On-Chip Adiabatic Couplers for Broadband Quantum-Polarization State Preparation

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Abstract: We present a unique wavelength-dependent polarization splitter based on asymmetric adiabatic couplers designed for integration with type-II spontaneous parametric-down-conversion sources. The system can be used for preparing different quantum polarization-path states over a broad band.

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1. Introduction

Integrated quantum photonic circuits (IQPCs) have been the core technology in building the quantum network systems. $LiNbO_3$ is a promising platform for developing the IQPCs because of its many attractive features [1]. In particular, high-brightness polarization entangled photon pairs can be generated via type-II phase-matched spontaneous parametric down-conversion (SPDC) based on periodically poled lithium niobate (PPLN) waveguides [2]. Such photon pairs from a single waveguide, once generated, typically requires a polarization beam splitting in order to utilize the path degree of freedom. However, typically-used bulk polarization beam splitters (PBSs) are not the most ideal systems for this application, as the coupling from bulk to photonic chips leads to additional losses and unwanted complexity. To overcome these issues, one can introduce on-chip beam splitting for the integration with waveguide-based SPDC sources. However, $LiNbO_3$ waveguide-based beam splitters are typically designed for specific wavelengths, resulting in a very narrow acceptable band. Despite $LiNbO_3$-based broadband adiabatic couplers designed for integration with type-0/type-I SPDC sources have been proposed and demonstrated [3, 4], it still remains a problem on designing feasible beam splitters in a fully integrated manner for a type-II SPDC source.

In this work, we demonstrate an on-chip polarization beam-splitter based on $LiNbO_3$ asymmetric adiabatic couplers (AAC) designed for integration with a type-II SPDC source. The AAC plays roles of being a pump filter and a broadband PBS featured by a wavelength-dependent polarization splitting, which allows to separate the V- and H-polarized signal/idler modes spatially, and can prepare different two-photon quantum-polarization states.

2. AAC design and characterization and its application in quantum-polarization state preparation

We integrated two adiabatic coupling structures of slash and taper types, which forms an AAC, to demonstrate the wavelength and polarization spatial mode splitter in the telecom band. Figure 1(a) shows the design configuration of the AAC composed of 7 waveguides (No. 1 to 7) with a device length of L_{AAC}. Here the slash and taper sections are with the length of L_{slash} and L_{taper}, respectively. There are one input port and three output exits (*L*, *C*, and *R* in Fig. 1(a)). Per the different coupling conditions of two cross-polarized modes, we designed in a way that the first section (with slash waveguides) of the AAC maintains 1480-nm V-polarized signals and 775-nm H-polarized pump in waveguide 1 and in the meanwhile maximizes the power of 1627-nm H-polarized idlers transferred to waveguide 5, which then leaves the device from exit R. By engineering accessible geometric parameters of waveguides, one can tailor the adiabaticity and therefore the splitting ratio spectrum that depends both on frequency and polarization. We utilize the Beam Propagation Method to simulate the output performance and confirm the optimal parameters of the AAC. The AAC parameters used in this work are L_{AAC}=51 mm; L_{slash}=30 mm; L_{taper}=15 mm; S_1=3 μm; S_2=8 μm; S_3=11 μm; S_4=10 μm; S_5=10 μm; S_6=14 μm; G_1=18 μm; G_2=67 μm; W_1=7 μm; W_2=5 μm. The AAC device was then fabricated in a 51-mm-long *z*-cut $LiNbO_3$ chip using the titanium thermal diffusion method. The polarization- and wavelength-dependent splitting ratios of the AAC were characterized by a cw laser tunable from 1495 to 1600 nm, as shown in Fig. 1(b) (solid circles), which is highly consistent with simulation predictions (made in a broader wavelength range). Specifically, the stars mark the wavelengths (1631 and 1477 nm) where the V- and H- modes are equally split to the two exits, in which the AAC can be utilized as a 50/50 non-polarizing beam splitter for photon pairs generated via type-II SPDC with an H-polarized 775 nm pump.

The non-trivial dependence of the splitting ratio of the AAC on polarization and wavelength allows for practical applications in controlling the quantum-polarization states. For photon pairs generated via type-II phase-matched waveguides and launched into an arbitrary beam splitter with exit paths ***a*** and ***b***, one can end up with a state described by $|\Psi\rangle = \alpha(|H\rangle_a |V\rangle_b) + \beta(|V\rangle_a |H\rangle_b) + \gamma(|H\rangle_a |V\rangle_a) + \zeta(|V\rangle_b |H\rangle_b)$. Here we focus on the cross-correlation between paths ***a*** and ***b***, where we can define a preparation efficiency as $\eta = |\alpha|^2 + |\beta|^2$. Figure 2(a) shows the simulated quantum polarization state preparation efficiency in frequency domain. The black line is the type-II phase-matched SPDC photon-pair tuning curve under an H-polarized 775 nm pump. We can reach different positions along the black line by varying the phase-matching condition (via, e.g., temperature) of the SPDC waveguide, where the quantum-polarization state through the polarization- and wavelength-dependent AAC will change accordingly. Figures 2(b)-2(d) show the simulated density matrices for the SPDC source when working with the unique AAC and operated at three phase-matched conditions for the V-polarized signal wavelengths at 1480, 1631, and 1790 nm, corresponding to those positions marked by blue circle, star, and triangle in Fig. 2(a), respectively. The results imply one can control/tune the quantum states by simply tuning the phase-matching condition of the SPDC over a broad band under the same pump wavelength without installing extra components or modulation mechanisms. The result shown in Fig. 2(c) suggests a unique working condition in which the type-II SPDC source can be possible to generate a Bell's state (a polarization-path entangled state with a fidelity of ~0.964) when working with the AAC [5].

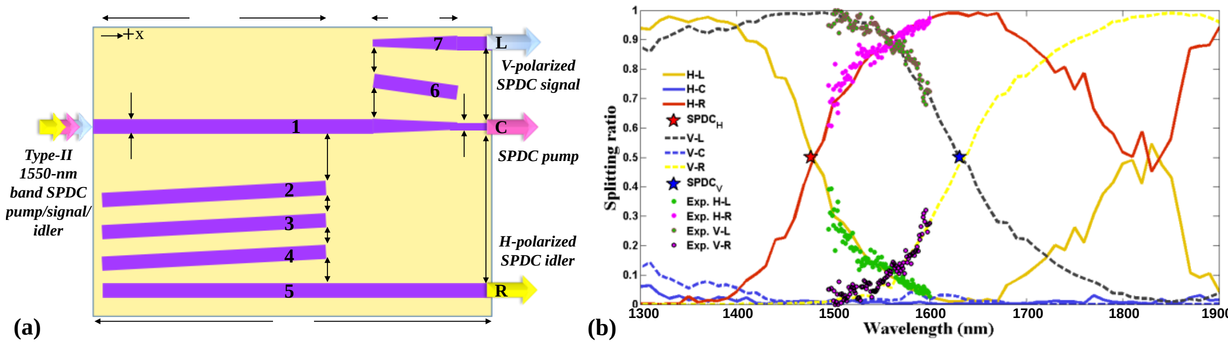

Fig. 1 (a) The schematic diagram of the asymmetric adiabatic coupler (AAC). (b) Measured (solid circles) and simulated wavelength-dependent splitting spectra of the AAC for V- and H-polarized fundamental modes (solid and dashed lines, respectively), where the stars mark 50%/50% splitting ratios on two special wavelengths at V-polarized 1631 nm and H-polarized 1477 nm, exactly a photon pair generated via a type-II SPDC when pumped by an H-polarized 775 nm laser.

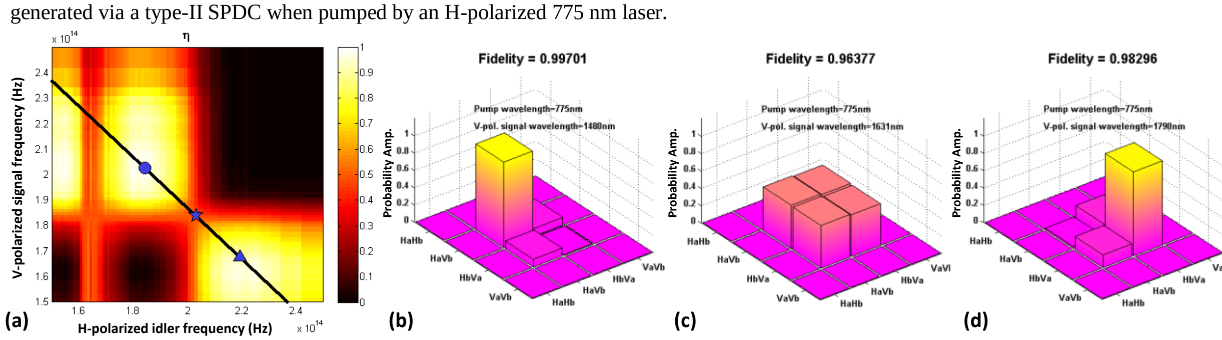

Fig. 2 (a) Simulated quantum polarization state preparation efficiency in frequency domain. The black line is the type-II phase-matched SPDC photon-pair tuning curve under an H-polarized 775 nm pump. (b), (c), and (d) are the simulated density matrices for a 775-nm pumped QPM type-II SPDC source when working with the AAC for phase-matched V-polarized signals at 1480, 1631, and 1790 nm (corresponding idlers at 1627, 1477, and 1367 nm), respectively.

3. Conclusion

We have developed a polarization splitter based on $LiNbO_3$ AAC designed for integration with a type-II SPDC source. Our experimental measurements reveal unique polarization beam-splitting regime with the ability to tune the splitting ratios based on wavelength. In particular, we measured a splitting ratio of 17 dB over broadband regions (>60 nm) for both H- and V-polarized lights and a specific 50%/50% splitting ratio for a cross-polarized photon pair from the AAC. The results show that such a system can be used for preparing different quantum polarization-path states that are controllable by changing the phase-matching conditions in the SPDC over a broad band.

4. References

1. S. Bogdanov et al., "Material platforms for integrated quantum photonics," Opt. Mater. Express **7**, 111-132 (2017).
2. T. Suhara, "Generation of quantum-entangled twin photons by waveguide nonlinear-optic devices," Laser Photonics Rev. **3**, 370-393 (2009).
3. C. W. Wu et al., "Photon pair generation and pump filtering in nonlinear adiabatic waveguiding structures," Opt. Lett. **39**, 953-956 (2014).
4. H. P. Chung et al., "Adiabatic light transfer in titanium diffused lithium niobate waveguides," Opt. Express **23**, 30641-30650 (2015).
5. H. P. Chung et al., "Asymmetric adiabatic couplers for fully-integrated broadband quantum-polarization state preparation," Sci. Rep. **7**, 16841 (2017).