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Gallium arsenide (GaAs) quantum photonic waveguide circuits

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ABSTRACT

Integrated quantum photonics is a promising approach for future practical and large-scale quantum information processing technologies, with the prospect of on-chip generation, manipulation and measurement of complex quantum states of light. The gallium arsenide (GaAs) material system is a promising technology platform, and has already successfully demonstrated key components including waveguide integrated single-photon sources and integrated single-photon detectors. However, quantum circuits capable of manipulating quantum states of light have so far not been investigated in this material system. Here, we report GaAs photonic circuits for the manipulation of single-photon and two-photon states. Two-photon quantum interference with a visibility of $94.9 \pm 1.3\%$ was observed in GaAs directional couplers. Classical and quantum interference fringes with visibilities of $98.6 \pm 1.3\%$ and $84.4 \pm 1.5\%$ respectively were demonstrated in Mach–Zehnder interferometers exploiting the electro-optic Pockels effect. This work paves the way for a fully integrated quantum technology platform based on the GaAs material system.

1. Introduction

Quantum information science exploits fundamental quantum mechanical properties—superposition and entanglement—with the goal of dramatically enhancing communication security, computational efficiency and measurement precision [1–4]. Photons have been widely considered as an excellent physical implementation of quantum information and communication technologies due to their low decoherence, fast transmission and ease of manipulation [2,5]. Bulk optical elements including single-photon sources, single-photon detectors and linear optical circuits have been successfully utilized to experimentally demonstrate quantum communication protocols, quantum metrology and small-scale quantum computation [6–9]. However, this bulk optics approach has severe limitations in terms of circuit stability, complexity and scalability.

The emergence of integrated quantum photonics (IQP) is revolutionising the field of photonic quantum technologies [10]. Utilizing well-developed integration technologies of classical photonics, IQP can shrink quantum experiments from a room-sized optical table onto a coin-sized semiconductor chip, and therefore greatly reduce the footprint of quantum devices and increase the complexity of quantum circuits [5,10–24]. IQP inherently offers near-perfect mode overlap at an integrated beamsplitter for high-fidelity quantum interference [11,15] and sub-wavelength stability of optical path lengths for high-visibility classical interference [13,14], which are both essential to photonic quantum information processing. Recently, two-photon quantum interference with a visibility of $> 99\%$, controlled-NOT quantum gate with a fidelity of 96%, and manipulations of entanglement have been demonstrated in the integrated photonic circuits, based on various platforms such as silica-on-silicon [11–15], laser direct writing silica [17–19], lithium niobate [20–22], silicon-on-insulator [23,24], etc. Moreover, IQP would enable on-chip generation, manipulation and detection of quantum states of photons, ultimately required by practical and scalable quantum information processing technologies. Recently,

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progress also has been made towards integrated single-photon sources and waveguide single-photon detectors. Periodically poled lithium niobate (PPLN) waveguides and silicon wire waveguides are examples of integrated waveguide sources for the generation of photon pairs via spontaneous parametric down conversion (SPDC) and spontaneous four-wave mixing (SFWM) respectively [25,26]. High-efficiency waveguides superconducting nanowire single-photon detectors (SNSPD) also have been successfully demonstrated in gallium arsenide (GaAs) waveguides and silicon wire waveguides [27,28].

Here, we report a low-loss GaAs/$Al_{0.3}Ga_{0.7}As$ ridge waveguide platform for the manipulation of quantum states of light. GaAs is one of the most mature semiconductor materials widely used in classical integrated photonics. GaAs devices have been used for 100 GHz low-power modulation of optical signals [29] based on the strong electro-optical Pockels effect (driven by the large χ^2 nonlinear coefficient of the GaAs material) whose refractive index is linearly proportional to the applied electric field [30], and could provide a route to fast control and manipulation of photons for applications in quantum communication and quantum computation. Moreover, efficient on-chip single-photon sources have been developed based on semiconductor quantum dot embedded in the GaAs photonic crystal waveguides/cavities [31–37]. Spontaneous pair generation techniques have also been investigated using Bragg-reflection waveguides on GaAs platform to achieve the required phase-matching condition for spontaneous parametric down conversion [38–41]. GaAs waveguide integrated superconducting detectors have been demonstrated with efficiencies of 20% and short dead time of few ns [27], and photon number resolving capabilities [42]. Recently, photoluminescence from quantum dots has been coupled into the GaAs ridge waveguides and detected using the waveguide SNSPDs [43]. However, to-date no operations of photon's quantum states have been reported in the GaAs waveguide photonic circuits. Based on our GaAs waveguide platform, we demonstrate the ability to control and manipulate two-photon quantum states, demonstrating two-photon quantum interference in directional couplers and utilizing Mach–Zehnder interferometers (MZIs) controlled electro-optically using the Pockels effect to realize quantum interference fringes. This work demonstrates important functionalities required for a GaAs integrated quantum technology platform, and presents essential quantum components for controlling quantum states, opening the way to the monolithic integration of quantum dot/SPDC single-photon sources, quantum photonic circuits and waveguide SNSPDs on a single GaAs wafer.

2. GaAs waveguides and experimental setup

Fig. 1(a) shows the cross section of a GaAs/$Al_{0.3}Ga_{0.7}As$ ridge waveguide with a GaAs core and $Al_{0.3}Ga_{0.7}As$ bottom/top claddings. The refractive indices of the GaAs core and $Al_{0.3}Ga_{0.7}As$ claddings are 3.431 and 3.282 respectively, at the wavelength of 1550 nm. In order to meet the single-mode condition, the GaAs layer is etched down by 1.5 μm, forming the ridge waveguide with a width of 3.5 μm and a height of 3.9 μm. Fig. 1(a) also shows the simulated field distribution of the transverse electric (TE) fundamental mode using a finite difference mode (FDM) solver. Optical intensity distribution within the fabricated GaAs waveguide has been captured using an infrared CCD camera (Fig. 1(b)), which shows the single mode distribution.

The $Al_{0.3}Ga_{0.7}As$/GaAs/$Al_{0.3}Ga_{0.7}As$ layers which form the vertical waveguiding structure were alternately grown on top of a (100) GaAs wafer using molecular beam epitaxy. Note that a 100 nm-thin GaAs cap was also grown upon the top cladding to protect the $Al_{0.3}Ga_{0.7}As$ layer against oxidation, and the GaAs substrate under the bottom cladding was doped to reduce the contact resistance. The waveguide circuits were defined by photolithography, using a 50 nm nickel film hard mask and lift-off process. The GaAs layer was inductively coupled plasma (ICP) etched, and the remaining nickel was removed before the chip was planarized by refilling the etched area with lift-off resist. A 200 nm gold film was sputtered after a second photolithography step, and gold contacts were patterned on top of MZI's arms by the lift-off process. Finally, the chip was cleaved for optical fiber coupling and mounted onto a chip holder for electrical connection. Fig. 1(c) shows the Scanning Electron Microscopy (SEM) images of the GaAs waveguides. Directional couplers and MZIs were both fabricated in this waveguide platform. The measured nominal propagation loss and coupling loss (between waveguides and lensed-fibers with a 2.5 ± 0.5 μm spot-diameter) using the Fabry–Perot method [44] was 1.6 dB/cm and 1.5 dB/facet respectively.

Photon pairs at 1550 nm wavelength were generated via type-II SPDC in a periodically poled potassium titanyl phosphate (PPKTP) nonlinear crystal, pumped with a 50 mW continuous-wave laser at 775 nm wavelength (Fig. 2). Dichroic mirrors and a long-pass filter were used to separate the bright pump light from the photon pairs. Photon pairs with orthogonal polarization were separated by a polarization beamsplitter (PBS) and collected into two polarization-maintaining fibers (PMFs). Photons with horizontal polarization (corresponding to the TE mode of the waveguides) were coupled to the GaAs devices via two lensed single-mode fibers (lensed-SMFs), where the polarization orientation was corrected using two fiber polarization controllers for injection into the test devices. After the chip, photons were collected by two lensed-SMFs and detected using two single-photon detectors. Coincidences were recorded using a PicoHarp 300 Time Interval Analyzer (TIA). We used two different types of 1550 nm single-photon detectors: 1) two fiber-coupled superconducting single-photon detectors mounted in a closed cycle refrigerator with 1% and 4% efficiencies and ~1 kHz dark counts [45], used for the quantum interference experiment in the GaAs directional couplers

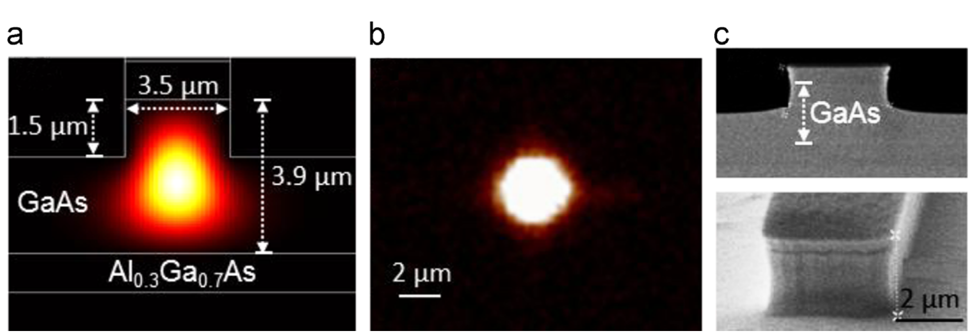

Fig. 1. (a) Cross section of the GaAs/$Al_{0.3}Ga_{0.7}As$ ridge waveguide and its simulated field distribution of the TE fundamental mode at 1550 nm wavelength, (b) measured intensity distribution of the TE fundamental mode at 1550 nm wavelength and (c) Scanning Electron Microscopy (SEM) images of the GaAs/$Al_{0.3}Ga_{0.7}As$ waveguide.