Hybrid III-V/Silicon photonic circuits embedding generation and routing of entangled photon pairs

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Abstract. Hybrid photonic devices, harnessing the advantages of multiple materials while mitigating their respective weaknesses, represent a promising solution to the effective on-chip integration of generation and manipulation of non-classical states of light encoding quantum information. We demonstrate a hybrid III-V/Silicon quantum photonic device combining the strong second-order nonlinearity and compliance with electrical pumping of the III-V semiconductor platform with the high maturity and CMOS compatibility of the silicon photonic platform. Our device embeds the spontaneous parametric down-conversion (SPDC) of photon pairs into an AlGaAs source and their subsequent routing to a silicon-on-insulator circuitry. This enables the on-chip generation of broadband telecom photon pairs by type 0 and type 2 SPDC from the hybrid device, at room temperature and with strong rejection of the pump beam. Two-photon interference with 92% visibility proves the high energy-time entanglement quality characterizing the produced quantum state, thereby enabling a wide range of quantum information applications..

1 Introduction

The demand for integrated photonic chips combining the generation and manipulation of quantum states of light is steadily increasing, driven by the need for compact and scalable platforms for quantum information (QI) technologies [1]. While photonic integrated circuits (PICs) with diverse functionalities are being developed in different single-material platforms, it has become crucial to realize hybrid photonic circuits harnessing the advantages of multiple materials while mitigating their respective weaknesses, resulting in enhanced capabilities. Among the available platforms, silicon, and more specifically silicon-on-insulator (SOI), stands out as one of the leaders in linear integrated photonics, thanks especially to its CMOS-compatible fabrication maturity [2]. Although nonlinear effects are accessible through its strong third-order susceptibility, it intrinsically lacks second-order nonlinearity; furthermore, its indirect bandgap hinders laser action. AlGaAs, on the other hand, features both strong second-order nonlinearity and direct bandgap, suitable for electrically injected photon-pair production [3], resulting perfectly complementary to silicon for the implementation of compact photonic chips for QI applications.

Here, we demonstrate a hybrid AlGaAs/SOI device operating at room temperature and embedding the generation by spontaneous parametric down-conversion (SPDC) of entangled photon pairs into an AlGaAs waveguide and their subsequent routing to a SOI circuitry, within a vertical adiabatic coupling scheme managing both polarization states.

2 Working principle and design

The working principle of our hybrid device is sketched in Fig. 1a: photon pairs, generated upon optical pumping in an AlGaAs waveguide (shown in shades of grey) are transferred to the SOI circuitry (blue) by evanescent coupling, preserving the properties of the produced quantum state. The AlGaAs source [4] is a nano-fabricated waveguide generating bi-photon states via SPDC: the pump beam is coupled into the waveguide and undergoes a down-conversion process, conserving the total energy. Bragg mirrors, obtained by tuning the aluminium concentration of the different AlGaAs layers, provide both a photonic bandgap confinement for the pump in the near-infrared range (NIR, ~ 775 nm) and total internal confinement for the produced photons in the telecom range (~ 1550 nm). Therefore, the pump and SPDC modes are characterized by different dispersion curves, allowing the phase-matching condition to be satisfied in the spectral range of interest. The source is designed to optimize the nonlinear conversion efficiency for two phase-matching processes: type 0 SPDC, where a TM polarized pump beam generates TM polarized photons, and type 2, where a TE pump beam generates orthogonally polarized photons. The hybrid structure is designed to achieve the adiabatic optical

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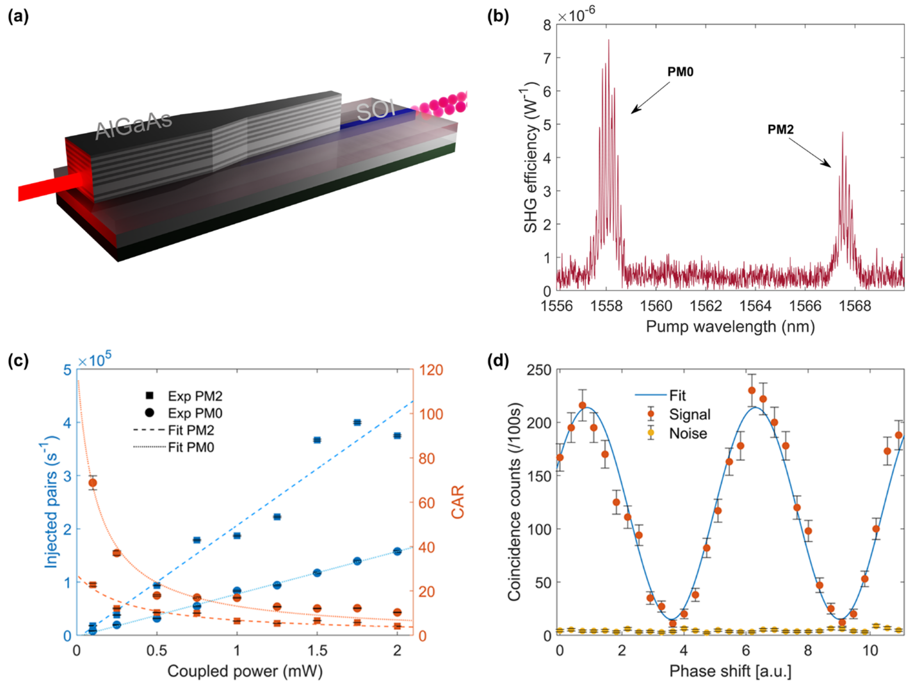

Figure 1. (a) Sketch of the hybrid structure (not in scale). (b) Measured type 0 and type 2 SHG in the hybrid device, as a function of the input laser wavelength. (c) Measured internal PGR (in blue) and CAR (in orange) as a function of the coupled optical power: circles for type 0, squares for type 2 phase-matching (PM) process; curve fittings help visualizing the expected trends. (d) Quantum interference pattern for the energy-time entanglement visibility measurement.

mode transfer from the AlGaAs waveguide to the silicon one, which are superimposed along the longitudinal direction corresponding to the mode propagation. The optical power transfer, for both TE and TM modes, is provided by a linear taper in the AlGaAs waveguide. The use of the described coupling design and of SPDC, where the pump and down-converted photons are well separated in frequency, allows an intrinsic filtering of the pump beam, by exploiting the natural absorbance of silicon.

3 Results and perspectives

The coupling design and the fabrication process of the hybrid device are validated by measuring the transmitted optical power in the telecom range, while its nonlinear response if verified through second harmonic generation (SHG) measurements. The result, displayed in Fig. 1b, shows that both type 0 and type 2 nonlinear processes are retrieved on the same chip with comparable efficiencies, and resonance wavelengths in the expected spectral range. In the quantum regime, both conversion processes are also accessible via SPDC, demonstrating the polarization versatility of the source. We estimate the number of photon pairs injected into the silicon waveguide to be $> 10^5$ pairs/s in both cases, with a coincidence-to-accidental ratio (CAR) up to $\sim 10^2$, as shown in Fig. 1c. The non-classicality of the emitted quantum state is characterized by an energy-time entanglement measurement, using a fibered Franson interferometer in the folded configuration. A 20 nm-large band-pass filter is used to narrow the signal bandwidth and reduce the contribution of the chromatic dispersion in the interferometer fibers. We obtain a net interference visibility of 93.8±3.1% for type 0 and 92.7±1.7% for type 2 (Fig. 1d), corresponding to a violation of the Bell inequalities by 7.4 and 12.9 standard deviations respectively, demonstrating the high entanglement quality of the produced photons and establishing the potential of the device for QI applications [6]. Notably, advanced protocols could be realized on-chip thanks to the maturity of the SOI platform, providing access to a wide variety of already demonstrated functionalities [5]. Combined with the possibility of electrical injection, these results open up the perspective of compact and standalone III-V/Silicon photonic circuits merging the assets of both platforms to progress towards out-of-the-lab implementations of QI protocols.

References

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