

Integration of a GaAs-based nanomechanical phase shifter with quantum-dot single-photon sources

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We demonstrate a small-footprint electromechanical phase shifter with a compact active length of 10 μm fabricated on a suspended GaAs membrane, offering versatile integration with quantum-dot single-photon sources. The phase shifter is based on a slot waveguide, whose slot width can be controlled by electrostatic forces, enabling a large effective refractive index change $\Delta n_{\text{eff}} > 0.1$. We observe up to 3π phase modulation with 10.6 V applied bias, and a figure of merit $V_{\pi}L = 5.7 \times 10^{-3}$ V cm. Integration with a Mach-Zehnder interferometer further allows routing of single photons with an extinction ratio of up to 24 dB at cryogenic temperatures. This device enables advanced manipulation of quantum emitters and the realization of reconfigurable quantum photonic integrated circuits.

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I. INTRODUCTION

Recent advancements in the growth and processing of GaAs photonic integrated circuits (PICs) have opened up promising avenues to the realization of quantum photonic integrated processors where single-photon emitters, routers, and detectors can be seamlessly integrated within a single chip [1,2]. By the combination of self-assembled InAs quantum dots (QDs) and programmable PICs, photon losses can be greatly suppressed, thereby boosting the performance of many quantum applications, such as quantum key distribution and quantum simulation [3], which frequently require hybrid or modular architectures [3–6]. Achieving the monolithic integration of all the functionalities in a single material platform poses considerable challenges. While both quantum emitters [7–9] and superconducting single-photon detectors [10,11] have been realized in GaAs, the implementation of scalable reconfigurable devices in this platform is still undeveloped. A compact, tunable phase shifter that operates at cryogenic

temperatures is crucial for quantum PICs, as it allows the programmable transformation of photonic qubits and the construction of logical gates [12].

Thermo-optic phase shifters, which modulate the phase by changing the refractive index through temperature variations, are preferred in silicon [13] and silicon nitride [14] PICs due to their low loss and ease of fabrication. However, this method is less suitable for the GaAs platform because of factors such as the low thermal conductivity, the near-zero thermo-optic coefficient at cryogenic temperatures, and the large device footprints. GaAs electro-optic phase shifters have been realized at telecom wavelengths with gigahertz-scale modulation rates and complementary metal-oxide semiconductor-compatible driving voltages [15], owing to the high refractive index of GaAs and moderate Pockels coefficients [16]. Nevertheless, this approach faces challenges at the wavelength of 930 nm, where QDs emit, due to Franz-Keldysh electroabsorption leading to excessive insertion loss [17,18]. An ideal alternative solution to achieve programmable circuits is offered by nano-optoelectromechanical systems (NOEMSs). In a NOEMS, light control is achieved by mechanical adjustment of the geometry of the guided mode, thereby altering its optical phase [19]. In previous work, we reported a gap-variable four-port directional coupler controlled by a NOEMS on GaAs that demonstrated the compatibility of nanomechanical motion with QDs at cryogenic temperatures [20]. A variety of reconfigurable NOEMS phase shifters, designed with the use

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of hybrid photonic-plasmonic modes, coupled-waveguide modes, and slot-waveguide modes, with subdecibel insertion loss, compact footprints, and low driving power have been demonstrated on silicon and silicon nitride platforms at room temperature [21–24]. In silicon photonics, slot-waveguide [25] electromechanical devices have been reported, featuring large phase shifts [26] and excellent performance at cryogenic temperatures [27].

In this work, we demonstrate a reconfigurable slot-waveguide NOEMS phase shifter interfaced with a QD single-photon source on suspended GaAs waveguides. The resulting device enables a low half-wave-voltage-length product $V_\pi L = 5.7 \times 10^{-3}$ V cm with a compact active length of $10 \mu\text{m}$ and an average insertion loss of -2.5 dB. The reported phase shifter in GaAs is the missing element to realize full nanomechanical unitary transformations of dual-rail encoded photonic qubits integrated with single-photon sources.

II. WORKING PRINCIPLE AND DESIGN OF THE PHASE SHIFTER

The phase shifter is realized on a suspended 160-nm-thick GaAs membrane with embedded self-assembled QDs and nanophotonic waveguides, as illustrated in Fig. 1(a). Figure 1(b) shows a scanning electron microscope image of the fabricated NOEMS phase shifter. The device features a slot waveguide formed by two 150-nm-wide single-mode waveguides, where one of them is connected to a Cr(10 nm)/Au(160 nm) electrostatic comb drive (highlighted in yellow) deposited on top of GaAs [20]. The length L of the slot waveguide, responsible for phase modulation, is $10 \mu\text{m}$, the longest that could be reliably fabricated without the addition of lossy support tethers and without mechanical failures being incurred. The waveguide is designed to support a single transverse electric mode, shown in Fig. 1(c), with low effective refractive index $n_{\text{eff}} \simeq 1.2$. The phase modulation $\Delta\phi = \Delta n_{\text{eff}} k L$ is achieved via control of n_{eff} by our driving the electrostatic actuator with a voltage source. Given the short length of the device, at least 5% modulation of the effective refractive index is required to achieve a π shift. Figure 1(d) shows the calculated phase shift as a function of the displacement Δy for different initial slot widths d_0 , obtained from finite-element simulations of the waveguide mode. When we take advantage of the large nonlinear dependence of n_{eff} on the slot width, shown in the left inset in Fig. 1(d), a phase shift of up to 3π is theoretically achievable when the slot width is reduced (negative displacements) by roughly 60 nm. The plot also illustrates that operation of the device in *push* mode is significantly more efficient in modulating the phase than operation of the device in *pull* mode (i.e., for positive displacements). Moreover, wider initial gaps d_0 (up to 200 nm) not only enable sufficient phase shift but also increase fabrication yield, ensuring

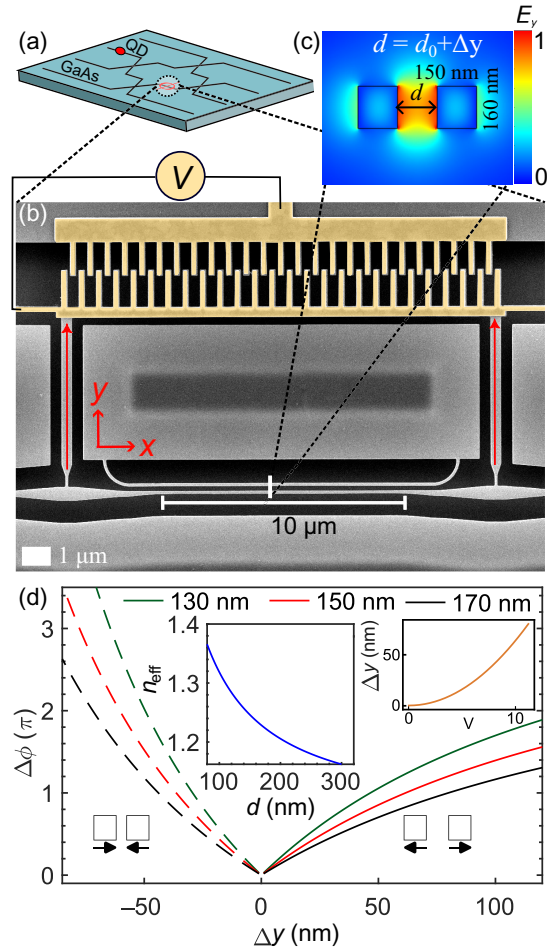


FIG. 1. Design and working principle of the NOEMS phase shifter. (a) GaAs photonic integrated circuits with QDs and reconfigurable phase shifters. (b) Scanning electron microscope image of the fabricated nanomechanical phase shifter comprising a $10\text{-}\mu\text{m}$ -long slot waveguide driven by an electrostatic comb drive (highlighted in yellow). (c) Finite-element simulation of the pseudo-transverse-electric mode in the slot waveguide. (d) Theoretical phase shift $\Delta\phi$ as a function of the displacement Δy for the slot waveguide for three different initial slot widths d_0 . The left inset shows the effective refractive index n_{eff} as a function of the slot width calculated at a wavelength of 950 nm. The right inset shows the simulated displacement Δy for the slot waveguide under an applied bias voltage.

reliable integration into photonic circuits and scalability. The mechanical adjustment of the slot width under an external applied bias voltage V exerted on the comb was modeled numerically, and the effect is plotted in the right inset in Fig. 1(d). It follows a quadratic response with the voltage,

$$d(V) = d_0 - \eta V^2, \quad (1)$$

with η representing the electromechanical transduction efficiency given by the geometry of the comb drive and the

stiffness of the mechanical structure [28]. We designed the suspension tethers holding the comb drive and waveguides using finite-element modeling to balance in-plane and out-of-plane device stiffness and maximize η to approximately 0.6 nm/V^2 , i.e., up to 60 nm with 10 V.

To keep losses at a minimum, the waveguides are first tapered out to 600 nm width, to avoid scattering losses at the position of the tether, and then adiabatically reduced to 150 nm. This is achieved with a piecewise linear taper, which is designed to gradually reduce the effective index along the propagation direction. Figure 2(a) shows the electric field distribution across the taper transition calculated via three-dimensional finite-element analysis. The calculated losses are shown as a function of wavelength in Fig. 2(b) (dash-dotted lines). We observe that each taper contributes 1–1.5 dB in the typical 930–950 nm wavelength range of QD emission, leading to a total insertion loss of between -2 dB and -3 dB per device. Moreover, losses tend to reduce at smaller slot widths, which could be explained by the higher confinement and effective index, facilitating an adiabatic transition. For comparison with simulations, we fabricated a large number of nominally identical phase shifters and compared the transmission across zero, one, two, or three devices connected in series at different wavelengths in the transmission range of our grating couplers [29]. The resulting loss per device matches the prediction of simulations with the measurement uncertainties. Further improvements of the adiabatic couplers are possible, for example, considering different optimization strategies and more advanced taper geometries.

III. CHARACTERIZATION OF THE PHASE SHIFTER

To test the NOEMS phase shifter, a Mach-Zehnder interferometer (MZI) was designed, as shown in Fig. 3(a). Two directional couplers are used as input and output beam splitters, designed to a 3 dB splitting ratio (SR) at a wavelength of 950 nm. Light is coupled into the chip from an objective into focusing grating couplers [29], whose cross-polarized orientation on the chip enables suppression of scattered light in transmission measurements.

The device is characterized in a vacuum and at room temperature first to evaluate the phase shift performance. A tunable continuous-wave laser is used to probe the devices, and the collected light is recorded with the use of Si avalanche photodiodes. Transmission measurements between the input ports [labeled as “1” and “2” in Fig. 3(a)] and the output ports (3 and 4) are taken to determine the intensity response I_{ij} between port i and port j . This approach allows precise evaluation of the intrinsic performance of the phase shifter, independent of grating coupling efficiency and collection efficiency between the output ports. In Fig. 3(b) the total coupling-independent

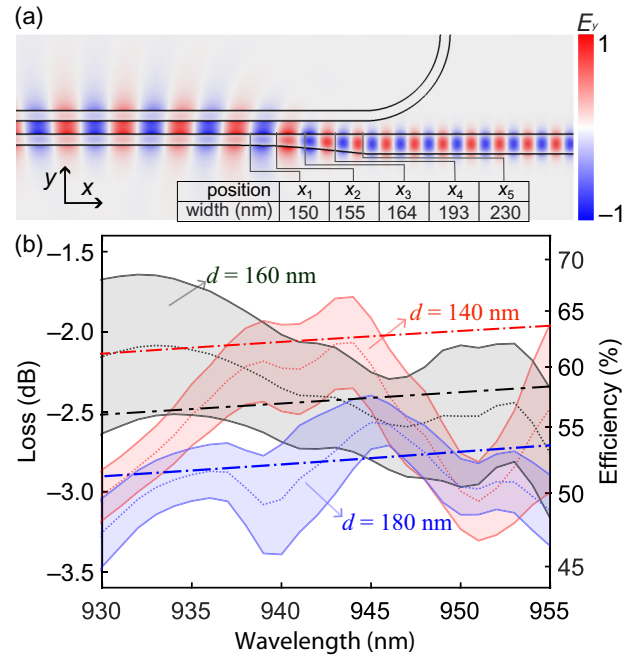


FIG. 2. (a) Finite-element simulation of the electric field in the $2\text{-}\mu\text{m}$ -long taper used for the slot-waveguide coupler. The table indicates the waveguide width as a function of position, where $x_n - x_{n-1} = 400 \text{ nm}$. (b) Wavelength-dependent insertion loss of the slot-waveguide phase shifter for three different slot widths d . The dash-dotted lines show theoretical losses, while the banded lines show measured losses, with the upper and lower limits of the band corresponding to measurement uncertainties.

SR of the MZI, defined as $\sqrt{\frac{I_{13}I_{24}}{I_{14}I_{23}}}$, is plotted as a function of the wavelength and of the applied voltage squared (proportional to the nanomechanical displacement of the slot waveguide). A clear oscillatory response to the applied bias is observed at all wavelengths. A global maximum (minimum) SR of $23.4 \pm 0.5 \text{ dB}$ ($-23.7 \pm 0.5 \text{ dB}$) is measured at 937 nm (961 nm). The SRs decrease as the wavelength shortens, suggesting the presence of asymmetric and wavelength-dependent loss mechanisms in the MZI. These are likely caused by a combination of imbalanced splitting ratios in the directional couplers, as well as a loss difference between the two arms of the MZI. A possible future approach to fully balance the interferometer at all wavelengths could be to replace the two fixed directional couplers with tunable nanomechanical devices [20]. The normalized intensity plot, taken at a single wavelength of 950 nm, is shown in Fig. 3(c). We model the transmission across the MZI as follows:

$$I_{\text{out},4} = \frac{I_0}{2} (1 + v_4 \cos(\phi_0 + \Delta\phi)), \quad (2)$$

$$I_{\text{out},3} = \frac{I_0}{2} (1 + v_3 \cos(\phi_0 + \Delta\phi)), \quad (3)$$

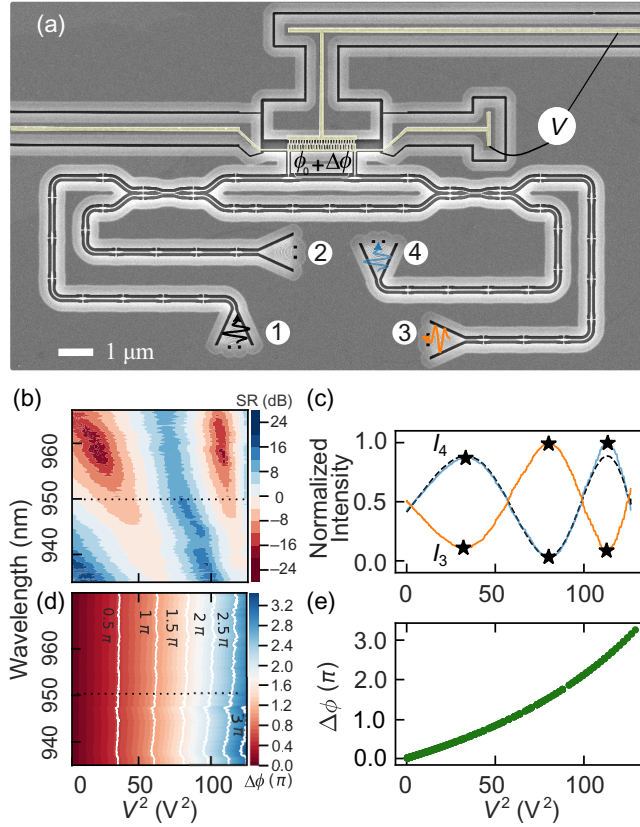


FIG. 3. Characterization of the NOEMS phase shifter at room temperature. (a) Experimental operation. A continuously tunable laser is coupled into the MZI via grating 1 or grating 2, with transmitted (reflected) light coupled out through grating 3 (grating 4). An external voltage bias is applied to the phase shifter to modulate the phase. (b) Coupling-independent SR dynamics are observed by our sweeping the wavelength and voltage bias. (c) Intensity modulation at output port 3 (orange) and output port 4 (blue) at a wavelength of 950 nm. The dashed line is a fit to the intensity modulation under the assumption of constant visibility. Phase modulation $\Delta\phi$ as a function of (d) wavelength and voltage bias and (e) voltage bias at 950 nm.

where v_4 and v_3 denote the (wavelength-dependent) interference visibility at port 4 and port 3, respectively. From the extrema of the fringes [marked with stars in Fig. 3(c)], we obtain $v_{4,1} = 0.80$, $v_{4,2} = 0.84$, $v_{3,1} = 0.92$, and $v_{3,2} = 0.93$, where “1” (“2”) denotes the first (second) extrema set, respectively. The small increase of visibility at higher bias is consistent with the theoretical prediction that the phase shifter insertion loss decreases with the slot width [see Fig. 2(b)]. The oscillatory response of the intensity can be used to directly compute the relative phase shift $\Delta\phi(V)$ at each voltage. The result is shown in Fig. 3(d) for all wavelengths and in Fig. 3(e) at 950 nm. The white isolines indicate the amount of phase shift relative to zero bias achieved at each wavelength, confirming the broadband operation of the device and almost near-identical performance over a 30 nm bandwidth. $\Delta\phi$ of 3π is achieved

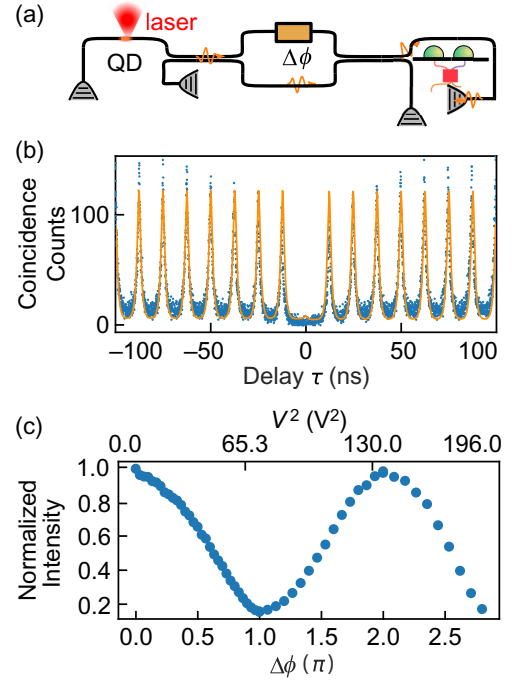


FIG. 4. (a) NOEMS photon router based on a tunable MZI. QDs are excited on the input arm and analyzed at one output. (b) Autocorrelation histogram for a QD with emission at 923 nm, showing clear antibunching at zero time delay. (c) Intensity modulation of the single-photon signal as a function of the applied squared voltage and corresponding phase shift.

with this compact phase shifter, requiring an applied potential of 10.6 V. We extract a figure of merit $V_\pi L$ of 5.7×10^{-3} V cm considering the voltage ($V_\pi = 5.7$ V) required to obtain a π phase shift from the unbiased device. V_π is further reduced to 1.7 V when we consider a biasing voltage $V_0 = 8.9$ V. Comparing this result with the simulated phase shift in Fig. 1(d), we estimate that the maximum mechanical displacement is approximately 80 nm from an initial gap of 150 nm, corresponding to an electromechanical transduction η at room temperature of approximately 0.6 nm/V^2 .

IV. SINGLE-PHOTON ROUTING

The performance of the NOEMS phase shifter at cryogenic temperature is characterized with InAs QDs operated at 10 K as a source of single photons. We use an 800 nm above-band pulsed diode laser to excite a QD located in a standard single-mode (300-nm-wide) waveguide, as indicated in Fig. 4(a), and we use the MZI as a photon router. The collected signal is filtered by a diffraction grating to select individual QD transitions. To confirm the single-photon nature of the emitter, an autocorrelation measurement $g^{(2)}(\tau)$ is performed on a single excitonic transition at 923 nm. The result is shown in Fig. 4(b), exhibiting a clear antibunching dip at zero delay [$g^{(2)}(0) = 0.007 \pm 0.003$],

which indicates the efficient suppression of the multi-photon component from laser leakage and re-excitation processes. The observed increase in peak intensity over the short timescale is due to artifacts in the photon counter instrumentation, and the value of $g^{(2)}(0)$ is obtained by normalization of the data at long times $\tau \simeq 1$ ms.

Figure 4(c) shows the intensity modulation of the same QD emission line at 923 nm. A higher applied bias is required at cryogenic temperature compared with room temperature. At the highest applied bias of 14 V, a 2.7π phase shift is achieved. We estimate that the electromechanical transduction η reduces by approximately two thirds of the room temperature value at 10 K. We attribute this behavior to two main factors: (1) At cryogenic temperature GaAs and the Cr/Au metal contacts exhibit thermal compression at different rates, owing to the different coefficients of thermal expansion, which causes the whole suspended structure to be displaced out of the plane. This could lead to a partial disengagement of the NOEMS electrostatic comb drive, resulting in a lower actuation force from the electrodes. (2) Changes in the elastic modulus of Au, which becomes significantly higher at cryogenic temperatures, making the structure stiffer [30].

V. CONCLUSIONS

We presented a cryogenically compatible NOEMS phase shifter on a GaAs platform, a critical component for photonic quantum information processing. This platform combines high-purity quantum emitters with the capability to perform on-chip optical routing. The phase shifter leverages the reconfigurable coupling of slot-waveguide modes, achieving an effective index change Δn_{eff} on the order of approximately 0.1 with nanoscale displacement (tens of nanometers) of the slot waveguides. Importantly the device performance remains robust at cryogenic temperatures, which is critical for applications involving quantum emitters such as InAs quantum dots and for static (typically 1–2 MHz) circuit reconfiguration [20]. The device performance can be further improved by one addressing slow (over hundreds of seconds) phase drifts by implementing active stabilization and feedback as well as methods to damp noise stemming from mechanical resonances [31]. Although the phase shifter introduces a modest insertion loss of less than 3 dB, primarily attributed to scattering and surface charge absorption, losses can be further mitigated through surface passivation techniques [32], improved taper designs, and high-efficiency chip-to-fiber coupling techniques [33]. Integration of the phase shifter with gap-variable directional couplers [20] would enable the realization of low-power arbitrary 2×2 unitary transformations [34] and potentially the scaling up further to large networks of multimode interferometers [35], with applications in boson sampling, quantum simulation [36], and machine learning [37]. Additionally, the integration of quantum

emitters and phase shifters in the same chip can be used to fine-tune light-matter interaction, for example, by tuning the local density of optical states and enabling remote control of spontaneous emission [38] or controlling the coupling between multiple emitters [39]. By advancing the scalability and compatibility of cryogenic photonic platforms, this device marks an important step forward in the realization of integrated quantum photonic architectures.

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The authors declare that they have no conflicts of interest.

CODE AVAILABILITY

The code used for data analysis and numerical simulations is available from the corresponding authors upon reasonable request.

DATA AVAILABILITY

The data that support the findings of this article are openly available [40].

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