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Towards on-chip photon-pair bell tests: Spatial pump filtering in a $LiNbO_3$ adiabatic coupler

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Nonlinear optical waveguides enable the integration of entangled photon sources and quantum logic gates on a quantum photonic chip. One of the major challenges in such systems is separating the generated entangled photons from the pump laser light. In this work, we experimentally characterize double-N-shaped nonlinear optical adiabatic couplers designed for the generation of spatially entangled photon pairs through spontaneous parametric down-conversion, while simultaneously providing spatial pump filtering and keeping photon-pair states pure. We observe that the pump photons at a wavelength of 671 nm mostly remain in the central waveguide, achieving a filtering ratio of over 20 dB at the outer waveguides. We also perform classical characterization at the photon-pair wavelength of 1342 nm and observe that light fully couples from an input central waveguide to the outer waveguides, showing on chip separation of the pump and the photon-pair wavelength. *Published by AIP Publishing.* https://doi.org/10.1063/1.5008445

Entangled and correlated photons enable a wide range of applications, including quantum computation,[1] communication,[2] spectroscopy,[3,4] and other quantum measurements.[5] Spontaneous parametric down-conversion (SPDC) and spontaneous four-wave mixing (SFWM), processes for the generation of photon pairs which are based on optical nonlinearity, are currently the leading approaches for the generation of entangled photons.[6]

Integrating optical elements onto a single chip reduces the contact with the environment, which is highly useful in quantum optics, since it reduces unwanted disturbances.[7] Integrated devices are also compact and stable, and so, they can be combined to build complex quantum circuits that otherwise would be too large to assemble in bulk. On-chip SPDC and SFWM have been realized in a wide range of systems, including waveguides and resonators,[8] using various materials, such as periodically poled lithium niobate (PPLN), AlGaAs, silicon on insulator (SOI), chalcogenide and Hydex glasses, and others.[9] Recently, various types of entanglement have been shown on a chip, including spectral,[10] time-bin,[11] time-energy,[12] and path[13–15] degrees of freedom. Path entanglement is particularly useful for on-chip implementation since coupling between the waveguides allows the realization of quantum logic for photonic circuits regardless of their polarization and dispersion properties, enabling the creation of quantum gates,[7] quantum walks,[16,17] and quantum teleportation.[18]

One of the key issues when generating photon pairs on a chip through SPDC or SFWM is filtering out the pump. Off chip[19] and in fibers,[14] one can use spectral filters, but pump filtering on a chip is more challenging since it requires advanced fabrication. The main two reasons why on-chip pump filtering is important are to prevent photon-pair generation in the unwanted parts of the circuit and to enable integration with on-chip single-photon detectors. Currently, filtering on a lithium niobate ($LiNbO_3$) chip is limited to 30 dB, while demanding highly precise fabrication.[15] Utilizing photonic crystals[20] might boost the suppression to 40 dB, but fabrication requirements become even more stringent. Multi-stage systems allow filtering of 95–100 dB in complex cascades of lattice filters[21] or multiple electrically tunable ring resonators integrated with a distributed Bragg reflector.[22] All the above approaches are also typically limited in the spectral bandwidth to several nm.

Wu *et al.*[23] proposed an optical waveguide structure that combines the generation of Bell states (maximally entangled states useful in quantum optics) with broadband pump filtering on a single chip. This waveguide structure consists of two central waveguides that are pumped with red laser light and two N-shaped couplers for pump light filtering (Fig. 1). The two central waveguides 3 and 4 can realize, under the right conditions, reconfigurable photon-pair path-entangled Bell-state generation.[19] This uses a pump wavelength of 671 nm propagating as a TE mode, which generates photon pairs through SPDC at 1342 nm propagating as a TM mode. The birefringent phase-matching can be achieved by heating the $LiNbO_3$ crystal to 380 °C. The switching between different Bell states can then be controlled by adjusting different parameters, such as the pump phase profile and device temperature[19] or pump wavelength.[13]

When two N-shaped couplers are combined with two central waveguides as illustrated in Fig. 1, the pump laser light remains in the central waveguides 3 and 4, while the generated

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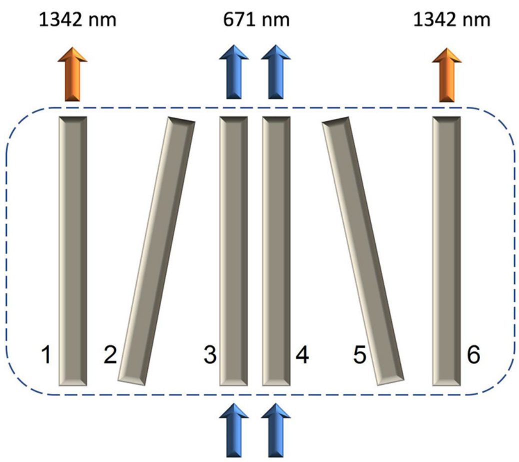

FIG. 1. Schematic of a 6-waveguide structure for tunable generation of spatially entangled photon-pair Bell states and simultaneous pump filtering. The pump laser with $\lambda_{\mathrm{pump}} = 671$ nm remains in two central waveguides 3 and 4, while the generated photon pairs with $\lambda_{\mathrm{SPDC}} = 1342$ nm are coupled to the edge waveguides 1 and 6.

photon pairs couple to the edge waveguides 1 and 6 via adiabatic passage.[24] Compared to standard directional coupling, adiabatic passage coupling works in a very broad wavelength range and is highly resistant to fabrication imperfections.[25]

In this work, we have fabricated and experimentally characterized a complete 6-waveguide structure (Fig. 1) and assessed its ability to perform pump filtering. We demonstrate 20 dB pump filtering, while operating in the adiabatic regime tolerant to fabrication imperfections. Even though by itself this filtering ratio is not sufficient for quantum optical applications, we anticipate that using it in a cascaded regime similar to other approaches[21] will provide sufficient filtering capacity. The waveguide structure is fabricated by photolithographically patterning Ti stripes with a thickness of 70 nm on the surface of an x-cut $LiNbO_3$ wafer. The widths of waveguides are slightly tapered to compensate for the Ti sideway diffusion of the converging waveguides.[24] The titanium stripes are orientated along the crystallographic y-direction. The titanium is diffused into $LiNbO_3$ in a wet oxygen atmosphere at 1010 °C for several hours. After the diffusion, the wafer is diced into 5 cm long chips and the chip end faces are polished to optical grade. The distance between the centers of waveguides 3 and 4 is 21.5 μm, the shortest distance between the centers of the tilted waveguides 2 and 5 and the corresponding straight waveguides is 7 μm, and the waveguides 2 and 5 are tilted at 0.0183° with respect to the straight waveguides.

Light propagation in such waveguiding structures can be modeled through the coupled supermode equations[26]

$$\frac{\mathrm{d}b_j}{\mathrm{d}z} - i\beta_j b_j = \sum_k C_{kj} b_k, \tag{1}$$

$$C_{kj} = \sqrt{\frac{\epsilon_0}{\mu_0}} \frac{k_0}{4} \frac{1}{\beta_k - \beta_j} \int_A e_k^* e_j \frac{\partial (n^2)}{\partial z} \mathrm{d}x\mathrm{d}y. \tag{2}$$

Here, β_j and β_k are the supermode propagation constants, C_{kj} are the coupling coefficients, z is the propagation distance, $j,k = \{1,2,3,4,5,6\}$ and $j \neq k$, ϵ_0 are the vacuum permittivity, μ_0 is the vacuum permeability, $k_0 = 2\pi/\lambda$ is the wavenumber in free space, e_j and e_k are the electric fields of the orthonormalized supermodes, $n(x,y,z)$ is the refractive index distribution, and the integration is performed over the mode structure transverse cross-section A. Then, the adiabatic condition for coupling from the central to the edge waveguides[24] is

$$|C_{kj}| \ll |\beta_k - \beta_j|. \tag{3}$$

The dependencies of the supermode effective refractive indices $n_j^{eff} = \beta_j/k_0$ along z are shown in Fig. 2. At the SPDC wavelength of 1342 nm, the pairs of TM-mode propagation constants (1,2), (3,4), and (5,6) remain far enough from each other [Fig. 2(a)] such that the adiabatic condition Eq. (3) is satisfied along the whole structure. This behavior should lead to over 90% adiabatic coupling of the photon pairs generated in the central waveguides to the edge waveguides. In contrast, the TE supermodes at the pump wavelength of 671 nm overlap strongly in the middle of the structure, 15 mm < z < 30 mm [Fig. 2(b)], which breaks the adiabatic condition Eq. (3) and should prevent the light from effectively coupling from the central to the edge waveguides. The magnitude of this effect can be hard to predict based on only the degree to which the adiabatic condition is broken and can be supplemented with the individual mode analysis.

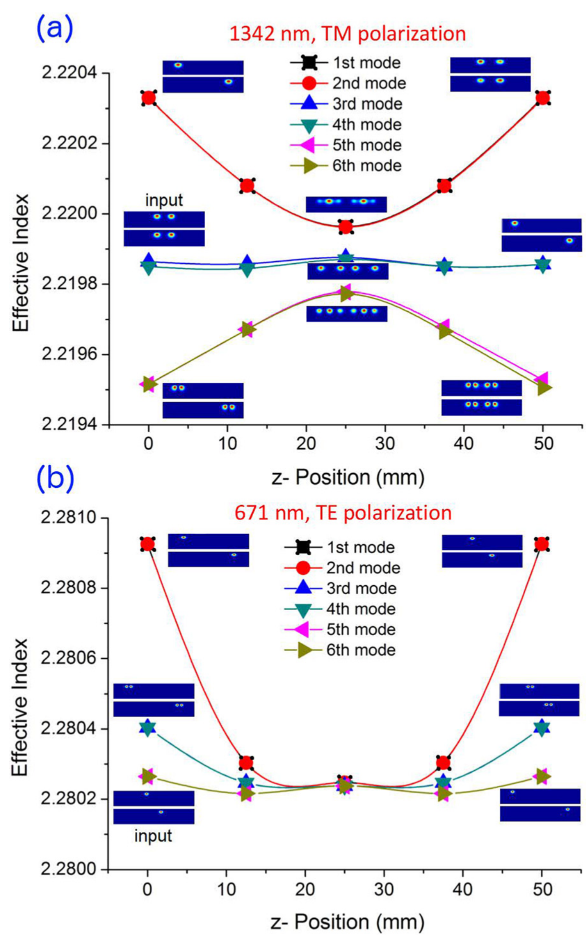

FIG. 2. Effective refractive indices of the supermodes vs the propagation distance along z for (a) TM polarization at the degenerate SPDC wavelength $\lambda_{\mathrm{SPDC}} = 1342$ nm and (b) TE polarization at the pump wavelength $\lambda_{\mathrm{pump}} = 671$ nm. The insets show the corresponding mode profiles at various points along z.

In terms of individual waveguide modes, if the waveguides are far enough from each other compared to the mode size at the middle of the structure, then we should expect the central waveguides not to be coupled to the edge waveguides. In our case, the degree of this decoupling is expected to be over 95%.

We test the coupling at 671 nm for TM polarization [Figs. 3(a) and 3(b)] and 1342 nm for TE polarization [Figs. 3(c) and 3(d)] both numerically and experimentally. The simulation results are obtained using a BPM method (Rsoft BeamPROP), with the light launched at $z = 0$ into the left central waveguide 3 and propagating for 5 cm [Figs. 3(a) and 3(c)]. Experimentally, the fabricated waveguides are optically characterized by coupling a laser with the corresponding wavelength into one of the central waveguides. The polarization of the 671 nm wavelength laser is set to TE so that it experiences the extraordinary refractive index, while the polarization of the 1342 nm wavelength laser is set to TM to mimic the generated photon pairs.[19] The filtering ratio of the inner to the outer waveguides is determined by imaging the chip end face using an objective lens and two cameras—a CCD camera for 671 nm and an InGaAs camera for 1342 nm [Figs. 3(b) and 3(d)].

Both the simulation and the experiment show that the pump light at 671 nm remains confined in the center [Figs. 3(a) and 3(b)], without coupling to the edge waveguides. The experimental extinction ratio determined as intensity in the edge waveguides divided by intensity in the central waveguides is 20 dB. The adiabatic transfer from the central waveguides to the edge waveguides of over 97% is achieved for the degenerate SPDC wavelength of 1342 nm [Figs. 3(c) and 3(d)]. We have also confirmed that using the right central waveguide instead of the left central waveguide does not change the performance.

To summarize, this approach to integrated pump filtering is a simple and straightforward way to separate the pump from the generated photons. It does not rely on precise fabrication[20] or tunability[22] and is expected to be broadband.[25] Whereas a single adiabatic coupler only provides limited filtering, a stack of such couplers, similar to other cascaded approaches,[21,22] might be able to provide pump extinction in excess of 100 dB, which can be an interesting topic of study in the future. Furthermore, as the particular implementation using titanium indiffused waveguides in lithium niobate is not very compact, it will be important to investigate whether waveguiding structures based on high-index-contrast waveguides[21,27] allow substantial reductions of the system dimensions while retaining the adiabatic filtering properties.

For the demonstrated structure to generate Bell states, the coupling strength between the individual waveguides should satisfy certain conditions. The possibility of tunable Bell state generation in a 2-waveguide coupler was shown in Ref. 19, where the structure length was equal to one half-beat coupling length, while in this work, the structure length is two half-beat coupling lengths. In this view, the adiabatic condition is important to satisfy for the generated biphotons not only to enable pump filtering but also to ensure that the generated biphotons are coupled between the central waveguides for the appropriate propagation length and then coupled out to the edge waveguides in the middle of the structure as shown in Fig. 3(c). This arrangement is predicted to enable efficient Bell state generation.[23] A slight drawback of this configuration is that only 50% of the length is utilized for usable photon-pair generation, while the photon pairs generated in the second half of the structure remain with the pump.

Combined with previous research showing that adiabatic coupling remains broadband in imperfect structures,[25] this system may be useful as a quantum source when integrated

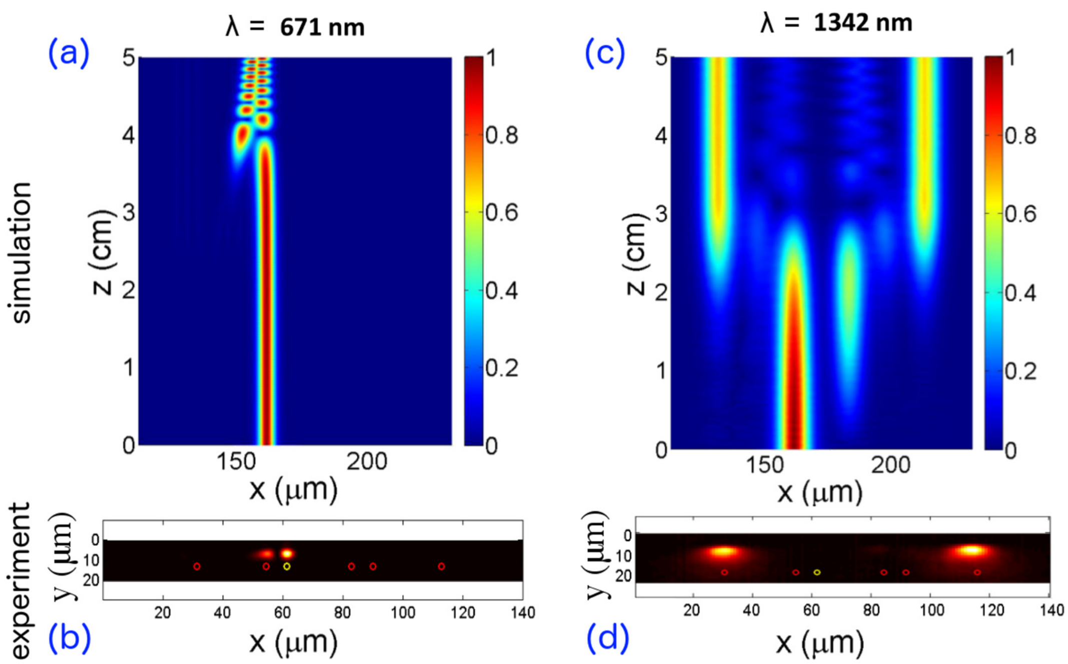

FIG. 3. (a), (c) Numerical simulation of light propagation and (b) and (d) experimental images of light leaving the end-facet of the waveguide chip. Circles in the experimental images indicate the positions of the waveguide outputs: yellow circles show the pumped waveguide and red circles show the other waveguides. (a) and (b) TE-polarized light at 671 nm remains in the central waveguides. (c) and (d) TM-polarized light at 1342 nm couples to the edge waveguides.

with on-chip logic[7] and detection.[28] It is expected to open new possibilities for quantum photonic device development with a variety of applications.

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