Broadband On-Chip Adiabatic-Coupling Polarization Mode Splitters in Lithium Niobate Waveguides

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Abstract: We report the first broadband (>120 nm at >97% splitting efficiency for both polarization modes) polarization mode-splitter in $LiNbO_3$ adiabatic light-passage configuration. This device can facilitate the on-chip implementation of pump-filtered, broadband tunable Bell-state generators.

OCIS codes: (130.2790) Guided waves; (230.3120) Integrated optics devices; (130.5440) Polarization-selective devices

1. Introduction

Broadband waveguide couplers are in demand for important applications in especially optical communication and networking systems. In particular, the development of broadband polarization splitters has received much attention as wavelength-independent polarization control has become an important optical processing function in integrated optical and emerging quantum optical circuit technologies [1]. $LiNbO_3$ is a popular material for building various integrated optical circuits/devices because of its versatility derived from its excellent electro-optic (EO), acousto-optic, nonlinear-optic, and piezoelectric properties with wide optical transparent range (~0.4-5 μm). Polarization mode splitters (PMS) have been implemented in $LiNbO_3$ waveguides, however, besides their limited operating bandwidths, the implementation of high polarization-extinction-ratio (PER) devices relies on a careful engineering of the waveguide configuration or more often involves a more complex fabrication procedure [2].

In this work, we demonstrate the first PMS based on adiabatic directional coupling mechanism in $LiNbO_3$. The novel device exhibits the broadest bandwidth ever reported in $LiNbO_3$ based PMS. The advance of adiabatic coupler technology especially in the $LiNbO_3$ platform creates advantageous photonic elements that feature a high fabrication tolerance, high power coupling efficiency, and broad operational bandwidth, beneficial to readily apply them to, e.g., integrated optical and quantum photonic circuits on a chip.

2. Device design and characterization and its application in quantum photonic sources

In this work, we develop an achromatic (wavelength-independent), high-PER PMS based on a $LiNbO_3$ adiabatic waveguide scheme and show its potential application on on-chip implementation of a broadband tunable entangled quantum-state generator. Figure 1(a) shows the schematic of such a waveguide system in Ti:$LiNbO_3$ that integrates two adiabatic directional couplers with one in the front section being a five-waveguide structure ($\boldsymbol{AC1}$) and the other one located downstream being a three-waveguide "shortcut to adiabaticity" structure ($\boldsymbol{AC2}$). $\boldsymbol{AC1}$ and $\boldsymbol{AC2}$ perform broadband adiabatic light transfer for TE- and TM-polarized fundamental modes, respectively, spanning telecom S, C, and L bands. The methodology used in this work for the study and design of an adiabatic waveguide system resembles that presented in our previous reports [3, 4]. The optimum structure parameters of the waveguide system in Fig. 1(a) are first determined according to the adiabatic conditions [3] served as a guideline for reaching a high adiabaticity (the process is termed as "adiabaticity engineering") and the system configuration is then confirmed by examining the mode evolution in the system simulated using the "Beam Propagation method" (BPM) [5]. The derived structure parameters are labeled in Fig. 1(a). Figure 1(b) shows the simulated evolutions of the wave intensity in this integrated adiabatic waveguide PMS (IAPMS) for a TE (or H)-polarized 775-nm pumped, 1550-nm TM (or V)- and TE (or H)-polarized signal and idler spontaneous parametric down-conversion (SPDC) process. It clearly shows the spatial splitting of the three modes is successfully achieved.

We fabricated the IAPMS device in a 51-mm long, 10-mm wide, and 0.5-mm thick z-cut $LiNbO_3$ chip mainly using the titanium thermal diffusion technique. The measurement of the fabricated IAPMS device was performed in an optical testbed using a linearly-polarized external cavity laser (ECL) tunable between 1495 and 1640 nm as the light source and a photodetector and an infrared CCD as the output power and mode profile measurement system. Figures 2(a) and 2(b) show the measured and calculated normalized output powers from the three output ports of the $LiNbO_3$ IAPMS as a function of wavelength for TE- and TM-polarized modes, respectively. The experimental data outside the ECL tuning range were obtained with distributed feedback laser diodes of different wavelengths. The measured data is in good agreement with the simulation prediction, showing a high splitting efficiency (>97%) over a broad bandwidth of >120 nm (1510-1630 nm) and >170 nm (1480-1650 nm) for the TM and TE polarization modes, respectively. Moreover, the unique device has a broad transmission band for the TE-polarized pump throughout the waveguide ***a*** (>20dB pump filtering between 750-850 nm), as the calculated data shown in Fig. 2(c).

The IAPBS can be further integrated with a type-II periodically poled lithium niobate (PPLN) SPDC pumped by a laser tunable around 775 nm and works as a pump filter besides working as a signal and idler mode splitter for doing the timing compensation on chip. The results in Fig. 2 imply that such an on-chip scheme (IAPMS integrated with SPDC in $LiNbO_3$) can realize a pump-filtered, broadband tunable Bell-state generator as the generated signal and idler pair photons and the corresponding pump photons from the SPDC source can now be processed in a spectral band within the broad working bandwidth of the IAPBS. For example, the polarization-entangled Bell state, $|\Psi^{\pm}\rangle = (1/\sqrt{2})(|H_A(\lambda)\rangle|V_B(\lambda)\rangle \pm |V_A(\lambda)\rangle|H_B(\lambda)\rangle)$ (probabilistically (50%)) can be generated in a broad signal/idler (degenerate case) wavelength range, tunable via tuning the pump wavelength and/or the quasi-phase-matched condition (via, e.g., temperature) of the PPLN source, where the subscripts *A* and *B* label the photons entering the paths ***A*** and ***B*** after a non-polarizing beam splitter in a coincidence measurement setup followed by the IAPBS.

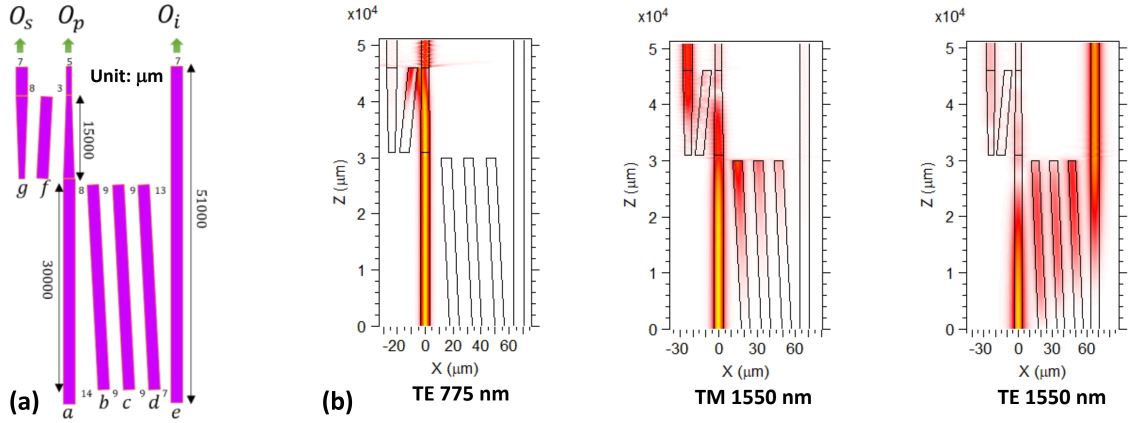

Fig. 1 (a) Schematic of the integrated adiabatic waveguide polarization beam splitter (IAPMS) in Ti:$LiNbO_3$, comprising two adiabatic directional couplers. (b) Simulated evolutions of the wave intensity in IAPMS for TE (or H)-polarized pump at 775 nm, TM (or V)- and TE (or H)-polarized signal and idler waves at 1550 nm.

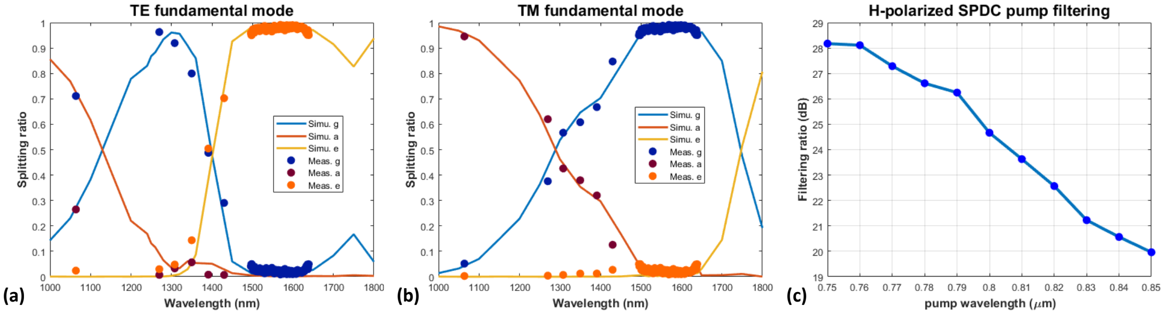

Fig. 2 Measured and calculated normalized output powers from the three output ports of the $LiNbO_3$ IAPBS as a function of wavelength for (a) TE- and (b) TM-polarized modes. (c) Calculated filtering ratio for the TE-polarized pump throughout the waveguide ***a***.

3. Conclusion

We have designed and realized a broadband polarization mode splitter based on an integrated adiabatic waveguide system cascading a five-waveguide and a three-waveguide "shortcut to adiabaticity" structures for performing adiabatic light transfer of TM- and TE-polarized (signal and idler) fundamental modes to two different output ports in a broad bandwidth of >120 nm (1510-1630 nm) and >170 nm (1480-1650 nm), respectively, at a high splitting efficiency of >97%. The IAPBS device, when integrated with a type-II PPLN SPDC, can thus facilitate the implementation of a broadband tunable maximally-entangled quantum source on-chip.

4. References

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