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# A design method of lithium niobate on insulator ridge waveguides without leakage loss

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**Abstract:** We evaluate structural dependency of leakage losses in lithium niobate on insulator ridge waveguides. Generally, shallow ridge waveguides based on isotropic materials have inherent leakage loss for TM-like mode. On the other hand, lithium niobate is anisotropic material, thus the optical properties of lithium niobate based ridge waveguides are different from those of isotopic material based ridge waveguides. In this paper, we investigate leakage losses of lithium niobate on insulator ridge waveguides. We show that the shallow ridge waveguide structure without leakage loss can be realized by choosing the waveguide parameters adequately.

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**OCIS codes:** (130.3730) Lithium niobate; (230.7370) Waveguides; (130.0130) Integrated optics; (130.3120) Integrated optics devices.

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## 1. Introduction

Due to their high refractive index contrast, silicon photonic wires based on silicon on insulator (SOI) can realize strong field confinement, and be used for ultra compact optical devices such as microring resonators [1], arrayed waveguide gratings [2], and splitters [3]. Electro-optic modulators are also fabricated [4] in SOI, but owing to its weak electro-optic effect [5], silicon is not suitable for such devices. On the other hand, lithium niobate (LN) offers excellent electro-optic, acousto-optic, and nonlinear optical properties [6], so LN has been applied to various active and passive devices, such as modulators [7], mode converters [8], polarizer [9], and lasers [10]. However, most of the reported waveguides were fabricated by using Ti in-diffusion or proton exchange [11]. These fabrication techniques induce very small index change, therefore the confinement of electromagnetic fields is not strong. In other words, it is difficult to miniaturize optical devices by using conventional LN waveguides.

Recently, crystal ion slicing combined with wafer bonding is reported as a fabrication method of LN smart guide [12]. This method can realize high index contrast LN on insulator (LNOI) waveguides with submicron core size. Therefore, LNOI can be a good candidate for various integrated functional optical devices. Ridge waveguides and photonic wires are fabricated in LNOI [13,14] and their applications such as modulators [13] or microring resonators [15] have been reported. Photonic wires can achieve very strong field confinement, but scattering loss is large owing to side-wall roughness. In Ref [14], LNOI wire was fabricated and the measured loss was 9.9 dB/cm. The main cause of the loss was scattering loss due to roughness of the side-wall. On the other hand, ridge waveguides achieve low scattering loss due to their low ridge height, although lateral optical confinement is weak. In Ref [13], scattering loss of fabricated LNOI ridge waveguide was negligible small after polishing for LN film and etching by Argon ion beam milling. Ridge waveguides are also used for lateral electrical access to apply for electro-optical devices, therefore ridge waveguides are important structure for such devices. It is known that shallow ridge waveguides based on isotropic materials have leakage loss which has cyclic minima and dependency on ridge width for TM-like mode [16–18]. LN is anisotropic material, and it is reported that LNOI slab waveguides have different characteristics from isotropic waveguides [19]. Optical characteristics of ridge waveguides relate closely to that of slab waveguides, therefore, we can predict that characteristics of LNOI ridge waveguides are also different from those of isotropic ridge waveguides. In this paper, we investigate leakage loss of LNOI ridge waveguides using vector finite element method (VFEM) [20].

This paper is structured as follows. In section 2, basic theory of leakage loss in ridge waveguides is explained. We show that leakage loss behavior of LNOI is different from that of conventional SOI based ridge waveguides. In section 3, leakage losses of LNOI ridge waveguides are investigated by using VFEM. We show that we can design LNOI ridge waveguide without leakage loss for both TE- and TM-like modes even if ridge is shallow. In section 4, we discuss design methods of ridge waveguides where leakage loss does not exist in details. In section 5, findings are summarized.

## 2. Theory of leakage loss in ridge waveguides

Inherently, there is leakage loss which depends on ridge width in shallow ridge waveguides [16]. The cause of the leakage loss is TE/TM mode conversion at the ridge boundary. This mode conversion makes leakage loss, therefore the leakage loss behavior can be estimated from optical intensity of unguided slab mode converted from guided mode [17,18]. When the effective index of guided mode in ridge waveguide is lower than that of unguided slab mode in lateral cladding, some guided slab waves are converted to slab mode and leak to lateral cladding due to discontinuity at the ridge boundary. In SOI shallow ridge waveguides, the

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effective index of TE-slab mode is higher than that of TM-like mode, and therefore, TM-like mode becomes leaky. In this case, some TM polarization waves of TM-like mode are converted to TE polarization waves at the ridge boundary. Some of the converted TE waves radiate directly to the lateral cladding, and combine with TE-slab mode. The other waves are reflected at the ridge wall and across the ridge and radiate to the lateral cladding at another ridge boundary, and also combine with TE-slab mode. These two different converted TE waves are approximately equal in magnitude $\phi_0$ and the phase difference is $\pi$. We can predict leakage loss behavior using these TE waves of TE-slab mode. To predict leakage loss behavior, we use optical intensity $I$ of TE-slab mode, represented as the following equation [17,18]:

$$I \propto 2\left|\phi_0\right|^2 \left(1-\cos k_1 w\right) \tag{1}$$

with

$$k_1 = k_0 \sqrt{n_{\mathrm{TE}}^2\left(t_1\right) - N_{\mathrm{eff,TM}}^2} \tag{2}$$

where $k_0$ is the wavenumber in vacuum, $n_{\mathrm{TE}}(t_1)$ is the effective index of TE-slab mode with slab thickness $t_1$ as shown in Fig. 1(a), $N_{\mathrm{eff,TM}}$ is the effective index of TM-like mode in ridge waveguides.

Then, we discuss the case of LNOI ridge waveguides. We consider a LNOI ridge waveguide as shown in Fig. 1(a), where $t_1$ and $t_2$ are the slab thicknesses at ridge and lateral cladding regions respectively, and $w$ is the ridge width. We assume under cladding is silica, its index is 1.444, and over cladding is air. We set LN ordinary index and extra-ordinary index as 2.210 and 2.138, respectively. Refractive index distribution of LN depends on crystal cut direction. Z-cut LN is widely used for applications such as modulators, but it is recently reported that X-cut LNOI has unique characteristics [19]. The effective indices of TE- and TM-slab modes coincide with each other in X-cut Y propagation LNOI slab waveguides, while this phenomenon does not arise in Z-cut LNOI slab waveguides. This is an important feature for the applications such as mode converters. Thus we consider two cut directions, Z-cut and X-cut. We plot the effective indices of TE- and TM-slab modes as a function of slab thickness in Z-cut and X-cut Y propagation slab waveguides as shown in Fig. 1(b) at $\lambda = 1.55$ μm in Figs. 2(a) and (b), respectively, where $\lambda$ is the wavelength. The effective index of TE-slab mode is always higher than that of TM-slab mode in Z-cut slab waveguides. Therefore,

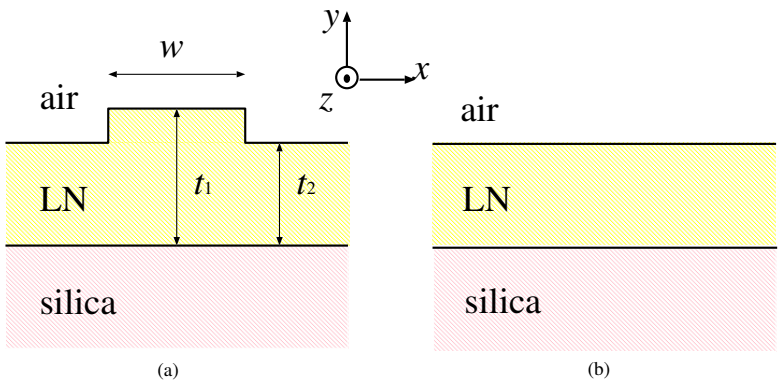



Fig. 1. Cross section of LNOI (a) ridge and (b) slab waveguides.

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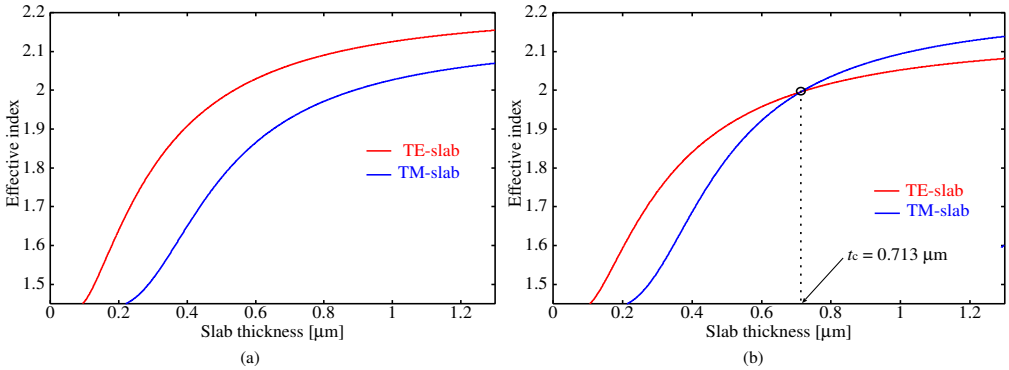



Fig. 2. Effective index of slab mode in (a) Z-cut and (b) X-cut Y-propagation LNOI slab waveguides as a function of slab thickness at λ = 1.55 μm.

TM-like mode becomes leaky in Z-cut ridge waveguides and leakage loss behavior is predicted in the same way as SOI ridge waveguides. On the other hand, the effective indices of TE- and TM-slab modes in X-cut slab waveguides coincide with each other at slab thickness of 0.713 μm. We define this slab thickness as $t_c$. If the slab thickness is thinner than $t_c$, the effective index of TE-slab mode is higher than that of TM-slab mode. Therefore, TM-like mode becomes leaky and the leakage loss behavior is predicted in the same way as Z-cut LNOI and SOI. If the slab thickness is thicker than $t_c$, the effective index of TM-slab mode is higher than that of TE-slab mode. Therefore, TE-like mode becomes leaky mode. In this case, we can predict leakage loss behavior using optical intensity of TM-slab mode. We can obtain optical intensity of TM-slab mode from Eq. (1), but we note that $k_1$ is replaced as

$$k_1 = k_0 \sqrt{n_{\mathrm{TM}}^2(t_1) - N_{\mathrm{eff,TE}}^2} \tag{3}$$

where $n_{\mathrm{TM}}(t_1)$ is the effective index of TM-slab mode with slab thickness $t_1$ and $N_{\mathrm{eff,TE}}$ is the effective index of TE-like mode in ridge waveguide. When the slab thickness equals $t_c$, it is expected that mode conversion does not occur. In other words, it is expected that we can design ridge waveguide without leakage loss for both the TE- and TM-like modes.

## 3. Evaluation of leakage loss behavior

### *3.1 Leakage losses of Z-cut LNOI ridge waveguides*

We evaluate Z-cut Y propagation LNOI ridge waveguides with $t_1$ = 0.55 μm and $t_2$ = 0.5 μm. Figure 3(a) shows leakage losses as a function of ridge width calculated by the following processes. The waveguide cross section is divided by curvilinear hybrid edge/nodal element. We calculate matrix eigenvalue equation with anisotropic-type perfectly matched layer (PML) [20]. By solving the eigenvalue equation, we obtain the complex propagation constant $\beta$. The leakage loss can be calculated by

$$\textit{Leakage loss} = 8.686\,\mathrm{Im}\{\beta\} \quad [\mathrm{dB/m}] \tag{4}$$

where Im stands for the imaginary part. Figure 3(b) shows optical intensity of TE-slab mode calculated by Eq. (1). We can confirm leakage loss which has cyclic minima for TM-like mode. The ridge width dependency of the leakage loss for TM-like mode well agrees with optical intensity of TE-slab mode shown in Fig. 3(b). Therefore, the leakage loss behavior of Z-cut LNOI ridge waveguides correlates with SOI ridge waveguides.

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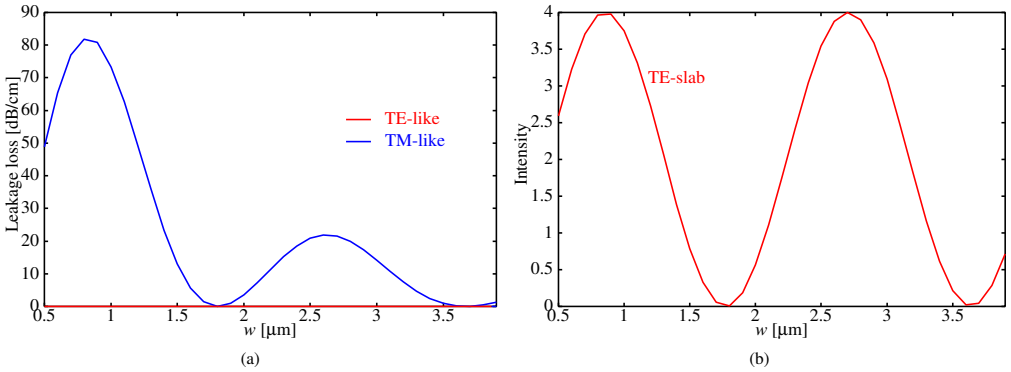



Fig. 3. (a) Leakage losses of TE- and TM-like modes and (b) optical intensity of TE-slab mode in Z-cut LNOI ridge waveguide with $t_1$ = 0.55 μm and $t_2$ = 0.5 μm as a function of ridge width at λ = 1.55 μm.

### *3.2 Leakage losses of X-cut LNOI ridge waveguides*

As shown in Fig. 2(b), the effective indices of TE- and TM-slab modes intersect at $t_c$ in X-cut LNOI slab waveguides. At first, we consider two structures of X-cut Y propagation LNOI ridge waveguides; ($t_1$, $t_2$) = (0.55 μm, 0.5 μm) and (1.1 μm, 1.0 μm). The first structure is predicted that TM-like mode becomes leaky, and the second one is predicted that TE-like mode becomes leaky. Figure 4(a) shows leakage losses of the first structure. We can see leakage loss for TM-like mode as expected, and its ridge width dependency well agrees with optical intensity of TE-slab mode in Fig. 4(b). Figure 5(a) shows leakage loss of the second structure. We can see leakage loss for TE-like mode, as expected. Its ridge width dependency well agrees with optical intensity of TM-slab mode in Fig. 5(b).

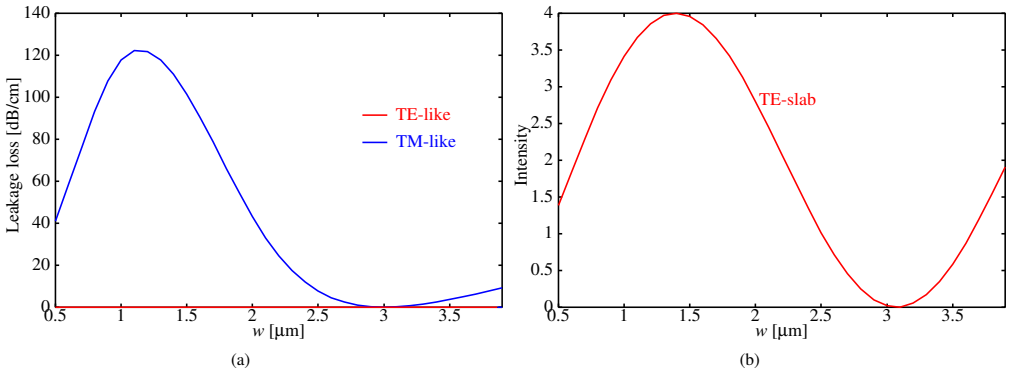



Fig. 4. (a) Leakage losses of TE- and TM-like modes and (b) optical intensity of TE-slab mode in X-cut LNOI ridge waveguide as a function of ridge width with $t_1$ = 0.55 μm and $t_2$ = 0.5 μm at λ = 1.55 μm.

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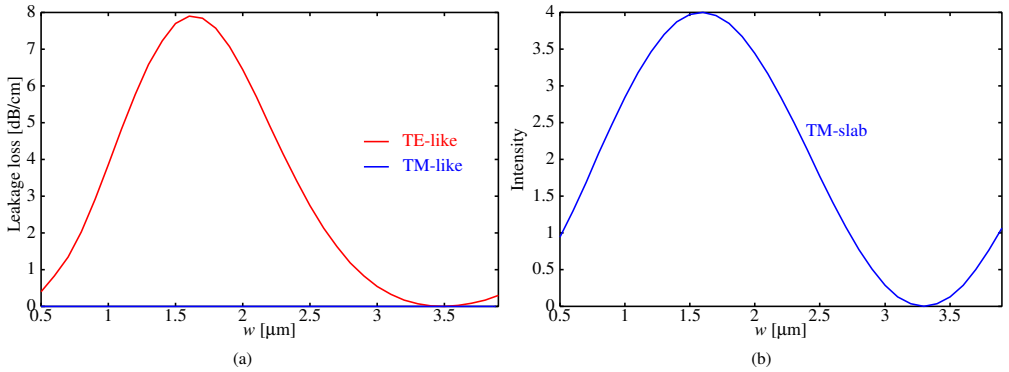



Fig. 5. (a) Leakage losses of TE- and TM-like modes and (b) optical intensity of TM-slab mode in X-cut LNOI ridge waveguide with $t_1$ = 1.0 μm and $t_2$ = 1.1 μm as a function of ridge width at λ = 1.55 μm.

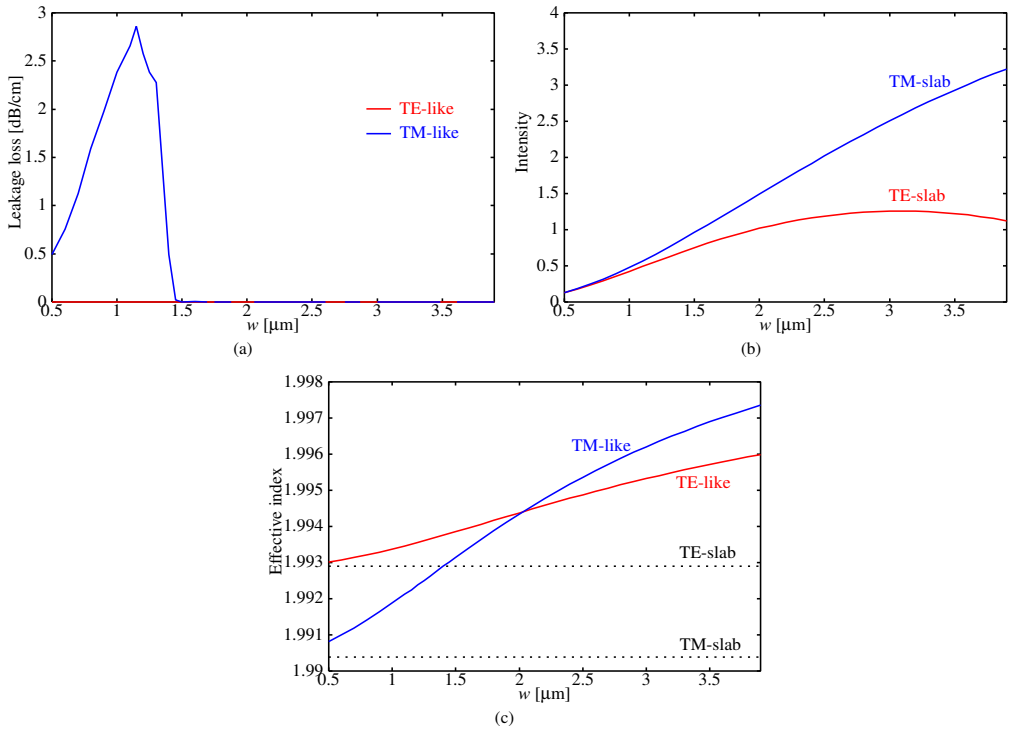



Fig. 6. (a) Leakage losses of TE- and TM-like modes, (b) optical intensity of slab mode, and (c) effective index in X-cut LNOI ridge waveguide with $t_1$ = 0.723 μm and $t_2$ = 0.703 μm as a function of ridge width at λ = 1.55 μm.

Next, we consider a shallow ridge waveguide with $t_1$ = 0.723 μm and $t_2$ = 0.703 μm, where the slab thicknesses, $t_1$ and $t_2$, are designed around $t_c$, namely, are determined by the following equation:

$$(t_1 + t_2)/2 = t_c \tag{5}$$

In this structure, it is expected that leakage loss does not exist as explained in the previous section. Figure 6(a) shows leakage losses of this structure and Fig. 6(b) shows optical intensity of TE- and TM-slab modes. We can see leakage loss for TM-like mode, however, the leakage loss is suppressed for both TE- and TM-like modes when $w$ > 1.4 μm. The ridge

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width dependency of the leakage loss does not agree with intensity of each slab mode. The reason can be understood by the effective index of the ridge waveguides in Fig. 6(c). Solid lines and dotted lines represent the effective indices of the guided mode in ridge waveguides and slab mode, respectively. The effective index of TM-like mode becomes higher than that of TE-slab mode when $w > 1.4$ μm. The effective index of TE-like mode is always higher than that of TM-slab mode. Therefore, mode conversion does not occur when $w > 1.4$ μm then the leakage loss is completely suppressed for both the TE- and TM-like modes.

Next, we consider a shallow ridge waveguide surrounded by silica. This structure can be used for bonding electrodes to the cladding to apply for electro-optical modulators [13]. We show the effective index of the X-cut LNOI slab waveguides in Fig. 7. We can see that the effective index of TE-slab mode and that of TM-slab mode intersect when the slab thickness is $t_c = 0.647$ μm. Figure 8(a) shows leakage losses of the ridge waveguide with $t_1 = 0.657$ μm, $t_2 = 0.637$ μm. These structural parameters are decided to satisfy Eq. (5). We can see that leakage loss exists for TM-like mode, however, it is suppressed when $w > 1.3$ μm. This can be explained in the same manner as previous discussion. We show the effective index of the ridge waveguide in Fig. 8(b). The effective index of TM-like mode becomes higher than that of TE-slab mode when $w > 1.3$ μm, and that of TE-like mode is always higher than that of TM-slab mode. Therefore, mode conversion does not occur when $w > 1.3$ μm then the leakage loss is completely suppressed for both the TE- and TM-like modes. In this case, we can see that the peak of leakage loss of the ridge waveguide with silica cladding is smaller than that of the ridge waveguide with air cladding. However, we note that bending loss will be large due

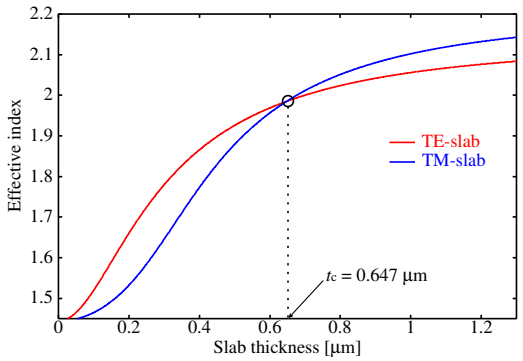



Fig. 7. Effective index of slab mode in X-cut embedded LNOI slab waveguides as a function of slab thickness at λ = 1.55 μm.

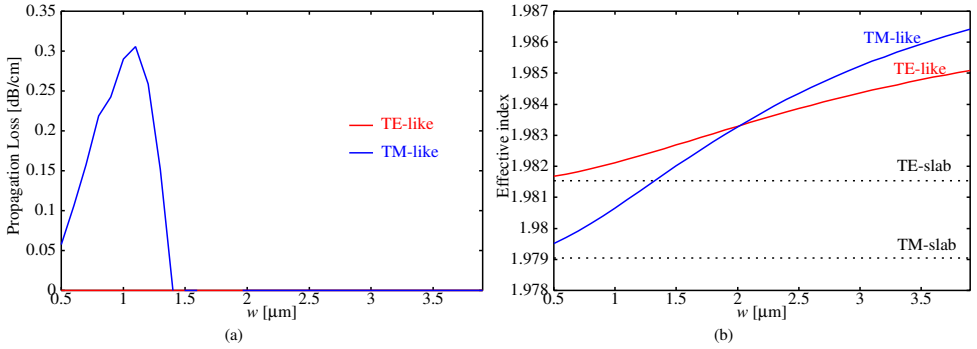



Fig. 8. (a) Leakage losses of TE- and TM-like modes and (b) effective index in X-cut embedded LNOI ridge waveguide with $t_1 = 0.637$ μm and $t_2 = 0.657$ μm as a function of ridge width at λ = 1.55 μm.

to its low index contrast.

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The previous two structures are decided to satisfy Eq. (5) and $t_1 - t_2 = 20$ nm. Next, we set the ridge height $t_1 - t_2 = 40$ nm, 70 nm, and 100 nm. The structural parameters are ($t_1$, $t_2$) = (0.733 μm, 0.693 μm), (0.748 μm, 0.678 μm), and (0.763 μm, 0.663 μm), respectively. Figure 9 shows leakage losses of these structures as a function of ridge width. We can see that leakage loss becomes larger as the ridge height becomes higher while the ridge width where the leakage losses are completely suppressed becomes smaller as the ridge height becomes higher. Thus, LNOI ridge waveguides without leakage loss can be realized even if $t_1$ and $t_2$ are changed, as long as Eq. (5) is satisfied.

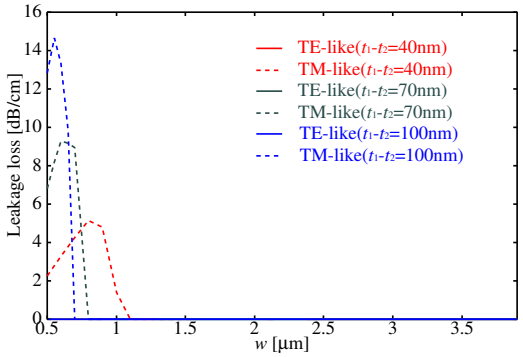



Fig. 9. Leakage losses of TE- and TM-like modes in X-cut LNOI ridge waveguides with several ridge heights of $t_1 - t_2$ as a function of ridge width at $\lambda = 1.55$ μm.

## 4. Investigation of structural parameters in ridge waveguides without leakage loss

In the previous section, the ridge heights, $t_1$ and $t_2$, are decided by Eq. (5). In this structure, $t_c$ is located at the midpoint of $t_1$ and $t_2$. Property of the leakage losses depends on the relationship of the effective indices between the slab waveguides and the ridge waveguides. Therefore, it is not necessary condition to satisfy Eq. (5) for achieving non-leakage loss ridge waveguide. At first, we evaluate leakage loss of the ridge waveguides with $t_2 = 0.7$ μm. Figure 10 shows leakage losses of the ridge waveguides with $t_1 = 0.721$ μm and 0.731 μm. We also plot the leakage loss of the ridge waveguides with $t_1 = 0.726$ μm which satisfies Eq. (5) as black line for comparison. We can see that leakage loss exists for TM-like mode, however, it is suppressed when $w$ becomes larger. We can also see that the ridge width where the leakage losses are completely suppressed becomes smaller as the $t_1$ becomes larger.

Next, we consider the case that $t_c$ is not located between $t_1$ and $t_2$. We consider two structures; ($t_1$, $t_2$) = (0.7 μm, 0.65 μm) and (0.735 μm, 0.715 μm). The former/latter structures are the ridge waveguides where $t_1$ and $t_2$ are smaller/larger than $t_c$. Figures 11(a), (b) and 12(a), (b) show leakage losses of TE- and TM-like modes, and effective indices in the first and the second structures, respectively. We can see that TM (TE)-like mode becomes leaky mode when $t_1$ and $t_2$ are smaller (larger) than $t_c$. However, leakage losses can be suppressed by designing ridge waveguides with the wide ridge width. These results mean that Eq. (5) is not absolute requirement to eliminate leakage loss from ridge waveguides. But choosing $t_1$ and $t_2$ near $t_c$ realize non-leakage loss structure with shallow ridge.

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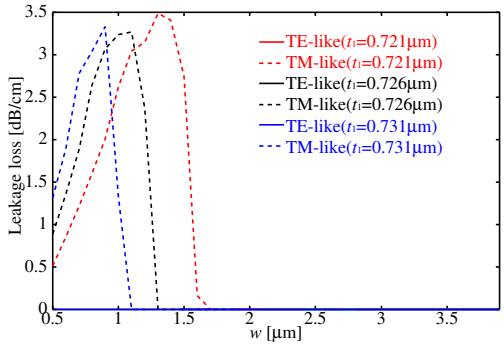



Fig. 10. Leakage losses of TE- and TM-like modes in X-cut LNOI ridge waveguides with $t_2$ = 0.7 μm and several values of $t_1$ as a function of ridge width at λ = 1.55 μm.

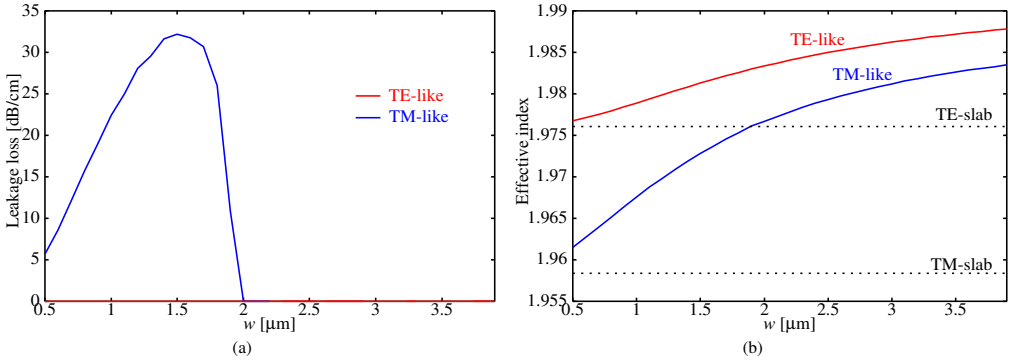



Fig. 11. (a) Leakage losses of TE- and TM–like modes and (b) effective index in X-cut LNOI ridge waveguide with $t_1$ = 0.7 μm and $t_2$ = 0.65 μm as a function of ridge width at λ = 1.55 μm.

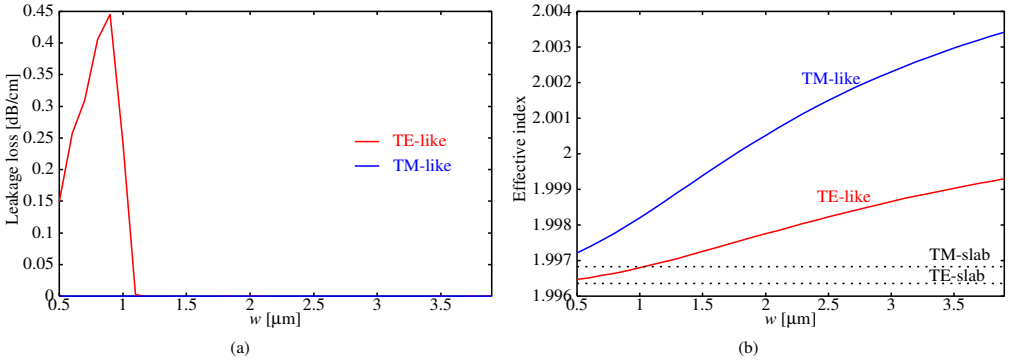



Fig. 12. (a) Leakage losses of TE- and TM-like modes and (b) effective index in X-cut LNOI ridge waveguide with $t_1$ = 0.735 μm and $t_2$ = 0.715 μm as a function of ridge width at λ = 1.55 μm.

## 5. Conclusion

We have introduced design methods of LNOI shallow ridge waveguides that do not have leakage losses for both TE- and TM-like modes. At first, we have briefly explained the theory of leakage losses in ridge waveguides. Then we have shown that leakage loss behavior of Z-cut ridge waveguides is similar to SOI ridge waveguides and that of X-cut is different. This is because that X-cut Y propagation LNOI slab waveguides satisfy a condition where the effective indices of TE- and TM-slab modes coincide with each other. This is a unique

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characteristic of the anisotropic materials based waveguide, therefore, it is impossible to achieve such characteristic in isotropic waveguides. Finally, we have investigated structural dependency of the leakage losses of LNOI ridge waveguide in details. LNOI ridge waveguides without leakage losses have potential to be applied for various integrated functional optical devices. We have also shown that the leakage loss of ridge waveguide with silica cladding is lower than that of ridge waveguide with air cladding. The leakage loss depends on the relation between effective indices of TM-like (TE-like) mode and TE-slab (TM-slab) mode. However, we note that bending loss of ridge waveguide embedded in silica should be large due to its weak lateral confinement. Therefore, investigating bending characteristics of LNOI waveguides is next issue.

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