Integrated Subwavelength Gratings on a Lithium Niobate on Insulator Platform for Mode and Polarization Manipulation

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Lithium niobate on insulator (LNOI) has emerged as a promising platform for photonic integrated circuits, with a fast-growing toolbox of components. This paper proposes, designs, and experimentally demonstrates compact subwavelength grating (SWG) waveguides on an LNOI platform for on-chip mode and polarization manipulation. To overcome the limitation of waveguide fabrication, the SWGs are designed and formed on a silicon nitride thin film deposited onto the surface of LNOI chip. As proof-of-concept devices, the SWG-based spatial mode filters (including a TE$_1$-mode-pass filter and a TE$_2$-mode-pass filter) and a TM-pass polarizer are fabricated successfully on the same chip, with the device lengths of only $\approx 50 \mu$m. The measured insertion losses for the devices are lower than 3.1 dB, with high extinction ratio larger than 30 dB, at a wavelength of 1550 nm. The proposed and demonstrated SWGs can serve as important building blocks in a series of mode and polarization handling devices for LNOI integrated photonics.

1. Introduction

Subwavelength gratings (SWGs), which are composed of periodically arranged dielectric segments with a pitch much smaller than the input light wavelength, have been widely investigated for developing high-performance integrated photonic devices with compact size, low loss, and large bandwidth.[1,2] In the last few years, SWG waveguides have been employed as one of the most important components to lead breakthroughs in silicon photonics, particularly for on-chip mode and polarization manipulation. A wide range of SWG-based devices including mode (de)multiplexers,[3] multimode waveguide bends and crossings,[4,5] mode filters,[6] polarization beam splitters,[7,8] polarizers,[9] etc. have been demonstrated. The inherent advantages of the devices are driving the SWG structures to be applied on more material platforms.

Recently, lithium niobate on insulator (LNOI) has emerged as a promising platform for future photonic integrated circuits, with attractive properties such as strong modal confinement, low-loss light propagation, high-speed electro-optical modulation, and high-efficiency optical nonlinearity.[10] With the improvements in etching of lithium niobate, the components toolbox of the LNOI platform is growing fast to satisfy the demands of varied applications, including active and passive components such as modulators,[11–13] wavelength converters,[14,15] and (de)multiplexers.[16–18] As the index contrast of LNOI platform is lower than that of silicon-on-insulator (SOI) platform, the LNOI devices are suffering from a relatively large footprint compared with silicon-based devices. Thus, it is attractive to form SWGs on the LNOI platform to construct compact optical components for high-density integration. However, the sidewall angle (typically 40°–80°) induced by lithium niobate dry etching can limit the minimum feature size between adjacent waveguides,[19] and thus, it is still not easy to fabricate SWGs with considerable controllability of the structural parameters on the LNOI platform. Moreover, the etching techniques developed for lithium niobate thin film are still specialized, resulting in limited reproducibility compared with other platforms, e.g., SOI.[20]

In this contribution, we propose and demonstrate compact SWG waveguides on a LNOI platform. To overcome the
aforementioned challenges, a silicon nitride thin film is deposited onto the surface of the LNOI chip, where the SWGs are designed and formed using mature CMOS-compatible etching processes developed by microelectronics industry. We have noted that there are also other candidates, however, silicon nitride is one of the most promising loading materials due to its similar but slightly lower refractive index and a similar transparent window to lithium niobate, as well as the mature and commercially available fabrication processes. Thus, the silicon nitride-loaded LNOI waveguides can preserve the excellent material property of lithium niobate whereas overcome the challenges faced by the direct etching waveguide fabrication.[21–23] For proof-of-concept, the SWG waveguides are used to realize spatial mode filters and polarizers which are important components in mode-division multiplexing (MDM) and polarization-division multiplexing (PDM) systems, respectively. We have obtained a TE₁-mode-pass filter, a TE₀-mode-pass filter and a TM-pass polarizer with the measured insertion losses of about 1.9, 3.1, and 1.3 dB, respectively, and the measured extinction ratio for all of the devices is larger than 30 dB, at a wavelength of 1550 nm. Furthermore, the fabricated device lengths are only ≈50 μm. To the best of our knowledge, this is the first experimental demonstration for the compact SWG-based mode and polarization handling devices on LNOI platform. This work also opens an opportunity for the realization of various SWG-based optical components on LNOI platform.

2. Principle and Design

2.1. SWG-Based Spatial Mode Filters

2.1.1. TE₁-Mode-Pass Filter

MDM has been developed for increasing the data capacity of optical interconnects by multiplexing different spatial modes in a multimode waveguide. As only a single-wavelength laser source is needed, MDM has attracted wide-spread attention due to its low cost, good system scalability, and small footprint.[24] However, one of the main challenges for the MDM systems is the superposition of inter-modal crosstalk when dozens to hundreds of devices are cascaded, resulting in serious signal degradation.[6] Mode filters are a type of device that can filter the undesired modes out of the system, and thus help to improve the signal-to-noise ratio performance. Since high-order modes have weaker confinement, they can easily be filtered out by means of tapering the waveguide to a cutoff width, hence mode filters provide usually solutions for blocking the low-order modes in a multimode waveguide.[25] Owing to the importance of the devices, several demonstrations have been reported on other material platforms.[8,23–28] However, there are still no demonstrations for mode filters on the LNOI platform. Figure 1a shows the schematic diagram of a proposed SWG-based TE₁-mode-pass filter. The device is designed along the crystallographic Z direction on a X-cut LNOI platform with a 300-nm-thick lithium niobate thin film on top of a 4.7-μm-thick buried oxide layer, following our previous work.[23] The birefringence of lithium niobate is considered in the design, which means the crystallographic Z direction has an extraordinary refractive index ($n_\parallel$) of ≈2.14, the crystallographic Y/X directions have an ordinary refractive index ($n_\perp$) of ≈2.21, at a wavelength of 1550 nm. The SWG structure is designed on a silicon nitride thin film on the surface of the LNOI platform, whose thickness is chosen to be 300 nm as well, for a strong mode confinement in the hybrid waveguide and a considerable mode confinement factor in the lithium niobate slab.[29] As silicon nitride has a similar but slightly lower refractive index to lithium niobate (≈1.99), the input optical mode is partially confined in the silicon nitride rib, which is important for the interaction between the optical mode and SWG structure.

For a TE₁-mode-pass filter, the hybrid SWG waveguide is expected to work in the Bragg regime for TE₀ mode and the sub-wavelength regime for TE₁ mode. Thus, the input TE₀ mode is reflected whereas the TE₁ mode is converted to the localized Bloch mode and propagates with low loss. It means that the Bragg conditions should be satisfied, which are expressed as:[30]

$$\Lambda = \frac{\lambda_0}{2 \cdot n_{eff0}} < \frac{\lambda_0}{2 \cdot n_{eff1}} \quad (1)$$

where $\Lambda$ is the grating pitch, $\lambda_0$ is the central wavelength of photonic stop band for TE₀ mode, $n_{eff0}$ and $n_{eff1}$ are the effective indices of TE₀ and TE₁ modes in the hybrid SWG waveguide. The SWG structure is optically equivalent to a homogeneous medium with a refractive index given by:[1]

$$n_{SWG}^2 = n_{SiN}^2 \cdot ff + n_{air}^2 \cdot (1 - ff) \quad (2)$$

where $n_{SiN}$ and $n_{air}$ are the refractive indices of silicon nitride and air clad, respectively. The $ff$ is the filling factor of the SWG, which is expressed as $ff = w_{t}/\Lambda$, where $w_{t}$ is the width of the SWG segment. Here, the $ff$ is designed to be 0.7, for an easy-to-fabricate minimum feature size as well as a relatively large effective index difference between different modes (refer to S1, Supporting Information, for details). Then, the effective refractive indices of the Bloch modes in the hybrid SWG waveguide are calculated by using a full-vector eigenmode solver,[31] as shown in Figure 1b. According to the results, the width of the SWG is designed to be $w_{t} = 2 \mu m$ for low-loss propagation of TE₀ mode, and the grating pitch is designed to be $\Lambda = 413 \mu m$ for a photonic stopband of TE₀ mode around 1550 nm. The transmission of TE₀ and TE₁ modes as a function of grating period number is simulated at a wavelength of 1550 nm, by using the 3D finite-difference time-domain (3D-FDTD) method,[32] as shown in Figure 1c. To achieve both low loss and high mode extinction ratio (MER), the grating period number is chosen to be 120. The simulated insertion loss for TE₀ mode is 1.7 dB and the MER between TE₀ and TE₁ modes is about 48 dB. The total length of our SWG-based TE₁-mode-pass filter is 49.56 μm. Figure 1d shows the simulated electric field profiles for TE₀ and TE₁ modes input into the device, at a wavelength of 1550 nm. It can be seen that the TE₀ mode passes through the device with low loss whereas the TE₁ mode is blocked. We also simulate the transmission spectra of different modes as a function of the input wavelength, as shown in Figure 1e. The designed device shows a bandwidth of about 46 nm (from 1524 to 1570 nm) for a MER larger than 20 dB, while the insertion loss for TE₀ mode stays below 3.5 dB.
2.1.2. TE2-Mode-Pass Filter

Most of the demonstrated mode filters block only one specific low-order mode, generally TE0 mode. It is still difficult to deal with the case that multiple modes need to be filtered out simultaneously, however, this function is important for the real-world application of the devices. Researchers proposed a few methods to solve this problem, such as cascading multiple directional couplers,[26] or introducing graphene as auxiliary material,[27] however, such devices have typically large footprint and relatively low extinction ratio. Thus, a compact and high-extinction-ratio mode filter that can filter out multiple optical modes simultaneously is still missing as a photonic circuit component. To fill this gap, we demonstrate our SWGs as an attractive choice to realize such a mode filter on the LNOI platform. For proof-of-concept, a TE2-mode-pass filter is designed here.

Figure 2a shows the schematic diagram of the proposed TE2-mode-pass filter. The hybrid SWG waveguide is designed to work
in the subwavelength regime for TE₂ mode, while work in the Bragg regime for TE₀ and TE₁ modes simultaneously. The Bragg conditions have been revised as:

$$\frac{\lambda_1}{(2 \cdot n_{e0})} < \Lambda_2 < \frac{\lambda_1}{(2 \cdot n_{e1})} < \frac{\lambda_1}{(2 \cdot n_{e2})}$$  \hspace{1cm} (3)$$

where $\Lambda_2$ is the grating pitch, $\lambda_1$ is the working wavelength, $n_{e0}$, $n_{e1}$, and $n_{e2}$ are the effective indices of TE₀, TE₁, and TE₂ modes in the hybrid SWG waveguide. For simplicity, we also design the ff to be 0.7, while the width of SWG is chosen to be $w_2 = 3.5 \mu m$ to support relatively low-loss propagation of TE₂ mode, as shown in Figure 2b. It can also be seen that the effective index difference between TE₀ and TE₁ modes is smaller than that between TE₁ and TE₂ modes. Thus, it can be predicted that the photonic stopbands of TE₀ and TE₁ modes are located closely to each other whereas well separated from that of TE₂ mode, which is important for filtering out the TE₀ and TE₁ modes simultaneously. According to the results, the grating pitch is designed to be $\Lambda_2 = 415 \text{ nm}$ for a device working at around 1550 nm. We also simulated the power transmission for different modes as a function of the input wavelength.

Figure 2. a) Schematic diagram of the proposed TE₂-mode-pass filter. b) Calculated mode effective indices as a function of SWG width in the Z-propagating hybrid SWG waveguide with a ff of 0.7. c) Simulated transmission of TE₀, TE₁, and TE₂ modes as a function of grating period number. d) Simulated electric field profiles for TE₀, TE₁, and TE₂ modes input into the device, at a wavelength of 1550 nm. e) Simulated transmission spectra of different modes as a function of the input wavelength.
of the grating period number at a wavelength of 1550 nm, by using 3D-FDTD method again, as shown in Figure 2c. According to the results, the grating period number is chosen to be 120 as well, resulting in the total length of the device to be 49.8 μm. The insertion loss for TE₀ mode is 1.2 dB and the MER between TE₀ and the low-order modes is larger than 41 dB. Figure 2d shows the simulated electric field profiles for TE₀, TE₁, and TM modes input into the device, at a wavelength of 1550 nm. It can be seen that TE₀ mode passes through the device with low loss whereas the low-order modes are blocked. Similarly, Figure 2e shows the transmission spectra of different modes as a function of the input wavelength. The designed device shows a bandwidth of 33 nm (from 1533 to 1566 nm) for a MER larger than 20 dB, while the insertion loss for TE₁ mode stays below 4.2 dB.

2.2. SWG-Based TM-Pass Polarizer

Similar to spatial mode filters, polarizer can stop one of the two polarization modes while letting the other one pass, and it plays a key role in PDM systems to reduce the crosstalk. Due to its attractive function, TE/TM-pass polarizers have been widely investigated based on different structures on the SOI platform. Fortunately, there are also a few works reported previously on the LNOI platform. For example, hybrid plasmonic gratings (HPG) have been proposed and numerically demonstrated for TE/TM-pass polarizers on the LNOI platform. The proposed devices are compact with only several to tens of micrometers length, and broad-tractive function, TE/TM-pass polarizers have been widely investigated. Thus, there is still a gap to realize a polarizer with compact size, low loss, and the low-order modes is larger than 41 dB. Figure 2d shows the simulated transmission spectra of different modes as a function of the input wavelength. The designed device shows a bandwidth of 33 nm (from 1533 to 1566 nm) for a MER larger than 20 dB, while the insertion loss for TE₁ mode stays below 4.2 dB.

3. Experimental Results

3.1. SWG-Based Spatial Mode Filters

Figure 4a shows the microscope image of the fabricated devices for TE₀-mode-pass filter, with a close-up scanning electron microscope (SEM) image of the SWGs. For the convenience of measurement, TE₀–TE₁ mode (de)multiplexers (MMUXs) are fabricated and connected to the TE₀-mode-pass filter. The input and output ports for TE₀ mode are denoted as I₁–O₁, while those for TE₁ mode are denoted as I₂–O₂, respectively. In order to eliminate the effects from the MMUXs to the device performance, a reference device with the SWGs replaced by a silicon nitride stripe is fabricated closely on the same chip (refer to S3, Supporting Information, for details). The corresponding ports are denoted as I₃–O₃ for TE₀ and TE₁ modes, respectively. The measured results are normalized to that of the reference device by using the formula as follows: $T = 10^{\frac{P_{\text{ref}} - P_{\text{in}}}{10}}$, where $T$ is the normalized transmission, $P_{\text{ref}}$ and $P_{\text{in}}$ are the measured output power for the proposed device and the reference device, respectively. Figure 4b shows the microscope image of the fabricated devices for TE₀-mode-pass filter, with the SWGs shown in a SEM image as well.
Similarly, TE₀–TE₁–TE₂ MMUXs are fabricated and connected to the filter for the convenience of multimode input and output. The input and output ports are denoted as I₀–O₀, I₁–O₁, and I₂–O₂ for TE₀, TE₁, and TE₂ modes, respectively. The experimental results are also normalized to that of the reference device without SWGs (refer to S4, Supporting Information, for details). The devices are interfaced by grating couplers with a grating period of 920 nm and a duty circle of 0.4.  

Figure 3. a) Schematic diagram of the proposed TM-pass polarizer. b) Calculated mode effective indices as a function of SWG width in the Y-propagating hybrid SWG waveguide with a 100 nm wide nanobridge and the ff is 0.8. c) Simulated transmission of TE₀ and TM₀ modes as a function of grating period number. d) Simulated electric field profiles for TE₀ and TM₀ modes input into the device, at a wavelength of 1550 nm. e) Simulated transmission spectra of different polarization modes as a function of the input wavelength.

Figure 4c shows the measured results of the TE₁-mode-pass filter. At a wavelength of 1550 nm, the device shows insertion loss for TE₁ mode of 1.9 dB and a MER of about 43 dB. Moreover, the experimental results exhibit a bandwidth of ≈44 nm (from 1515 to 1559 nm) for a MER of 20 dB, and the insertion loss for TE₁ mode is lower than 3.2 dB within the wavelength range. Figure 4d shows the measured results of the TE₂-mode-pass filter. The measured insertion loss for TE₂ mode is 3.1 dB, and the MER
is about 34 dB, at a wavelength of 1550 nm. Moreover, the device shows a bandwidth of ≈29 nm (from 1525 to 1554 nm) for a MER of 20 dB, and the insertion loss for TE₂ mode is lower than 6 dB within this wavelength range. The relatively large insertion loss may be induced by the sidewall roughness as there is a significant overlap between the TE₂ mode field and the etched silicon nitride sidewall. To reduce the insertion loss, we can optimize the etching process in the future to reduce the sidewall roughness of silicon nitride, by slowing down the etching rate or using resist reflow before etching.

3.2. SWG-Based TM-Pass Polarizer

Figure 5 shows the microscope image of the fabricated devices for TM-pass polarizer, including the SEM image of the SWGs.
with a nanobridge. We use the polarization splitter and rotator (PSR) to input and output different polarization modes for the ease of measurement. The input and output ports for TE₀ mode are denoted as I₀ and O₀, while those for TM₀ mode are denoted as I₁ and O₁, respectively. The reference device without the SWGs is also fabricated (refer to S5, Supporting Information, for details). The devices are interfaced by grating couplers with a grating period of 940 nm and duty circle of 0.4. The normalized results are shown in Figure 5b. The measured insertion loss for TM₀ mode is about 1.3 dB, and the PER is about 30.6 dB, at a wavelength of 1550 nm. The fabricated device shows a bandwidth of ≈36 nm (from 1521 to 1557 nm) for a PER of 20 dB, and the insertion loss for TM₀ mode is lower than 1.5 dB within the 36 nm wavelength range.

4. Discussion

Overall, the measured results are close to our simulation. We have noted the measured central wavelengths of the photonic stopbands are blue shifted compared with the design. This can be attributed to the slight deviations in the fabrication (refer to S6, Supporting Information, for details). Even so, the fabricated devices can still provide good performance in the C band. The central wavelengths can be tuned to desired wavelengths by a pre-compensation of the structural parameters in the future.

To the best of our knowledge, this is the first demonstration of higher-order mode pass filter on the LNOI platform. Our mode filter provides an attractive choice due to its compact size, low loss, high MER and scalable functionality, even compared with the devices reported on other material platforms (refer to S7, Supporting Information, for details). Moreover, our device can also be fabricated by using mature CMOS-compatible etching processes developed by microelectronics industry, while preserving the ability to explore high-speed electro-optic devices and high-efficiency optical nonlinear devices based on the LNOI platform.

A brief summary of previously reported TM-pass polarizers on the LNOI platforms is provided in Table 1. So far, there are still few experimental demonstrations of TM-pass polarizer on
the LNOI platforms. It can be seen that the demonstrated device provides one of the best options to have a compact size, low loss, and high PER simultaneously.

5. Conclusion

In summary, we have investigated SWG waveguides for on-chip mode and polarization manipulation on a silicon nitride loaded LNOI platform. The proposed SWGs are compact and easy-to-fabricate, benefiting from the maturely developed fabrication processes of silicon nitride. In support of this, the SWG-based spatial mode filters and TM-pass polarizer are designed and fabricated successfully, with the device lengths of ≈50 µm. For spatial mode filters, we have obtained a TE1-mode-pass filter and a TE2-mode-pass filter for blocking the low-order modes in a multi-mode waveguide. The measured insertion losses for TE1 and TE2 modes are 1.9 and 3.1 dB, respectively, and the MER is larger than 34 dB, at a wavelength of 1550 nm. For a TM-pass polarizer, the measured insertion loss for TM0 mode is 1.3 dB, and the PER is 30.6 dB, at a wavelength of 1550 nm. Moreover, the fabricated devices show reasonable wide bandwidths for a high ER larger than 20 dB, which can also be used for further applications combining the MDM/PDM with the wavelength-division multiplexing (WDM) technology. The demonstrated SWGs are expected to be implemented into a large number of compact optical components for mode and polarization manipulation on the LNOI platform.

6. Experimental Section

Device Fabrication: The devices were fabricated on a LNOI chip provided by NanoLN, with the designed parameters. The silicon nitride thin film was deposited onto the surface of the LNOI chip by using reactive sputtering, following the previous work.[31] The waveguide and grating coupler structures were formed by a single-step electron beam lithography (EBL) following by an inductively coupled plasma (ICP) etching process. The propagation loss of the fabricated waveguide was measured to be about 0.25 dB cm⁻¹, by using the cutback method.

Device Characterization: The fabricated devices were measured by using a tunable laser, a polarization controller, an off-chip circulator, and an optical spectrum analyzer. In the experiment, light with a wavelength range of 1500–1580 nm was transmitted from the tunable laser to the polarization controller, then passed through the circulator and on-chip devices, and finally was received by the optical spectrum analyzer (refer to S8, Supporting Information for details). The off-chip circulator aimed to prevent the high-power reflected light from damaging the tunable laser.

Table 1. Comparison of some TM-pass polarizers reported on LNOI platforms.

| Refs. | Results | Size [µm] | Loss at 1550 nm [dB] | PER at 1550 nm [dB] |
|-------|---------|-----------|---------------------|---------------------|
| [36]  | Simulated | 23        | ≈2                  | ≈20                 |
| [38]  | Simulated | 1000      | ≈0.3                | ≈24                 |
| [39]  | Experimental | 300       | ≈2                  | ≈20                 |
| This work | Experimental | 55       | 1.3                  | 30.6                |

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

filters, lithium niobate on insulator (LNOI), mode and polarization control, silicon nitride

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