Heterogeneously Integrated Photonic Chip on Lithium Niobate Thin-Film Waveguide

Xing Wei 1,* and Samuel Kesse 2

1 Department of Physics, Sun Yat-Sen University, Guangzhou 510275, China
2 School of Pharmacy, Shanghai Jiao Tong University, Shanghai 200240, China; kessejnr@yahoo.com
* Correspondence: weixing5@mail.sysu.edu.cn; Tel.: +86-159-5047-2802

Abstract: Lithium niobate thin film represents an ideal material substrate for quantum photonics due to its strong electro-optic effect and high-speed modulation capability. Here, we propose a novel platform which heterogeneously integrates single self-assembled InAs/GaAs quantum dots for a single-photon source on a lithium niobate photonic chip. The InAs/GaAs quantum dots can be transferred to the lithium niobate waveguide via a substrate transfer procedure with nanometer precision and be integrated through van der Waals force. A down-tapered structure is designed and optimized to deliver the photon flux generated from the InAs quantum dots embedded in a GaAs waveguide to the lithium niobate waveguide with an overall efficiency of 42%. In addition, the electro-optical effect is used to tune, and therefore to tune the beam splitting ratio of the integrated lithium niobate directional coupler, which can simultaneously route multiple photons to different spatial modes, and subsequently fan out through grating couplers to achieve single-photon sub-multiplexing. The proposed device opens up novel opportunities for achieving multifunctional hybrid integrated photonic chips.

Keywords: Lithium Niobate; Heterogeneously integrated photonic chip; InAs/GaAs quantum dots; grating coupler; directional coupler

1. Introduction

Single-photon sources are essential for realizing quantum communication [1,2], optical quantum computing [3–5], single-photon solid-state quantum networks [6–10], etc. Among all single-photon generation systems, solid-state quantum dots have drawn intense research interest due to their ability to be integrated into micro-cavities and to generate single and entangled photons [11,12]. They have been successfully used to prepare super bright sources of single or entangled photons [13,14]. In order to further boost the outcome of a single photon emitting device, and to overcome the limits constrained by a single quantum dot, there is an inevitable trend, at present, to establish optical quantum chips containing hybrid and multifunctional quantum systems. For instance, a quantum memory that can store and retrieve single photons has been demonstrated by integrating quantum dots with atomic systems [15]. Quantum dots can be integrated into an optical fiber network via an efficient quantum wavelength conversion to a telecommunication wavelength [16]. A strongly coupled quantum system can be formed by integrating quantum dots into an optical cavity [17]. Under this context, there is a significant need to establish quantum chips with low power consumption, high efficiency, and high indistinguishability. M. Davanco reported on a heterogeneous integration platform that used chip bonding technology to organically combine active materials with direct band gaps and passive materials with ultra-low loss, and thus formed a heterogeneous quantum chip [18]. Direct integration of GaAs waveguides and nanocavities containing InAs/GaAs quantum dots can also be integrated with III-V semiconductor materials and low-loss Si3N4 waveguides [19,20]. A coupling efficiency larger than 90% between Si3N4 waveguides and GaAs single quantum dots has been demonstrated. R. Katsumi and Y. Ota reported on a technique to exploit...
PDMS or thermal conduction tape to transfer the quantum dots in the nanocavity to the GaAs waveguide surface and further fabricate a hybrid integrated photonic chip of quantum dots in a nanocavity and GaAs waveguide [20].

In addition, lithium niobate (LiNbO$_3$) thin-film waveguides have recently been characterized by their low loss, fast electro-optical response, and high nonlinear coefficient [21–25]. They have been used to construct passive photonic chips with electro-optical modulation or nonlinear frequency conversion. In the case of electro-optical modulation or frequency conversion for single self-assembled quantum dot single-photon source, it is mandatory to couple the single photon emitted by the quantum dots from the III-V semiconductor chip to free space (or via optical fiber), and then couple the photons back into the LiNbO$_3$ waveguide. Due to the unavoidable mismatch of optical modes, the loss in optical coupling processes is relatively high, which limits the overall efficiency of the entire electro-optical modulation or frequency conversion process. Therefore, it is beneficial to integrate the functions of single-photon emission, electro-optical modulation, and frequency conversion on the same chip. LiNbO$_3$ material, however, cannot be directly used as a photon source, and therefore a hybrid integration technique is required to achieve the goal.

Here, we address this issue via proposing a novel heterogeneous integration platform in which single self-assembled InAs/GaAs quantum dots is transferred to the surface of a lithium niobate thin-film waveguide [26]. In order to realize the high-efficiency single-photon source, a tapered structure along with a Bragg mirror is especially designed to bridge the gap in the effective mode index between the GaAs and LiNbO$_3$ waveguides. Gold electrodes are also introduced at both ends of the LiNbO$_3$ thin-film waveguide to tune the split ratio of a directional coupler via applied voltage, which can be used to ensure that multiple photons in the same stream can be simultaneously routed to different spatial modes, and finally be efficiently coupled out through optimized LiNbO$_3$ gratings. Note that, in [27–29], only the laser source was reported and integrating other structures, the full integration, and optimization strategies of the entire chips have not been reported before.

2. Chip Design

The structure of the heterogeneously integrated photonic chip is illustrated in Figure 1a. It is composed of a single-photon source, a lithium niobate directional coupler, and fan-out grating couplers. As shown in the zoom-in inset, an InAs quantum dot is embedded inside a GaAs waveguide. The splitting of the single and double exciton fine structure of the InAs quantum dots is less than 5 $\mu$eV [30], indicating low-threshold single-photon emission can be realized at a wavelength of 920 nm. In addition, InAs quantum dots can achieve an emission efficiency greater than 90%, with the single-photon purity greater than 99% and the single photon indistinguishability greater than 90%. Since the band gap of GaAs is larger than that of InAs, limiting the electron-hole movement of InAs nanocrystals to a very small size (less than the De Broglie wavelength of InAs $\sim$40 nm). Therefore InAs/GaAs materials are used in order to generate photons at 900 nm wavelength. To boost the quantum efficiency, one end of the embedded GaAs waveguide is designed with a series of circular holes to form a highly reflective mirror, and the other end is a down-tapered structure to guide the generated photon to the LiNbO$_3$ substrate. A LiNbO$_3$ directional coupler is used to route the photons to different paths. The splitting ratio of the beam is adjustable via tuning the voltage. Different photons can be re-routed to the corresponding path by varying the voltage over time, and finally photons are fanned-out to a fiber lens by gratings. Such an integrated chip can be prepared by firstly depositing silicon dioxide on a silicon substrate, and then transferring a LiNbO$_3$ film onto the silicon dioxide. LiNbO$_3$ thin-film waveguides and grating couplers can be accurately fabricated by photolithography together with inductively coupled plasma (ICP) etching (Instruments from the State Key Laboratory of Optoelectronic Materials and Technology). Then, the GaAs waveguide with circular holes at one end is transferred to the surface of the LiNbO$_3$ thin-film waveguide by a substrate transferring technique [20] and the heterogeneous integration is formed by Van Der Waals is force. Gold electrodes are deposited on both ends.
of the waveguide to prepare a directional coupler. The method of imaging with electron multiplying charge coupled device (EMCCD) lens and coherence measurement via delay lines can be used to test the multiplexing of the generated photons.

Figure 1. (a) Schematic diagram of proposed InAs-GaAs-LiNbO$_3$ chip. Inset: zoom-in of the single photon source part integrating an InAs/GaAs quantum dot (QD), LiNbO$_3$ waveguide chip, and LiNbO3 directional coupler; (b) the cross-section view of the photon source part.

3. Simulation Results

3.1. The Single-Photon Source

Figure 1b shows a cross-section view of the single photon part composed of the GaAs waveguide, the LiNbO$_3$ waveguide, and the substrate. A shallow-etched LiNbO$_3$ waveguide was used to ensure the single-mode operation of the GaAs quantum dot at 920 nm, while maintaining a relatively large top surface area for transferring the GaAs waveguide. The LiNbO$_3$ waveguide is x-cut and is doped with MgO. Light propagation direction is along the y-axis. The light has been converted to TE mode, and the refractive index is 2.2444. A similar optimization strategy was reported by [20], the Bragg reflector at one end of the GaAs waveguide consists of a periodic array of holes with a period of 230 nm and a radius of 59.8 nm to ensure that the quantum dot emission only propagates in one direction. The detailed parameters of the optimized InAs embedded quantum dot are summarized in the Supplementary Information. The single-photon nature of the emission was experimentally confirmed by a photon coherence measurement [31].

A down-tapered structure was designed to achieve an efficiency mode conversion from GaAs waveguide to LiNbO$_3$ waveguide. We performed finite-difference time-domain (FDTD) simulations to estimate the efficiency of single-photon coupling. In our simulations, the quantum dot was modeled as a magnetic dipole emitter with planar polarization located at the center of the waveguide. The thickness of the SiO$_2$ substrate is 2.4 $\mu$m, and the thickness of the silicon layer is 7 $\mu$m. Figure 2b plots the simulated taper transmission at 920 nm versus the length of the taper ($L_{\text{taper}}$). It can be seen that the taper transmittance is close to unity when $L_{\text{taper}}$ is greater than 50 $\mu$m. A taper length of 50 $\mu$m was used in our design. Figure 2a plots the electric field distribution of GaAs and LiNbO$_3$ waveguide integrated chips at positions along the taper. The left-hand panel of Figure 2a shows the electric field ($|E|^2$) in the GaAs waveguide at coordinates $x = 0$, $y = 0$, and $z = 0$ (where the waveguide starts in Figure 1a). The middle panel of Figure 2a shows that when $x = 0$, $5 \mu$m < $y$ < 25 $\mu$m, $-1 \mu$m < $z$ < 1 $\mu$m, where the GaAs and LiNbO$_3$ waveguide are phase-
matched along the mode converter over a certain length, and the power is transferred effectively from GaAs to LiNbO$_3$ waveguide. Beyond the phase matching length, the tapering process shifts the phase matching condition, preventing energy from returning back to the top GaAs waveguide. The right-hand panel of Figure 2a shows that when $x = 0$, $y = 64 \, \mu m$ and $z = 0$, where the GaAs mode has been converted to LiNbO$_3$ mode. The simulation results clearly demonstrate the necessity of the tapered structure to form an efficient heterogeneously integrated chip.

![Figure 2](image-url)

**Figure 2.** (a) Simulated amplitude of electric field ($|E|^2$) of partial cross-sections of the light source under different x-coordinates. Left-hand ($x = 0, y = 0$, and $z = 0$), middle ($x = 0, 5 \, \mu m < y < 25 \, \mu m, -1 \, \mu m < z < 1 \, \mu m$), right-hand ($x = 0, y = 64 \, \mu m, z = 0$); (b) the transmittance of the directional coupler versus the taper length ($L_{tape}$). The dip at around $145 \, \mu m$ is induced by the limit in the numerical accuracy in the simulation; (c) the coupling efficiency of the GaAs taper to the LiNbO$_3$ waveguide with (red line) and without (black line) the Bragg mirror. The blue line represents the efficiency of waveguide mode coupling into lithium niobate.

To highlight the contribution of the Bragg mirrors formed by the 23 circular holes, Figure 2c shows the comparison of the ratio of the total dipole emission power of the quantum dot coupled to the GaAs mode with ($\beta_2$) and without ($\beta_1$) circular holes. Among them, the $\beta$ is the coupling coefficient of quantum dot to GaAs waveguide. It can be seen that $\beta_2 \approx 2\beta_1$. Once the quantum dot is coupled to the GaAs waveguide mode, it can further couple to the LiNbO$_3$ mode with close to unity efficiency regardless of the Bragg mirror. This is demonstrated as the blue line in Figure 2c, in which case $\eta_2 = \eta_1 \approx 1$. The overall efficiency of the single-photon source to the LiNbO$_3$ waveguide with the Bragg mirror is $\eta_1\beta_2 \approx 42\%$. The slight increase in $\beta_2$ at long wavelength is caused by the better mode matching between the quantum dot to the waveguide mode.

### 3.2. The Directional Coupler

Figure 3a,b illustrates the structure and the cross-section view of the designed LiNbO$_3$ directional coupler. The thickness and width of the waveguide for the directional coupler was set as 300 and 500 nm respectively, which is determined by the size and efficiency of the fan-out grating (see Section 3.3). The length of the coupling zone was $50 \, \mu m$, which is enough to cover a complete coupling cycle for the coupler. Gold electrodes deposited at
both ends of the LiNbO$_3$ waveguide were added to provide the external voltage. In the simulation, the gap between the LiNbO$_3$ waveguide and the electrodes was set as 2.75 $\mu$m and the etching depth is 140 nm. The effective refractive index of the LiNbO$_3$ waveguide mode can be controlled by the applied voltage [32]

$$\Delta n_{\text{eff}} = \frac{r_{33}n_{\text{eff}}^3V}{2d}$$

(1)

where $d$ is the width along the $z$ axis of the LiNbO$_3$ waveguide, $n_{\text{eff}}$ is the effective refractive index of the waveguide, $r_{33}$ is the electro-optic coefficient of LiNbO$_3$.

Figure 3a,b illustrates the structure and the cross-section view of the designed directional coupler. Figure 3c shows that an increase in the absolute value of the applied voltage induces a decrease in the refractive index. The change in the beam splitting ratio of the directional coupler versus $n_{\text{eff}}$ is plotted in Figure 3d, in which cross and bar represent, respectively, the exit port of the coupler corresponding to the curved and straight waveguides. Using the device parameters ($n_{\text{eff}} = 1.962$, $r_{33} = 32$ pm/V, and $d = 500$ nm), $V = 27.1$ V is required to switch the beam splitting ratio between the cross and bar ends of the coupler from 100:0 to 0:100, which can be used to route the photons to different paths. Note that the switching time of the directional coupler when tuning the voltage locates in the nanosecond range (i.e., with GHz modulation rate), which is comparable to the shortest time interval between the generated photons (around 13 ns reported in a comparable system) [18]. Moreover, the half-wave voltages, $V_{\pi}$, corresponding to the devices with 3 and 5 mm length are 7.4 and 5.1 V, giving a voltage-length product of 2.2 and 2.5 V.cm, respectively. This indicates that the required modulation efficiency is higher than conventional LiNbO$_3$ modulators (10 V.cm) [28]. An increase in the device length can further reduce the $V_{\pi}$ value of the proposed device.

3.3. The Fan-Out Grating Coupler

The structure of the focusing grating coupler is a fan-shaped structure, as shown in Figure 4a, which can be directly coupled to a fiber lens. When the guiding mode of the waveguide passes through the grating region, the radiation mode can be excited such that the guided modes transfer energy to the vertical above the grating through the diffracted
beam. The inset of Figure 4a shows the plots of the simulated coupling coefficient between adjacent couplers as a function of their gap. It can be seen that the mutual crosstalk between gratings can be effectively suppressed when the distance between adjacent gratings exceeds 0.6 μm. The spacing between adjacent grating coupler was set as 1.5 μm in our design. The pitch of the proposed grating coupler is limited by the sidewall angles of the processed and etched LiNbO₃ waveguide (~70 degrees [28]). Figure 4b displays the cross-section view of the grating coupler. Figure 4c,e shows, respectively, the change of the transmittance of the grating coupler with wavelength and etching depth calculated by finite-difference time-domain approach. It can be seen that the grating transmittance reaches maximum at 920 nm wavelength when the etching depth is 140 nm. The focusing grating coupler directly focuses light from a 10 μm wide LiNbO₃ waveguide onto a 500 nm wide waveguide. The detailed parameters of the grating coupler are listed in Table S1. The thickness of the underlying oxide has an important influence on the coupling efficiency. Figure 4d depicts the change in the grating transmission versus the thickness of the SiO₂ substrate. The periodic variation of grating transmission is mainly induced by the coherent interference between the local spatial modes formed by the boundary of the two materials. Therefore, the oxide thickness was chosen as 2.4 μm. Figure 4f shows the plots of the estimated coupling efficiency of the focusing grating coupler as a function of the relative angle between the fiber lens tip and the vertical direction (x-axis). In addition, the curve, shown in Figure 4g, is the variation of the grating transmittance with the gap. In reality, the fiber lens can be fixed above the grating using a six-dimensional motion stage, wherein the tilt angle can be precisely adjusted to optimize the coupling efficiency. It can be seen that a maximum efficiency of 49% can be achieved when the fiber tip is tilted by ~7°.

Figure 4. (a) Structure of the fan-out grating and fiber lens; (b) cross-section view of the multilayer structure of the grating simulated grating transmission versus (the y axis is perpendicular to the xz plane) (c) wavelength, (d) thickness of the SiO₂ substrate, (e) etching depth, and (f) relative angle of the coupling fiber with respect to the vertical direction; (g) the curve describes the variation of the grating transmittance with the gap.
4. Conclusions

The proposed heterogeneously integrated photonic chip can emit near-infrared single photons from the LiNbO$_3$ thin-film waveguide with high efficiency. The output photons can be directly coupled to the optical fiber. The proposed chip can be used to realize on-chip single-photon wavelength division multiplexing, laying a foundation for multiplexing multiple quantum dot light sources for quantum information processing, for example, for Boson sampling. The high quantum efficiency, thanks to the direct integration of single self-assembled quantum dots in the LiNbO$_3$ platform, will also benefit its application in the fields of on-chip high-speed single-photon switching, quantum routing, and nonlinear frequency conversion.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/cryst11111376/s1, the Supplementary Material contains Table S1. Table S1: Design parameters for the proposed quantum integration chip.

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