On-chip piezo-optomechanical dynamic single photon routing and rotation of a photonic qubit

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Abstract

Integrated photonic circuits are key components for photonic quantum technologies and for the implementation of practical chip-based quantum devices. Future applications demand flexible architectures which overcome common limitations of many current devices, for instance the lack of tunability or built-in quantum light sources. Here, we report on a dynamically reconfigurable integrated photonic circuit comprising integrated quantum dots (QDs), a Mach-Zehnder interferometer (MZI) and surface acoustic wave (SAW) transducers fabricated on a monolithic semiconductor platform. We demonstrate on-chip single photon generation by the QD, initializing a photonic qubit. Two independently applied SAWs piezo-optomechanically rotates the single photon in the MZI or spectrally modulated the QD emission wavelength. In the MZI, SAWs imprint a time-dependent optical phase and modulate the qubit rotation to the output superposition state. This enables dynamic single photon routing with frequencies exceeding one gigahertz. Finally, the combination of the dynamic single photon control and spectral tuning of the QD realizes wavelength multiplexing of the input state and demultiplexing at the output. Our approach is scalable to multi-component integrated quantum photonic circuits and is compatible with hybrid photonic architectures and other key components for instance photonic resonators or on-chip detectors.
**Main Text**

Photonic quantum technologies\(^1\)-\(^6\) have seen rapid progress and hallmark quantum protocols have been implemented using integrated quantum photonic circuits (IQPCs)\(^7\)-\(^13\). For many applications, integrated quantum emitters e.g. quantum dots\(^14\)-\(^21\) or defect centers\(^22\)-\(^26\) are of great importance. Already in first ground-breaking proposals reconfigurable architectures have been recognized as being of pivotal relevance\(^21,27,28\). To date, many different tuning mechanisms have been implemented to control light propagation in photonic elements which exploit, for instance thermo-optic\(^29\)-\(^31\), electro-optic\(^32\)-\(^34\) or acousto-optic\(^35\)-\(^39\) effects or micromechanical actuation\(^40\)-\(^42\). Similarly, the emission properties of integrated quantum emitters can be manipulated by electric fields\(^43\)-\(^45\) or strain\(^46\)-\(^50\).

Among these mechanisms, acoustic phonons are an attractive choice because they couple to literally any system\(^51\) enabling strong optomechanical modulation and dynamic reconfiguration\(^52\)-\(^54\). In the form of radio frequency Rayleigh SAWs\(^55\) or Lamb waves\(^56\), phonons can be routed on-chip\(^57\)-\(^59\) and interfaced with integrated photonic elements\(^60\)-\(^64\), quantum emitters\(^65\)-\(^72\) or superconducting quantum devices\(^73,74\).

In this article, we report on a piezo-optomechanically reconfigurable quantum photonic device with integrated tuneable quantum emitters, schematically shown in Figure 1. The validation of fully-fledged dynamic single photon routing, single qubit logic and single photon wavelength (de)multiplexing is illustrated in Figure 1b-d. First, we excite a QD, which emits a single photon and initializes a photonic qubit in a monolithically fabricated, integrated and dynamically tuneable MZI. Second, we employ SAWs to dynamically route the single photons between the outputs by tuning the time-dependent phase gate which creates a superposition state. Third, dynamic spectral modulation of the QD in combination with the tuneable phase gate enables freely programmable spectral multiplexing of single photons.

Our device is based on a waveguide IQPC monolithically fabricated on a GaAs semiconductor platform\(^21,75,76\). The piezoelectricity of this class of materials enables the direct all-electrical excitation of SAWs using interdigital transducers (IDTs)\(^77\). The SAW tunes the integrated MZI via a time-modulated photoelastic effect and switches photons between the two outputs. Importantly, the heterostructure contains (In,Ga)As QDs, one of the most mature semiconductor quantum emitter system\(^78\). These QDs are established as high quality sources of single photons with high indistinguishability\(^79,80\) and their potential has been proven in the implementation of fundamental quantum protocols\(^81\)-\(^83\) and integration in IQPCs\(^17,21,76\).

**Implementation**

*Device layout*
Figure 1 – Device and qubit rotation – (a) Schematic representation of the dynamically tuneable ridge waveguide integrated quantum photonic circuit (IQPC). The concept, based on a Mach Zhender Interfermeter (MZI) comprises two input waveguides (Input WG-A and Input WG-B) connected to a 2×2 multimode interference device (MMI1) whose outputs are connected by two WGs to MMI2 with two output WGs (Output WG-A and Output WG-B). Two interdigital transducers (IDTs) generate SAWs for spectral modulation of single QDs (IDT_{SM}) in the Input WGs and optomechanical phase modulation of the MZI (IDT_{PM}). (b) Representation of the single qubit initialization via selective single photon generation by a QD; (c) single qubit rotations shown on Bloch spheres. The evolution of the qubit states is indicated by the green arrows (Beamsplitter gates through MMI1 & MMI2, respectively) and a red arrow (SAW induced dynamic phase gate). (d) projection measurement of the qubit superposition state by collection and detection from the Output WGs (Output WG-A / Output WG-B) using a lensed optical fiber.

Our device, schematically shown in Figure 1a, comprises key functionalities required of an IQPC: it contains integrated, tunable quantum emitters for in-situ wavelength multiplexed qubit initialization. A combination of two static and one programmable elementary single qubit gates rotates the qubit and controls its output state which is detected in a projection measurement. The IQPC itself is based on etched GaAs ridge waveguides (WGs) on an (Al,Ga)As cladding layer. During crystal growth of the semiconductor heterostructure, a single layer of (In,Ga)As QDs is embedded in the active region to provide high-quality built-in, anti-bunched quantum emitters. The photonic circuit consists of two symmetric WGs, referred to as WG-A and WG-B, and two 4-port multimode interference (2×2 MMI) beamsplitters. To achieve fully-fledged tuneability, our device is equipped with IDTs to generate two SAW beams with the same frequency of $f_{SAW} \approx 525$ MHz.

We can consider the QD emitted single photons as photonic qubits which are controlled in the IQPC. Specifically, dual rail encoding of photonic qubits is given by $|1_A, 0_B\rangle = |0\rangle$ and $|0_A, 1_B\rangle = |1\rangle$, with indices $A, B$ denoting WG-A and WG-B, respectively\(^\text{17}\). As shown schematically in Figure 1b, the single qubit state can be directly and faithfully initialized by selective optical excitation of a single QD and subsequent emission of a single photon into one of the two Input WGs. Moreover, these QDs are tuneable. They can be dynamically strained by a SAW generated by IDT_{SM}. The dynamic local phase of the SAW $\varphi_{SAW,SM}(t) = 2\pi f_{SAW,SM} t$ programs the emission wavelength of the QD emitted single photons $\lambda(t) = \Delta\lambda \cdot \sin 2\pi f_{SAW,SM} t$ used to encode the input\(^\text{50}\).
The initialized photonic qubit encoded in the emitted single photon is controllably rotated in the IQPC.

The two input WGs are connected to the first 2×2 MMI beamsplitter, labelled MMI1 which executes a combination of an Hadamard gate, $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$, and a Pauli-Z gate, $Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$, on the input state. Thus, the rotation caused by the MMI can be expressed as $MMI = Z \cdot H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$.

Therefore, MMI1 creates a superposition state from the input photonic qubit, $|0\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$ = |−⟩ and $|1\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) = |+⟩$. The superposition state propagates to the second 2×2 MMI beamsplitter, MMI2. There the input states |−⟩ and |+⟩ are rotated again by the second MMI gate and mapped to their respective output states |1⟩ and |0⟩, respectively. The full rotation of the static IQPC can be described by $IQPC_{static} = MMI \cdot MMI = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} = Z \cdot X$, which corresponds to the combination of a Pauli-X gate (NOT-gate) and a Pauli-Z gate. Since the Pauli-Z gate only affects the phase of the qubit, but not the projection of the qubit on the base states |0⟩ and |1⟩, and the qubit is measured after exiting the IQPC the Z-gate does not influence the outcome of the experiments presented in this work.

The SAW generated by IDT$_{pm}$ optomechanically modulates the optical phase difference between the WGs connecting the two MMIs$^{61,84}$. For this operation, the two arms (length 140 µm) of the MZI connecting the MMIs are separated by 1.5$\Lambda_{SAW,PM}$, with $\Lambda_{SAW,PM} = 5.6$ µm, being the acoustic wavelength of the applied SAW. This geometric separation ensures that the optical phase modulations in the two arms are antiphased, which can be expressed as $\phi_{A,B}(t) = \mp \Delta \phi \sin(t)$, with − for WG-A and + for WG-B. Here, $\phi_{SAW,PM}(t) = 2\pi f_{SAW,PM}t$ is the dynamic phase of the SAW. $\Delta \phi$ is the amplitude of the optical phase modulation, which is given by the strength of the underlying acousto-optic interaction$^{61}$. Most importantly, $\Delta \phi$ can be tuned by the electrical radio frequency (rf) power of the electrical signal $P_{rf,PM}$, applied to the IDT. Thus, the total optical phase shift amounts to $\phi (\phi_{SAW,PM}) = 2 \cdot \Delta \phi \sin (\phi_{SAW,PM}) + \phi_0$. In this expression $\phi_0$ is a finite optical phase offset due to fabrication imperfections. The full gate is then given by $R_{\phi}(t) = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\phi(t)} \end{pmatrix}$. Thus, we implement a dynamic phase gate to control the interference condition at MMI2. Most notably, this allows us to program the output state of the qubit $|\Psi\rangle = \alpha (\phi_{SAW,PM})|0\rangle + \beta (\phi_{SAW,PM})|1\rangle$ with SAW phase dependent complex amplitudes $\alpha (\phi_{SAW,PM})$ and $\beta (\phi_{SAW,PM})$ obeying $|\alpha|^2 + |\beta|^2 = 1$. Figure 1a shows the respective rotations on the Bloch sphere starting from the initial |0⟩ qubit state propagating through the modulated device. The first MMI rotates the input state into the xy-plane of the Bloch sphere to the |−⟩ state. The programmable acoustic phase shift $\phi (\phi_{SAW,PM})$, rotates the Bloch vector in the equatorial plane (xy-plane) and the final MMI rotates the Bloch vector from the xy- to the yz-plane.

The full dynamic IQPC can be described by $IQPC(\phi) = MMI \cdot R_{\phi}(t) \cdot MMI = \frac{1}{2} \begin{pmatrix} 1 - e^{i\phi} & 1 + e^{i\phi} \\ 1 - e^{i\phi} & 1 + e^{i\phi} \end{pmatrix}$. Thus, assuming an input state of $|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$, or $|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ the output state will be given by $\frac{1}{2} \begin{pmatrix} 1 - e^{i\phi} \\ 1 + e^{i\phi} \end{pmatrix}$ or $\frac{1}{2} \begin{pmatrix} 1 + e^{i\phi} \\ 1 - e^{i\phi} \end{pmatrix}$, respectively. This means that the output states are dynamically rotated by the SAW in the yz-plane, allowing for a complete switching of the probability for measuring the output-photon either in the |0⟩ or the |1⟩ state. To dynamically create an arbitrary
output state, the device must be supplemented by an additional phase gate $R_p$ at the output, which can be realized by an additional phase modulating IDT.

Devices were fabricated monolithically on a semiconductor heterostructure grown by molecular beam epitaxy. Full details on the semiconductor heterostructure, the experimental setup and device fabrication are included in the Methods Section and Supplementary Sections 1 and 2. The optical and SAW-properties of the as-fabricated devices were as follows: the optical waveguide losses of $(10.8 \pm 2.50)$dB $\cdot$ cm$^{-1}$ of the fabricated IQPCs are competitive with the state of the art in this material system$^{14,15}$. The insertion loss of the delay line of $S_{21} = 28$ dB at low temperatures. The full electromechanical conversion efficiency including the cryostat wiring is 4%, proving efficient generation of the SAW on the comparably weak piezoelectric GaAs. Full details are included in Supplementary Sections 3.1 and 3.2. In the experiments presented in the remainder of the paper, SAWs are generated by a continuous wave (cw) rf signal(s) applied to one or two IDTs. We then assess the $\varphi_{\text{SAW}}$-dependence using a cw laser to photoexcite the QD and initialize the input qubit by the subsequentially emitted single photon. We then detect the output signals in the time domain from which the $\varphi_{\text{SAW}}$-dependence is deduced. This scheme allows us to elegantly detect the dynamic modulation by the SAW. In our proof-of-principle study, the cw applied rf power leads to unwanted sample heating. The latter can be significantly suppressed by using a pulsed SAW excitation scheme$^{50}$ or in hybrid devices comprising a strong piezoelectrics e.g. LiNbO$_3$ with heterointegrated semiconductor QDs$^{85}$. Full details on the experimental setup are presented in the Methods Section and in Supplementary Section 2.

*Tuneable single photon routing and qubit rotation*
Figure 2 — Dynamic routing of quantum dot emission — (a) Schematic representation of the experimental configuration: although the optical transition of a single QD in Input WG-A is not modulated (IDT_SM is kept off, illustrated in shade), the response of the MZI is modulated (IDT_PM is turned on, illustrated in bright colors) as the photons passes through. Emission is collected by a lensed fiber from either Output WG-A (red) or Output WG-B (black). (b) Phase-integrated emission spectra of the same single QD measured without SAW applied (top panels, IDT_PM off) and with a SAW applied ($P_{\text{PM}} = 23 \text{ dBm}$, lower panels). (c) Measured SAW phase dependent intensity of the main QD emission line ($\lambda_0$ in b) detected via Output WG-A (red symbols) and Output WG-B (black symbols) for different $P_{\text{PM}}$. The simulation results (solid lines) for modulation amplitudes of the phase $\Delta \phi = 0.3, 0.5, 0.8$ and 1.3 rad are also shown for both outputs. The upper panel shows the time resolved SAW induced optical phase shift $\phi_{A/B}$ in the upper (WG-B, solid line) and lower arms (WG-A, dashed line) of the MZI. The right-hand side panel shows the $Z$-projection of the qubit for the measurement and the corresponding simulation. (d-f) Rotations of the qubit states in equatorial plane of the Bloch sphere at three distinct phases during the acoustic cycle. Symbols mark these phases in the projection data in (c).

We continue with the characterization of the dynamic modulation of the quantum interference in the MZI with a SAW generated by IDT_PM. The operation principle relies on the local modulation of the refractive index in the two MZI WGs and depends on the local phase of the SAW, $\phi_{\text{SAW,PM}}$. The change in refractive index causes an optical phase shift $\phi(\phi_{\text{SAW,PM}})$ between WG-A and WG-B and leads to a dynamic modulation of the interference at MMI2 and, thus, the superposition state $|\Psi\rangle =$
\(\alpha(\varphi_{\text{SAW,PM}})|0\rangle + \beta(\varphi_{\text{SAW,PM}})|1\rangle\) of the output photonic qubit. Figure 2a shows the schematic of the measurement configuration. A single QD is optically excited in Input WG-A to prepare a \(|1_A, 0_B\rangle = |0\rangle\) state of the photonic qubit at Input WG-A and WG-B.

First, we compare the phase-integrated photon output characteristics for the as-fabricated passive and active device in Figure 2b. As confirmed in the upper panel, the device cross-couples photons of the excited QD from Input WG-A to Output WG-B (\(|\beta(\varphi_{\text{SAW,PM}})|^2\), right, black) and almost no emission is detected from Output WG-A (\(|\alpha(\varphi_{\text{SAW,PM}})|^2\), left, red). This result corresponds precisely to the inversion of the input photonic qubit \(|0\rangle \rightarrow |1\rangle\) with a high fidelity of 0.94 ± 0.01. The small deviation arises from the fabrication-related imperfections’ static phase \(\phi_0 = 0.51\) rad. Supplementary Section 3.3 contains a full set of simulation data.

When an acoustic power of \(P_{\text{rfPM}} = 23\) dBm and a frequency of \(f_{\text{SAW,PM}} = 525\) MHz is applied to IDT\(_\text{PM}\) (lower panels), the signal is routed dynamically between both outputs. Thus, the phase-integrated spectra detected from Output WG-A (lower left panel, red) and Output WG-B (lower right panel, black) are almost perfectly identical. Note the spectra in the lower panels are shifted to longer wavelengths accompanied by a small reduction of the total emission intensity due to an increase of the temperature when the radio frequency signal is applied\(^6\). This is described in detail in Supplementary Section 3.6. For clarity, corresponding emission lines in the spectra are marked by \(\lambda_0\). Importantly, no additional broadening is observed. Thus, no unwanted spectral modulation occurs when the quantum interference of the photonic qubit is dynamically controlled by \(R_\phi(\varphi_{\text{SAW,PM}})\).

Second, we study the modulation of the qubit rotation induced by the \(R_\phi(\varphi_{\text{SAW,PM}})\)-gate as a function of \(\varphi_{\text{SAW,PM}}\). The upper panel in Figure 2c shows the time and phase dependence of the antiphased optical phase modulations, of \(\phi_{A,B}\), in WG-A (dashed line) and WG-B (solid lines) of the MZI, respectively. In the left panels below, we analyze the intensity of the dominant QD emission line \(\lambda_0 = 874\) nm collected from Output WG-A (red, \(|\alpha(\varphi_{\text{SAW,PM}})|^2\)) and Output WG-B (black, \(|\beta(\varphi_{\text{SAW,PM}})|^2\)) as a function of the acoustic phase, \(\varphi_{\text{SAW,PM}}\), with the applied rf power increasing from top to bottom. At the lowest drive power \(P_{\text{rfPM}} = 9\) dBm the modulation of the refractive index and thus \(\Delta\phi\) is weak. Even at this low power level, the signals detected from the two outputs exhibit the expected antiphased modulation. This indicates that the pure \(|1\rangle\)-output state of the unmodulated MZI is dynamically adopting \(|0\rangle\)-character due to the oscillation of \(\phi(\varphi_{\text{SAW,PM}})\). When \(P_{\text{rfPM}}\) increases, the modulation amplitude of the optical phase, \(\Delta\phi\), increases further and the resulting interference in the modulated MZI develops a pronounced oscillation. To better visualize the dynamic nature of the qubit rotation by the SAW, we extract the \(Z\)-projection of the qubit, \(\langle S_Z \rangle = \frac{|\alpha(\varphi_{\text{SAW,PM}})|^2 - |\beta(\varphi_{\text{SAW,PM}})|^2}{|\alpha(\varphi_{\text{SAW,PM}})|^2 + |\beta(\varphi_{\text{SAW,PM}})|^2}\), which is plotted in the right panels. For low \(P_{\text{rfPM}}\), the qubit is predominantly in the \(|1\rangle\) state, i.e \(\langle S_Z \rangle = -1\). For the highest \(P_{\text{rfPM}}\), the Bloch vector is rotating between \(\langle S_Z \rangle = -0.71\) and \(\langle S_Z \rangle = +0.82\). Importantly, it is rotated into the equatorial plane (\(S_Z = 0\)) at well-defined phases during the acoustic cycle. The non-zero static phase, \(\phi_0\), gives rise to the observed device-characteristic beating of the dynamic qubit rotation while for a perfectly symmetric MZI (\(\phi_0 = 0\)) the frequency of this oscillation is given by \(2f_{\text{SAW,PM}} = 1.05\) GHz. Note non-zero \(\phi_0\) does not represent a limitation of our concept because it can be adjusted after calibration if deemed...
necessary. A rigorous analytical model of this beating is detailed in the Supplementary Section 3.4 together with the respective theoretical optical field intensity propagations.

Third, we validate our experimental findings by performing beam propagation method simulations taking into account $\phi(\varphi_{SAW,PM})$ in the MZI. Phase dependent simulation results are indicated by the solid lines in Figure 2c. They show that the experimental data can be nicely reproduced for $\Delta \phi$ ranging between $\Delta \phi = 0.3$ rad and $1.3$ rad and near-unity $|\langle S_z \rangle|$ can be predicted from the projection of the strongest modulation. Figures 2d-f then show the rotation of the qubit states in the equatorial plane of the Bloch sphere at three distinct acoustic phases, $\varphi_{SAW,PM} = -0.06\pi$, $0.14\pi$ and $0.5\pi$, which are accordingly marked in the projection measurement data in Figure 2c. Clearly, the data presented in Figure 2 validate that the applied SAW induces a dynamic $R_R(\varphi_{SAW,PM})$-gate and such driven qubit rotations enable the faithful generation of a superposition state in the equatorial plane of the Bloch sphere. Since these rotations are gated with $f_{SAW,PM} = 525$ MHz, the data prove dynamic routing of the on-chip generated single photons on sub-nanosecond timescales which are challenging to reach in alternative electro-opto-mechanical approaches.

Conservation of single photon character

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Figure 3 – Photon antibunching of on-chip routed quantum dot emission – Upper panels show a schematic representation of the experimental configuration: the optical transition of a single QD in Input WG-A (a, red) or Input WG-B (b, black) is not modulated (IDT$_{SM}$ is kept off, illustrated in shade) while the response of the MZI is modulated (IDT$_{PM}$ is turned on, illustrated in bright colors) as the photons passes. Emission is collected from Output WG-B in both cases. Main panels show the measured second order correlation function $g^{(2)}(\tau)$ (blue) for the QD in Input WG-A (a) and Input WG-B (b) for $P_{SAW,PM} = 17$ dBm and $f_{SAW,PM} = 525$ MHz. The red lines are best fits to the data yielding: $g^{(2)}(0) = 0.38 \pm 0.06$ and $g^{(2)}(0) = 0.42 \pm 0.09$ in (a) and (b), respectively. Insets show the fast Fourier transform (FFT) of the data with a clear signal at $f_{SAW,PM}$.

As the next step of our proof-of-principle study, we now prove that the single photon nature of the qubit is conserved. We measure the second order correlation function $g^{(2)}(\tau)$ using a standard Hanbury-Brown and Twiss setup and Supplementary Section 4 shows data of a reference QD with no
modulation applied. These anti-bunching data in Supplementary Figure S14 show \( g^{(2)}(0) = 0.48 \pm 0.03 < 0.5 \). The observed values of \( g^{(2)}(0) \) in our experiments are limited by the finite time resolution of our detectors and the non-resonant, above bandgap optical pumping and not by the SAW modulation and there exists no fundamental limitations \(^{72,86,87}\) to reach the \( g^{(2)}(0) \) levels reported on this platform\(^{14,15}\). Importantly in the context of this paper, \( g^{(2)}(0) > 0.5 \) enables us to conduct proof-of-principle experiments and assess the impact of SAW modulation of our IQPC on the stream of single photons. In Figure 3, we compare \( g^{(2)}(\tau) \) of two different QDs with a frequency \( f_{\text{SAW,PM}} = 525 \) MHz SAW applied to IDT\(_{\text{PM}}\) at a power level of \( P_{\text{RF,PM}} = 17 \) dBm. As shown by the schematics in the upper panels, the two QDs located in Input WG-A (Figure 3a) and Input WG-B (Figure 3b), initialize \( |0\rangle \) and \( |1\rangle \) input photonic qubit states, respectively. The time-dependent qubit rotations of both QDs are presented in Supplementary Section 4.2. Correlations are measured from Output WG-B, i.e. the time-dependent \( |\beta(\varphi_{\text{SAW,PM}})|^2 \) projection of the qubit on its \( |1\rangle \) component. Data are fitted using a procedure provided in Supplementary Section 4.3. For the QD in Figure 3a, the emitted single photon is routed to Output WG-B, i.e. \( |0\rangle \rightarrow |1\rangle \) in the static case. At the applied power level, the modulation of the output intensities is weak [c.f. Figure 2c]. Thus, \( g^2(\tau) \) of this QD is expected to be like that of the unmodulated case with a weak \( f_{\text{SAW,PM}}^{-1} = 1.9 \) ns-periodic modulation superimposed. The measured \( g^{(2)}(\tau) \) (blue line) shows precisely the expected anti-bunching behaviour and \( f_{\text{SAW,PM}} \) is clearly resolved in the fast Fourier Transform (FFT) of the data shown as an inset. From a best fit (red line) to the data taking into account the timing resolution of our detectors, we obtain \( g^{(2)}(0) = 0.38 \pm 0.06 \). For the QD in Figure 3b, the emitted single photon is routed to Output WG-A, i.e. \( |1\rangle \rightarrow |0\rangle \) in the static case. At the selected SAW amplitude [c.f. Figure 2c], the time-dependent \( |\beta(\varphi_{\text{SAW,PM}})|^2 \) projection measured from Output WG-B is non-zero for short time intervals. Thus, the measured \( g^2(\tau) \) exhibits a clear \( f_{\text{SAW,PM}}^{-1} = 1.9 \) ns-periodic modulation confirmed by the FFT of the data shown as an inset. Most importantly, the data (blue line) exhibit a clear suppression of coincidences at \( \tau = 0 \), with \( g^{(2)}(0) = 0.42 \pm 0.1 \) obtained from a best fit (red line). Both \( g^{(2)}(0) \) values agree well with that of the unmodulated QD shown in Supplementary Section 4.1. Our proof-of-principle experiments unambiguously show that the antibunched single photon nature of the transmitted light and thus photonic qubit is preserved with the dynamic \( R_\varphi(\varphi_{\text{SAW,PM}}) \)-gate applied, which is a key requirement for practical applications.

*Dynamic wavelength selective single photon multiplexing*

Finally, we apply spectral modulation of the QD and implement a proof-of-principle multiplexing and demultiplexing of the single photon qubit. To this end, we simultaneously modulate the spectral emission characteristics of the QD using IDT\(_{\text{SM}}\) and dynamically control the qubit in the MZI using IDT\(_{\text{PM}}\). A schematic of the experimental configuration is shown in Figure 4a. We study a QD located in Input WG-B initializing a \( |1\rangle \)-input qubit and read-out is performed at Output WG-B (\( |\beta|^2 \)). Both SAWs are active as we set \( f_{\text{SAW}} = f_{\text{SAW,SM}} = f_{\text{SAW,PM}} = 524.12 \) MHz and \( P_{\text{RF,SM}} = P_{\text{RF,PM}} = 19 \) dBm. Importantly, we can program the relative phase \( \Delta \varphi_{\text{SAW}} = \varphi_{\text{SAW,SM}} - \varphi_{\text{SAW,PM}} \) between the SAWs driving the spectral and phase modulations, simply by setting the phases of the driving electrical signals.
Figure 4 – Single photon (de)multiplexing – (a) Schematic representation of the experimental configuration: Both IDTs are kept on (illustrated in bright colors). The optical transition of a single QD in Input WG-B is modulated by IDT\textsubscript{SM} while the response of the MZI is modulated by IDT\textsubscript{PM} as the photons passes through. (b) Upper panel: Acoustic phase-dependent spectral modulation of the QD. Lower panel: intensity modulations at Output WG-B at four distinct relative phases $\Delta \phi\text{SAW}$ (line colors and symbols). (c-f) Acoustic phase-dependent emission spectra of the QD measured from Output WG-B for the four distinct relative phases marked in (b). (g) Programmable spectral demultiplexing of the
maximum ($\lambda_{\text{max}}$, red symbols), center ($\lambda_0$, black symbols) and minimum ($\lambda_{\text{min}}$, blue symbols) of the spectral modulation as a function of $\Delta \varphi_{\text{SAW}}$. Colored lines are best fits to the data.

First, we confirm spectral modulation of the quantum emitter. The measured phase-dependent emission spectra of the QD are shown in false-color representation as a function acoustic phase, $\varphi_{\text{SAWsm}}$, and optical wavelength in the upper panel of Figure 4b. The upper axis is in units of time during the SAW-cycle. The emission exhibits the expected sinusoidal modulation $\lambda(t) = \Delta \lambda \cdot \sin 2\pi f_{\text{SAW}} t$ due to the SAW-induced modulation through the deformation potential coupling. For our devices we find total a tuning bandwidth of $2\Delta \lambda = 0.8$ nm (cf. Supplementary Fig. S10), comparable to recent reports of static Stark tuning on this platform. A detailed analysis is included in Supplementary Section 3.4. In the experiments presented in the following, we set $\Delta \lambda = 0.05$ nm. The data clearly proves that a single photon is emitted at a well-defined wavelength at a given phase during the acoustic cycle. Since the QD is optically pumped by a continuous wave laser, all wavelengths are injected into the MZI and are thus, multiplexed at the respective phases. This spectral oscillation sets the reference for the MZI modulation driven by the SAW generated by IDT $\text{PM}$. The lower panel of Figure 4b shows the dynamic single photon routing (QD in Input WG-$B$, i.e. [1] initialization of the qubit) as a function of phase from Output WG-$B$ ($|\beta (\varphi_{\text{SAWsm}})|^2$) for four different $\Delta \varphi_{\text{SAW}} = 0$, $\pi/2$, $\pi$ and $3\pi/2$. The vertical lines connect to the emission wavelengths of the QD when the dynamically tuned quantum interference projects the input $|1\rangle$-state to the output $|1\rangle$-state. Clearly, $\varphi_{\text{SAW}}$ programs the projected wavelength: the center wavelength ($\lambda_0 = 876.35$ nm) is detected from Output WG-$B$ for $\Delta \varphi_{\text{SAW}} = 0$ (purple) and $\Delta \varphi_{\text{SAW}} = \pi$ (orange), while for $\Delta \varphi_{\text{SAW}} = 0.5\pi$ (green), and for $\Delta \varphi_{\text{SAW}} = 1.5\pi$ (blue), the maximum ($\lambda_{\text{max}} = 878.6$ nm) and minimum wavelength ($\lambda_{\text{min}} = 876.3$ nm) leave via this output, respectively. This dynamic, single photon wavelength demultiplexing is demonstrated in phase resolved experiments. In Figure 4c-f, we show the phase-dependent emission of the QD. The symbols mark the above selected $\Delta \varphi_{\text{SAW}}$. First, we observe that emission is detected only at distinct phases of the acoustic cycle. This confirms that the SAW-modulated MZI is operated as a tuneable, dynamic signal router. Second, as $\varphi_{\text{SAW}}$ is tuned, the wavelength of the photons exiting via Output WG-$B$ changes. At $\Delta \varphi_{\text{SAW}} = 0$ (Figure 4c) and $\Delta \varphi_{\text{SAW}} = \pi$ (Figure 4e) the QD emission is coupled out during the rising and falling edge of the spectral modulation, respectively. At $\Delta \varphi_{\text{SAW}} = 0.5\pi$ (Figure 4d), $\lambda_{\text{max}}$ is filtered, perfectly antiphased to the detection of $\lambda_{\text{min}}$ at $\Delta \varphi_{\text{SAW}} = 1.5\pi$ (Figure 4f). We further corroborate the faithful demultiplexing in Figure 4g. We plot the intensities at $\lambda_{\text{max}}$ (red), $\lambda_{\text{min}}$ (blue) and $\lambda_0$ (black) over two complete cycles of $\Delta \varphi_{\text{SAW}}$. These data unambiguously confirm that $\lambda_{\text{max}}$ and $\lambda_{\text{min}}$ are filtered at well-defined $\Delta \varphi_{\text{SAW}}$. Furthermore, the center wavelength ($\lambda_0$) oscillates at $2f_{\text{SAW}}$ because the applied demultiplexing filters this wavelength at both the rising and falling edges of the spectral modulation.

Conclusions and outlook
In conclusion, we designed, monolithically fabricated, and demonstrated proof-of-principle operation of key functionalities important for hybrid photonic and phononic quantum technologies. We used integrated quantum emitters to generate single photons in an IQPC with acoustically tuneable wavelength. The emitted single photon itself initializes a rail-encoded photonic qubit which is rotated in the IQPC. We executed dynamic and tuneable qubit rotations in a compact SAW-modulated MZI which faithfully preserve the single photon nature of the qubit. We show dynamic $f_{\text{SAW}} \approx 525$ MHz routing of the QD-emitted single photons between the two outputs. Moreover, our scheme enables the generation of output states perfectly located in the equatorial plane of the Bloch sphere. Finally,
we implemented spectral multiplexing of the emitted single photons two SAWs, one dynamically straining the emitter which are demultiplexed by a variable acoustic phase-lock to the second SAW driving the single qubit rotation.

The reported proof-of-principle results open several exciting perspectives. First, full arbitrary single qubit rotations\textsuperscript{88} are straightforward and can be realized simply by adding another IDT to operate a second phase gate at the Output WGs. Second, the purity of the single photon emission can be enhanced by embedding the QDs in SAW-tuneable photonic cavities\textsuperscript{38,89}. When establishing stable phase lock between a train of excitation laser pulses the SAW modulates the cavity-emitter coupling and precisely triggers the Purcell-enhanced emission of single photons\textsuperscript{86}. Third, the low propagation loss of SAWs allows to modulated multiple photonic systems and QDs by a single SAW beam\textsuperscript{90} for parallelized control schemes. Fourth, power levels required for switching can be significantly reduced further by embedding the photonic components in phononic resonators and waveguides to enhance the interactions\textsuperscript{57,58,71,91–93}. Fifth, all demonstrated functionalities can be transferred to hybrid architectures in particular heterointegration on LiNbO\textsubscript{3} SAW and IQPC devices\textsuperscript{85,94}, with 100-fold enhanced electromechanical coupling compared to monolithic GaAs devices.

Additionally, we note that the presented concept can be directly applied to other types of quantum emitters\textsuperscript{24,26,69,95,96} and spin degrees of freedom\textsuperscript{70,97}, even in the resolved sideband regime\textsuperscript{66,72}. Moreover, they can be combined with static electric field\textsuperscript{45,98} or stressors\textsuperscript{47} tuning to dissimilar QDs could be tuned into resonance to create multi-qubit systems. The integration density can be increased for instance by implementing a phase gate in a single MMI\textsuperscript{99} and multi-port MMIs enable phased-array wavelength-division multiplexing\textsuperscript{100}.

Methods

Sample design and fabrication

The heterostructure was grown by molecular beam epitaxy on a semi-insulating (001) GaAs substrate. It consists of a 1500 nm Al\textsubscript{0.2}Ga\textsubscript{0.8}As cladding layer followed by a 300 nm thick GaAs waveguide layer with a single layer of optically active self-assembled (In,Ga)As QDs in its centre. Devices were fabricated monolithically on these substrates using optical lithography. The IQPCs were etched using inductively coupled plasma reactive ion etching ICP-RIE. IDTs (10 nm Ti / 30 nm Al / 10nm Ti) were fabricated by a standard lift-off process.

Device simulation

MMI dimensions were calculated using established numerical simulation methodologies\textsuperscript{101}. The full IQPC comprising individual MMI dimensions, tapered waveguides, S-bends and the respective waveguide interfaces was optimized by finite difference 3D beam propagation method simulations using commercial software packages. For the simulation of the active device a sinusoidal modulation of the refractive index in the optomechanical interaction region of the MZI arms was applied. Device parameters and full details on the model used for the modulated transmission behaviour can be found in the Supplementary Section 1 and 3.

Experimental setup

Experiments were conducted in a cryogenic photonic probe station which is equipped with custom-made radio frequency lines. A schematic of the full setup and a detailed description are included in
Supplementary Section 2. In essence, QDs were optically excited by a non-resonant continuous wave laser ($\lambda_{\text{laser}} = 660$ nm) under normal incidence. The QD emission is collected from the cleaved end facets using a lensed fiber and spectrally filtered by a 0.75 m grating monochromator. A cooled CCD detector or up to two silicon single photon detectors (timing resolution 300 ps) are used for time-integrated and time-resolved detection, respectively. The outputs of up to two locked radio frequency signal generators are applied to the IDTs for SAW generation. Additionally, time-resolved optical detection was referenced to these electrical signals\(^{49}\).

Data availability
The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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18
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H. J. K. conceived and designed study and coordinated project. D. D. B. and M. W. coordinated the experimental work. D. D. B. designed device supported by M. M. d. L., A. C. P., M. W. and E. D. S. N.. M. W. conducted experiments. D. D. B. and M. W. analyzed data. A. C. P. and P. V. S. fabricated device. K. M. and J. J. F. provided the semiconductor heterostructure. H. J. K. and M. M. d. L. supervised the project. H. J. K. and D. D. B. wrote the manuscript.

Ethics declarations
The authors declare no competing interests.