Supplementary Information

Integrated subwavelength gratings on a lithium niobate on insulator platform for mode and polarization manipulation

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**Abstract:** In this Supplementary Information document more details are provided on (S1) design consideration of the TM-pass polarizer, (S2) design and experimental results of the reference device consisting of TE0-TE1 MMUXs for TE1-mode-pass filter, (S3) design and experimental results of the reference device consisting of TE0-TE1-TE2 MMUXs for TE2-mode-pass filter, (S4) design and experimental results of the reference device consisting of PSRs for TM-pass polarizer, (S5) a comparison of some reported mode filters on different material platforms, (S6) schematic diagram of the experimental setup.

**S1.** **Design considerations of the TM-pass polarizer**

The TM-pass polarizer is designed along the crystallographic Y direction of lithium niobate for a relatively strong confinement of TM0 mode in the hybrid SWG waveguide, compared with that along the crystallographic Z direction. Figure **S1**a shows the calculated mode effective indices as a function of SWG width in the Z-propagating SWG waveguide with a *ff* of 0.8. It can be seen that TM0 mode has become an unguided mode which can suffer from large propagation loss, as the effective index of the TM0 waveguide mode is lower than that of the TE slab mode.

However, mode hybridization between TM0 and TE1 modes has been demonstrated successfully in our previous work1, which can occur when the waveguide transitions between different widths along crystallographic Y direction, resulting in excess loss. Thus, the structural parameters of SWGs should be considered carefully to aviod the mode hybridization widths. The mode effective indices as a function of silicon nitride width in Y-propagating waveguide are shown in Figure **S1**b. It indicates that the TM0 and TE1 modes hybridize in a Y-propagating waveguide with a silicon nitride width of 2.1 μm. To achieve low-loss propagation of TM0 mode, the SWG width should be far away from the mode hybridization width. Thus, we choose a relatively large *ff* of 0.8 in this work to reduce the minimum SWG width required for TM0 transmission. The calculated mode effective indices as a function of SWG width in the Y-propagating SWG waveguide are shown in Figure **S1**c. However, we found that the TM0 mode is still cutoff below a width of 1.95 μm which is very close to the mode hybridization width, and thus, mode hybridization can occur in the taper waveguide connecting the SWG waveguide and normal waveguides. Thus, a 100-nm-wide nanobridge is designed to further improve the mode effective indices. It can be seen from Figure **3**b that the minimum width required for TM0 transmission moves to about 1.75 μm. Finally, the SWG width is chosen to be 1.8 μm, which is far away from the mode hybridization width.



**Fig. S1**. **Design considerations of the TM-pass polarizer.** Calculated mode effective indices in **a** Z-propagating SWG waveguide with a *ff* of 0.8, **b** Calculated mode effective indices in Y-propagating normal waveguide and **c** Y-propagating SWG waveguide without a nanobridge.

**S2.** **Design and experimental results of the reference device for TE1-mode-pass filter**

The reference device consists of two asymmetric directional coupler (ADC)-based TE0-TE1 MMUXs with the same structural parameters as that in the proposed device for TE1-mode-pass filter measurements. Figure **S2**a shows a top view of the reference device, with the structural parameters indicated. The mode effective indices as a function of silicon nitride width in Z-propagating waveguide are shown in Figure **S2**b. The ADC-based MMUXs have been designed to satisfy the phase-matching condition. The width of single-mode waveguides is chosen to be *w*0’=0.8 μm, and the corresponding width of the wider waveguide supporting TE1 mode is *w*1’=2.163 μm. The single-mode and wider waveguides are connected by using linear taper waveguides with a length of 100 μm. The coupling gap is designed to be *g*=300 nm, and the coupling length is optimized to be *L*1=4 μm, including the effects of the bending waveguides with a radius of *R*=150 μm. Figure **S2**c shows the measured transmission spectra of the reference device. The results have been normalized by the transmission of reference straight waveguide fabricated closely, as shown in Figure **4**a. The measured insertion losses of TE0 and TE1 modes are lower than 2.1 dB, and the inter-modal crosstalk is lower than -23 dB, for a wavelength range of 1500-1580 nm.



**Fig. S2**. **Design and experimental results of** **TE0-TE1 MMUX.** **a** Top view of the reference device consisting of TE0-TE1 MMUXs. **b** Calculated mode effective indices as a function of silicon nitride width in a Z-propagating waveguide. **c** Measured transmission spectra of the reference device.

**S3.** **Design and experimental results of the reference device for TE2-mode-pass filter**

Figure **S3**ashows the schematic diagram of the reference device for TE2-mode-pass filter. Similarly, the structural parameters are all the same as that in the proposed device for TE2-mode-pass filter measurements. The TE0-TE1-TE2 MMUX is formed by cascading the TE0-TE1 MMUX with an ADC-based TE0-TE2 mode converter. The width of the widest waveguide supporting TE2 mode is designed to be *w*2’=3.537 μm to meet the phase-matching condition, as shown in Figure **S2**b. The coupling gap of the TE0-TE2 mode converter is also *g*=300 nm, and the coupling length is optimized to be *L*2=12 μm, considering the effects of the bending waveguides with a radius of 150 μm. Figure **S3**b-d show the normalized measurement results of the reference device consisting of TE0-TE1-TE2 MMUXs. The measured insertion losses for TE0, TE1 and TE2 modes are lower than 2.1 dB, while the inter-modal crosstalk is lower than -17 dB, at a wavelength range of 1500-1580 nm.



**Fig. S3**. **Design and experimental results of** **TE0-TE1-TE2 MMUX. a** Top view of the reference device consisting of TE0-TE1-TE2 MMUXs. Measured transmission spectra at different ports when light input into **b** TE0 channel, **c** TE1 channel and **d** TE2 channel.

**S4.** **Design and experimental results of the reference device for TM0-pass polarizer**

The reference device consists of two ADC-based PSRs with the same structural parameters as that in the proposed device for TM0-pass polarizer measurements, as shown in Figure **S4**a. The used ADC-based PSR has been proposed and experimentally demonstrated in our previous work.[1] The main structural parameters are designed as follow: *w*3’=1.2 μm, *w*4’=2.839 μm, *w*5’=2.1 μm, *w*6’=0.6 μm, *L*3=100 μm, *L*4=29 μm, *L*5=300 μm. The radius of the bending waveguides is 150 μm. The measured insertion losses are lower than 9 dB, and the crosstalk is lower than -20 dB, at a wavelength range of 1500-1580 nm. The relatively large insertion loss is measured at long wavelengths for TM0 mode, as the peak wavelength shifts to shorter wavelength compared with the design, due to the fabrication deviations. The peak wavelength can be tuned to desired wavelength by adjusting the length of polarization rotator (*L*3).



**Fig. S4**. **Design and experimental results of** **TE0-TE1-TE2 MMUX. a** Top view of the reference device consisting of PSRs. **b** Measured transmission spectra at different ports.

**S5. A comparison of previously reported mode filters on different material platforms**

A comparison of some previously reported mode filters on different material platforms is provided in **Table S1**. Most of the previous works focus on blocking only one specific low-order mode, lacking scalability to filter multiple modes. In Ref. [3], researchers developed a selective mode filter capable of filtering multiple modes simulatanously, by cascading multiple ADCs on a polymer platform. The designed structure is flexible and scalable, however, the device size reaches up to several millimeters and the measured insertion losses are realtively large. In Ref. [4], researchers proposed another scheme to filter multiple modes on a SOI chip, with the help of graphene nanoribbons integrated on the waveguide. Though the device size can be reduced greatly, the proposed mode filter suffers from large insertion loss and low MER. Compared with the previous works, our SWG-based mode filter on the LNOI platform is attractive to offer compact size, low loss, high MER and scalable functionality simultaneously.

**Table S1.** Comparison of some spatial mode filters reported on different material platforms

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Reference | Platform | Results | Mode number | Size (μm) | Loss at 1550 nm (dB) | MER at 1550 nm (dB) |
| [2] | Polymer | Experimental | 2 | 11000 | 2.2 | 20.8 |
| [3] | Polymer | Experimental | 3 | 9710 | 6.7 | 20.57 |
| [4] | SOI | Simulated | 3 | 200 | 8.4 | 5.37 |
| [5] | SOI | Experimental | 2 | 15 | ~1.8 | 48 |
| [6] | SOI | Experimental | 2 | ~500 | ~2 | ~18 |
| **This work** | **LNOI** | **Experimental** | **3** | **~50** | **3.1** | **34** |

**S6. Schematic diagram of the experimental setup**



**Fig. S5**. **Schematic diagram of the experimental setup.** TL, tunable laser; PC, polarization controller; DUT, device under test; OSA, optical spectrum analyzer.

**References**

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