Cavity QED with atomic vapors and photonic integrated circuit microresonators

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We are studying the interaction of a small ensemble of atoms in a warm Rb vapor with photonic integrated circuit (PIC) microresonators in the context of compact, standalone devices. Figure 1 shows an overview of different developments, some of which are reported in Ref. 1. We have developed a PIC platform that includes integrated buried heaters that enable feedback control and stabilization of air-clad microresonators interacting with Rb atoms (Fig. 1(a)-(d)). Combining such PICs with epoxy-bonded vapor cells, we have observed vacuum Rabi splitting in the coupling of dozens of atoms to a microring resonator cavity mode (Fig. 1(e)), and single-photon-level saturation effects in the regime of a few atoms interacting with the cavity (Fig. 1(f)). We are also developing photonic crystal microring resonators (Ref. 2) in which high quality factors ($> 10^5$) are retained while localizing light to a volume $> 10\times$ smaller than that of conventional rings, with Fig. 1(g)-(i) showing recent progress on devices optimized for 780 nm operation. Finally, we are working to develop more robust and scalable methods for integrating warm alkali vapors with PICs, including the use of anodic bonding methods [Fig. 1(j)].

[1] R. Zektzer, et al., Strong interactions between integrated microresonators and alkali atomic vapors: towards single-atom, single-photon operation, *arXiv*: 2404.04372 (2024).
[2] X. Lu, et al., High-Q slow light and its localization in a photonic crystal microring, *Nat. Phot.*, **16**, 66-71 (2022).

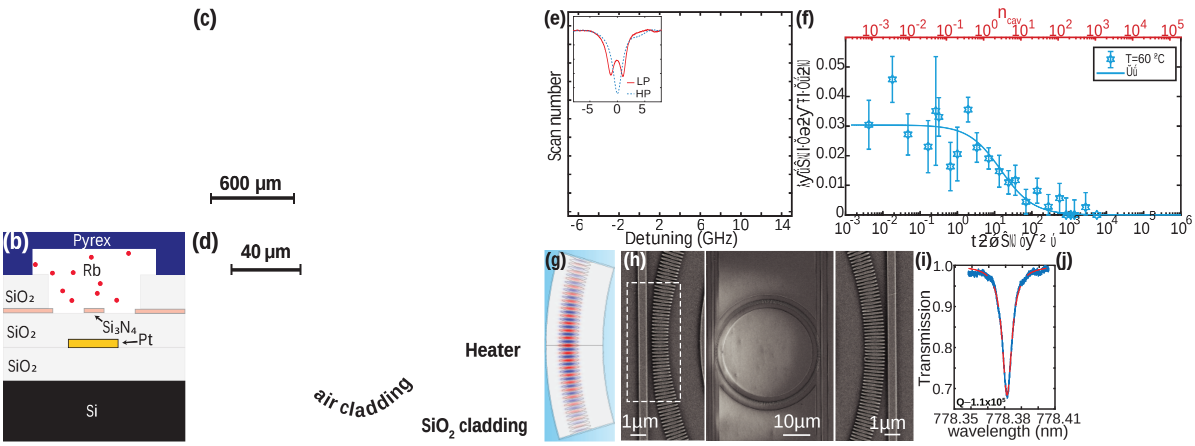

Figure 1. (a)-(d) Vapor cavity QED platform based on epoxy-bonded Rb vapor cells with Si_3N_4 photonic integrated circuit (PIC) microresonators. The PICs contained buried integrated heaters for fine cavity tuning and feedback stabilization of the cavity frequency. (e) Series of cavity transmission spectra as the cavity frequency is tuned across the ^{87}Rb D_2 transitions, for a vapor temperature of 120 C (corresponding to about 180 atoms in the cavity), which exhibits anti-crossing and vacuum Rabi splitting. The inset shows high power (HP) and low power (LP) transmission spectra when the cavity is on-resonance with the ^{87}Rb $F = 2$ transition. (f) Extracted interaction factor when the cavity is on-resonance with the ^{87}Rb $F = 2$ transition, for a temperature of 60 C (corresponding to about 3 atoms in the cavity), and as a function of average intracavity photon number and input waveguide power. (g)-(i) Photonic crystal defect micoring resonator design, fabricated devices scannign electron microscope images, and measured cavity quality factor, for increasing the atom-cavity interaction strength through $> 10\times$ reduced volume. (j) Photograph of a PIC device created through a more robust anodic bonding process in comparison to the epoxy bonding in (a).