the bonding strength according to literature [11]. In the end, we have successfully diced the freshly bonded assembly into cubes. Fig 2b shows a photo of one of the cubes, which has a quality factor of 1.5 billion. To further evaluate the performance of these resonator cubes, we perform phase noise measurement on one of them, and the result is shown in Fig. 2c. The measured phase noise illustrated by the red line roughly follows the theoretical prediction from 10 Hz to 1 kHz offset frequency but deviates in the lower and higher offset frequency regions, which indicates that the resonator holds a certain level of vacuum but not likely the level that we pump to. The exact vacuum level is still under investigation, but our approach already shows promises in large-scale fabrication of compact vacuum-gap Fabry-Pérot resonators.

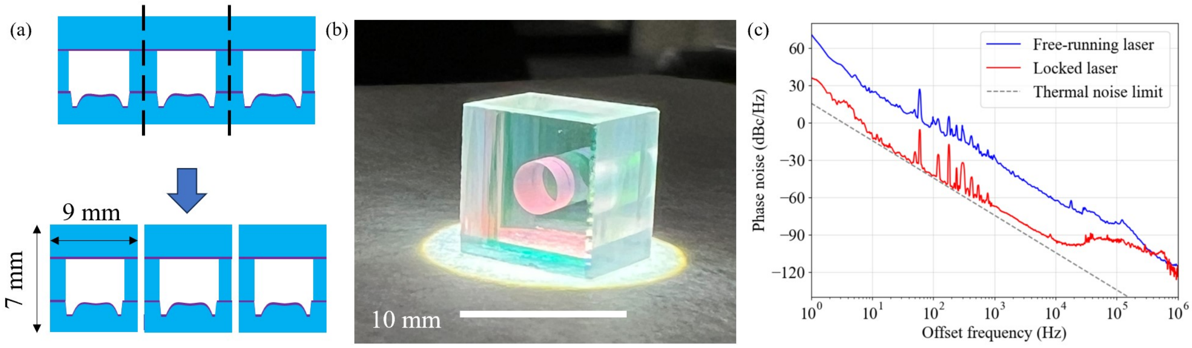

Fig. 2. (a) Illustration of the last step in our fabrication process: dicing the resonator array into individual cubes. (b) Photo of a diced resonator cube. (c) Result of the phase noise measurement on one of the cubes.

3. Conclusion and Outlook

In conclusion, we have presented a wafer-level fabrication approach for vacuum-gap Fabry-Pérot resonators. Exhibiting billion-level quality factors and low phase noise in a compact packaging form, these resonators are poised for integration into a broader spectrum of applications including stable laser, fiber sensing and optical clock systems. Building on these results, the compact vacuum-gap Fabry-Pérot resonators can further be integrated with on-chip devices via grating couplers [12], which could combine the capabilities of Fabry-Pérot resonators with expansive on-chip functionalities and yield powerful compact optical systems.

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