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Bowtie photonic-crystal waveguides as strong light-matter interfaces

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The efficient emission of on-demand quantum states of light into propagating channels that can be interfaced with conventional passive photonic components is at the core of future on-chip quantum technologies. From this viewpoint, photonic-crystal waveguides (PhCWs) offer precise control over the optical environments that can host solid-state emitters. The light-matter interaction strength is governed by the local density of optical states (LDOS), which determines the Purcell factor. For an optimally oriented dipole-like emitter at position $\mathbf{r_0}$ in a PhCW, the LDOS reads [1],

$$\rho(\boldsymbol{r_0},\omega) = \frac{n_g(\omega)}{\pi c}\frac{a}{\varepsilon(\boldsymbol{r_0})V_{\text{cell}}} \qquad (1)$$

with $n_\text{g} = c/v_\text{g}$ the group index and $V_\text{cell} = ([\varepsilon(\boldsymbol{r_0})|\boldsymbol{E_k}(\boldsymbol{r_0})|^2])^{-1}$ the effective mode volume per unit cell of periodicity a. The traditional strategy to enhance the LDOS has been to target high n_g. However, backscattering due to unavoidable fabrication imperfection scales with n_g^2, leading to significant propagation losses, thus limiting the application of slow light for waveguide quantum electrodynamics (QED) experiments. Even waveguides built with photonic topological edge states, which had generated great expectations to combat backscattering, are bounded by the same limitation [2]. A less explored and alternative route to enhancing the LDOS is reducing the mode volume, V_{cell}, cf. Eq. (1), because it was believed that confinement in dielectrics was limited by the diffraction limit. Recent theoretical [3] and experimental developments in photonic nanocavities [4,5] have evidenced that the use of bowtie-like structures fosters light confinement down to features of size only limited by nanofabrication.

In this work, we investigate the use of bowtie structures to develop two-dimensional photonic-crystal waveguides (W1-BTs, Fig. 1(a)) allowing Purcell factors in the linear dispersion region (n_g ~ 7) that largely overcome those found on conventional W1 photonic-crystal waveguides (W1s, Fig. 1(b)) in the same dispersion region (n_g ~ 8). For example, a silicon bowtie of 10 nm, which is within reach with of our nanofabrication process [4], leads to a 15-fold enhancement of the LDOS (colormaps in Fig. 1(c)). However, the intense fields near the sidewalls of the narrow bowtie bridges may also promote roughness-induced scattering losses, compromising the performance of W1-BTs for waveguide QED experiments where fragile quantum states of light are manipulated. To address this issue, we fabricate suspended photonic circuits that include W1-BTs on a silicon-on-insulator platform with a 220 nm device-layer thickness and measure the wavelength-dependent propagation losses (Fig. 1(d)) using the cutback method [2]. We find a negligible enhancement of the waveguide losses with decreasing bowtie width and a 15-fold increase of the losses relative to conventional W1 waveguides in the linear dispersion region (approx. 2 dB/cm [2]), indicating that the presence of holes along the line defect plays a more significant role than the exact bowtie width. Despite this growth in the losses, short waveguide segments in near-unity transmission terminations, which we design, may still enable the operation of W1-BTs coupled to quantum dots [1] or to atomically thin materials [6] as broadband light-matter interfaces for the efficient generation of single photons with a large degree of quantum coherence.

[1] P. Lodahl et al., Rev. Mod. Phys. **87**, 347 (2015).
[2] C. Rosiek et al., Nat. Photon. **17**, 386 (2023).
[3] M. Albrechsten at al., Opt. Express **30**, 15458 (2022).
[4] M. Albrechsten at al., Nat. Commun. **13**, 6281 (2022).
[5] A. N. Babar et al., arXiv:2303.09610 (2023).
[6] E. V. Denning et al., Phys. Rev. B **105**, 085306 (2022).

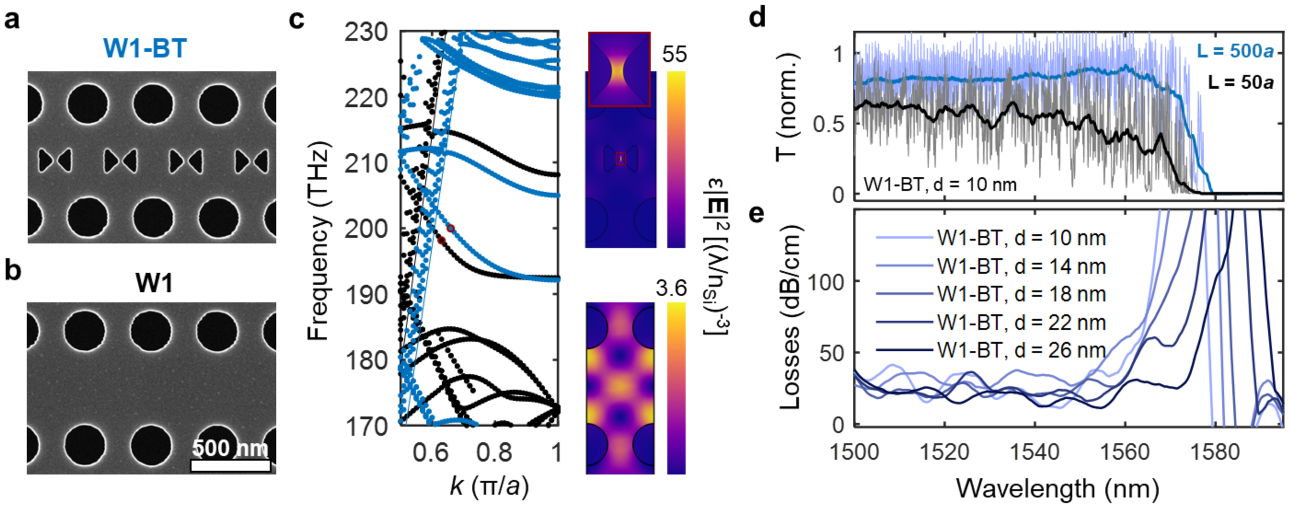

Figure 1. Two-dimensional bowtie photonic-crystal waveguides. (**a**,**b**) Scanning electron micrograph (SEM) of a suspended silicon bowtie photonic-crystal waveguide (W1-BT) and a conventional photonic-crystal waveguide (W1). (**c**) Dispersion diagrams of a W1-BT waveguide with bowtie width d = 10 nm (blue) and of a W1 waveguide (black). The normalized electric energy density of the Bloch mode highlighted in the dispersion with a red circle is given. (**d**) Optical transmission through suspended photonic circuits including W1-BT waveguide sections of 50 and 500-unit cells. (**e**) Propagation losses in W1-BT waveguides with different bowtie width.