

Moiré effects in silicon photonic nanowires

Tahmid H. Talukdar, Anna Hardison, and Judson D. Ryckman*

Holcombe Department of Electrical and Computer Engineering, Clemson University, Clemson, SC, USA

*jryckma@clemson.edu

Abstract: We implement 1D moiré patterns in silicon photonic nanowires to demonstrate a wide range of effects such as tunable photon transport and localization, high-Q cavities and coupled resonator optical waveguide behavior by modulation of lattice mismatch and crystal length. © 2022 The Author(s)

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Moiré effects and magic-angle phenomena caused by the superposition or twisting of distinctly oriented bilayer van der Waals materials have garnered significant research interests recently due to their tunable and novel properties [1]. Similarly unique phenomena can be expected in photonic analogues and some recent demonstrations have now reported novel effects derived from wavelength scale photonic moiré lattices. This includes demonstrations of flat band physics and localization-delocalization transitions [2], optical solitons [3], magic-angle lasers [4], and various types of metasurfaces derived from 2D photonic moiré lattices [5]. Compared to stacked 2D van der Waals materials that are constrained by fixed lattice constants, the study and realization of moiré effects in wavelength scale photonic media offers significantly more freedom due to the ability to realize arbitrary lattice constants and on-demand patterning. In addition to the $\Delta\theta$ twisting of a 2D sub-lattice as depicted in Fig. 1(a), moiré effects can be realized in 1D bichromatic photonic structures incorporating a lattice mismatch $\Delta\Lambda$ between two superimposed sub-lattices as depicted in Fig. 1(b). Recent experiments involving related moiré lattices have now demonstrated highly tailorable optical filters [6], high Q-factor resonators and compact optical parametric oscillators [7], [8], and physically unclonable photonic circuits [9].

In this work, we study light transport and localization arising from 1D photonic moiré lattices defined in silicon photonic nanowires and validate our theoretical findings by experimentally realizing devices in a standard 220 nm device layer silicon on insulator (SOI) platform cladded by silica. Specifically, we superimpose two subgratings with periods Λ_1 and Λ_2 on either side of a sidewall modulated silicon nanowire as shown in Fig. 1(a). Analogous to 2D “twistronic” systems where $\Delta\theta$ plays a key role, here we utilize the lattice mismatch parameter $\Delta\Lambda = \Lambda_1 - \Lambda_2$ to realize moiré effects such as the formation of moiré resonators and moiré based coupled resonant optical waveguides (CROWS). By considering finite moiré lattices we also demonstrate that the total crystal length L and moiré fringe phase $\Delta\phi$ (initial phase offset between sub-lattices) play crucial roles in dictating behavior.

Superimposing two sub-lattices with periods Λ_1 and Λ_2 produces a moiré fringe pattern with a beat length given by $L_B = \Lambda_1\Lambda_2/\Delta\Lambda$. For periods of $\Lambda_1 = 317 \text{ nm}$ and $\Lambda_2 = 318 \text{ nm}$, the lattice mismatch is $\Delta\Lambda = 1 \text{ nm}$ and the beat length $L_B = 100 \mu\text{m}$. By systematically varying the lattice mismatch $\Delta\Lambda$ under a fixed crystal length $L = 100 \mu\text{m}$

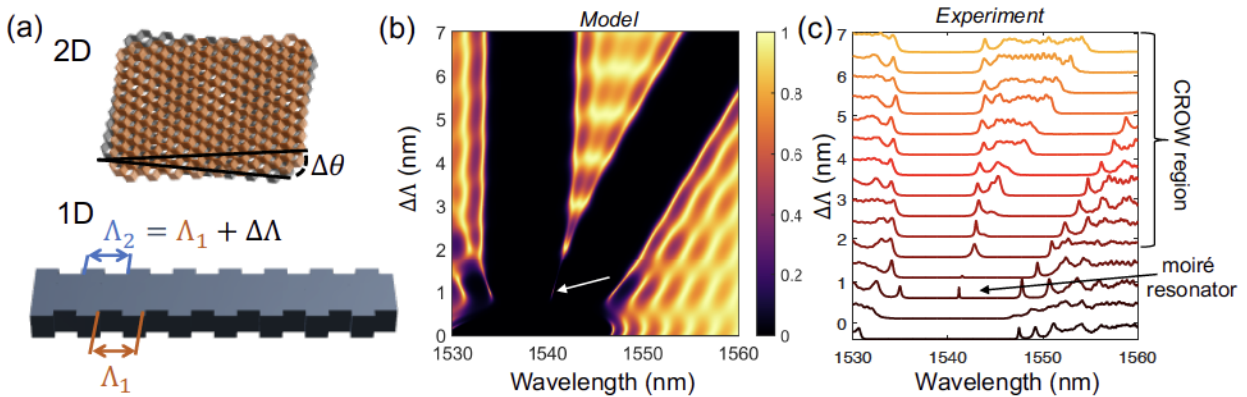


Fig. 1. (a) Moiré lattices realized in 2D and our 1D platform, (b) modeled and (c) experimentally measured transmission spectra as a function of lattice mismatch $\Delta\Lambda$, demonstrating moiré resonator(s) in silicon nanowires.

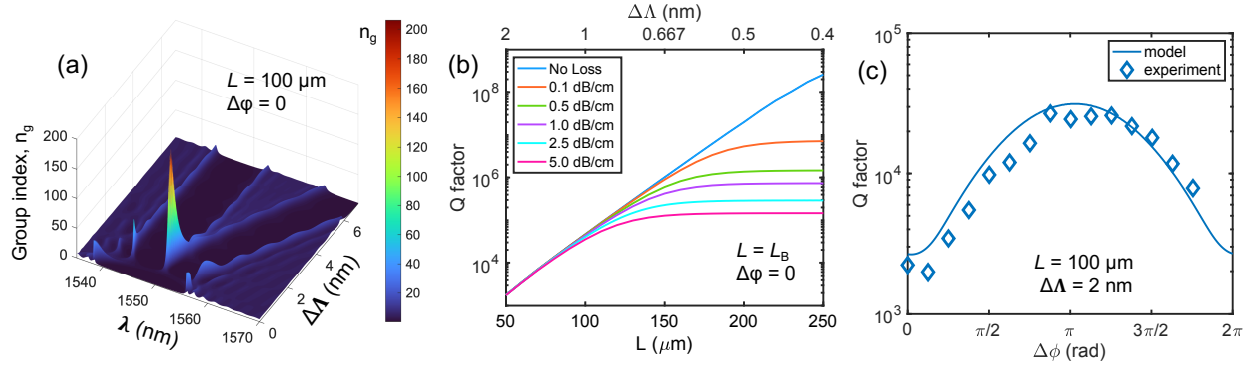


Figure 2. (a) Group index $n_g(\lambda)$ vs. lattice mismatch $\Delta\Lambda$, (b) Q factor vs. moiré crystal length, for various loss values (dB/cm), and (c) Q factor vs. moiré fringe phase $\Delta\phi$. Additional degrees of freedom: $\Delta\Lambda$, $\Delta\phi$, and/or L are specified in the figure insets.

and fringe phase $\Delta\phi = 0$, we studied several regimes of operation spanning: (i) $L < L_B$, (ii) $L = L_B$ and (iii) $L > L_B$; as depicted in Fig. 1 (b,c). In regime (i) we observe apodized grating behavior, whereas regimes (ii) and (iii) produce a moiré lattice supporting either a single potential well or multiple cascaded potential wells respectively, giving rise to moiré resonators and moiré CROWs as noted in Fig. 1(c). These effects are achieved simply with the natural moiré potential without use of any complex design apodization techniques or tapering.

The resonant modes supported within the moiré lattice can strongly couple to the feeding waveguide, fostering high optical transmission which coincides with an enhancement to the density of modes and the waveguide group index, as illustrated in the example considered in Fig. 2(a). With the appropriate selection of design parameters, namely $L = L_B = \frac{\Lambda_1 \Lambda_2}{\Delta\Lambda}$ and $\Delta\phi = 0$, a single moiré resonator can support a strongly enhanced group index or correspondingly a high loaded Q factor as predicted in Fig. 2(b). For example, for $\Delta\Lambda = 0.4 \text{ nm}$ the required crystal length is $250 \mu\text{m}$ and the simulated Q factor a device with our $\pm 30 \text{ nm}$ sidewall modulation is $\sim 10^5$ assuming a nominal waveguide loss of 2.5 dB/cm . Lastly, whereas in infinite moiré lattices, the relative phase between sub-lattices has limited significance, our model and experimental results demonstrate $\Delta\phi$ has a significant effect on light transport and localization in finite moiré lattices. As an example, we report in Fig. 2(c) a special case within regime (iii): $L = 2L_B$, where $\Delta\phi = 0$ produces two cascaded potential wells/resonators which evolves into a single potential well/resonator residing in the finite crystal in the case $\Delta\phi = \pi$. The moiré fringe phase $\Delta\phi$ was also observed to significantly alter transport and localization in regimes (i) and (ii) (not shown here for brevity).

In summary, we performed a theoretical and experimental study on 1D moiré effects in wavelength scale silicon photonic nanowires. Beyond mapping a well-studied 2D magic-angle effect to a 1D regime, we highlight a range of moiré effects that can be used to tailor light transport and localization, such as the realization of high Q factor photonic crystal nanowire cavities and CROWs naturally formed from a moiré effect.

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