

基于质子交换和刻蚀工艺的体铌酸锂阵列波导光栅

袁佳茜, 刘嘉程, 杜江兵*, 何祖源

上海交通大学区域光纤通信网与新型光通信系统国家重点实验室, 上海 200240

摘要 提出一种将质子交换技术和刻蚀技术结合的体铌酸锂波导和器件加工方案, 基于质子交换的铌酸锂晶体相变特性改变, 降低了质子交换区直接刻蚀难度, 结合质子交换的纵向折射率改变和刻蚀波导的横向结构改变, 波导尺寸显著降低, 采用粒子群算法优化波导尺寸, 最小可达 $2.5 \mu\text{m}$ 。基于该工艺方案设计了中心波长为 1550 nm 、四通道且通道间隔为 400 GHz 的阵列波导光栅, 该阵列波导光栅的传输损耗约为 6 dB , 相邻通道间串扰均低于 22 dB , 整体尺寸仅为 $850 \mu\text{m} \times 620 \mu\text{m}$, 在高密度铌酸锂光子集成互连等场景具有较大的应用潜力。

关键词 光栅; 铌酸锂; 质子交换; 粗波分复用; 阵列波导光栅

中图分类号 TN256

文献标志码 A

DOI: 10.3788/AOS222148

1 引言

近年来, 光通信、5G、数据中心互连、AR/VR、机器学习等领域快速发展, 对光子集成电路(PIC)提出了更高的要求。许多材料已经被研究和应用于集成光子学, 如硅(Si)、磷化铟(InP)、氮化硅(SiN)、砷化镓(GaAs)、硅玻璃等^[1]。在这些材料中, 绝缘体上的硅(SOI)因具有低光传播损耗、高集成密度、与标准互补金属氧化物半导体(CMOS)工艺兼容等优点得到广泛应用。但就算对于SOI来说, 也不能同时支持超低传播损耗、高速率光调制和高效的全光非线性。

铌酸锂(LN)作为光子工业界的重要材料, 具有较强的电光(EO)效应、较大的非线性光学系数和很好的化学稳定性^[2]。同时, 铌酸锂晶体制备简单, 可以很好地控制生长成本^[3], 因此被作为电光材料、非线性光学材料广泛应用于集成光学领域, 高速非线性的体铌酸锂调制器已被广泛应用于传统的光纤通信系统中^[4]。传统的铌酸锂波导通过钛(Ti)扩散或质子交换来制备^[5], 不同的钛离子浓度可以使得折射率 n_e 增加 $0.001 \sim 0.04$, 质子交换可以使得 n_e 增加约 0.1 , 通过这两种方式制备的波导和包层折射率对比度低, 光学约束性弱, 模态面积大, 导致波导宽度高达 $5 \mu\text{m}$ ^[6], 波导弯曲半径高达 mm 量级, 这就限制了传统铌酸锂波导应用于小尺寸光学器件。为了解决这一问题, 人们对薄膜铌酸锂(TFLN)进行了研究, 并取得了重大进

展。与基于体铌酸锂平台的传统波导相比, TFLN上的高对比度和低损耗波导使该平台成为实现低功率的紧凑非线性器件的另一选择^[7]。Smart Cut技术是目前生产高质量TFLN的主要技术, 但这种工艺十分复杂, 成本较高, 很难实现大批量生产, 同时, 铌酸锂晶体属于惰性材料, 很难被直接刻蚀, 而已有的工艺如聚焦离子束刻蚀等又存在效率低、和传统工艺不兼容等问题^[8], 这也给TFLN平台器件加工带来了一定困难。

在光通信网络中, 波分复用技术的出现很好地解决了通信网络数据传输容量大的问题。阵列波导光栅作为传统的波分复用器件, 具有分辨率高、尺寸小、通道数多等优点^[9], 目前已有TFLN平台的阵列波导光栅(AWG)^[10-12]被研究。因此, 兼容体铌酸锂加工方案的高集成度阵列波导光栅既可以实现低成本, 又可以利用铌酸锂的电光效应、非线性效应实现强大的单片集成。

针对铌酸锂平台器件尺寸过大的问题, 本文提出一种新的工艺方案, 结合粒子群算法优化波导尺寸, 能够在体铌酸锂平台上制备低成本且具有高折射率对比度的波导, 有利于实现铌酸锂平台器件小型化与大规模集成。同时, 采用该工艺方案设计了基于体铌酸锂的四通道且通道间隔为 400 GHz 的阵列波导光栅, 该阵列波导光栅的传输损耗约为 6 dB , 相邻通道间串扰均低于 22 dB , 进一步验证了该方案的可行性。

收稿日期: 2022-12-16; 修回日期: 2023-02-24; 录用日期: 2023-03-07; 网络首发日期: 2023-03-13

基金项目: 国家重点研发计划(2018YFB1801804)、国家自然科学基金(61935011, 62122047)

通信作者: *dujiangbing@situ.edu.cn

2 基于质子交换和刻蚀工艺的光波导加工原理

钛扩散是改变铌酸锂折射率的典型方法之一。钛扩散铌酸锂光波导的制作工艺可分为三步:首先,将金属薄膜镀在晶体表面,常见的镀膜方式有电子束蒸发镀膜、真空蒸发镀膜和磁控溅射镀膜;然后,进行高温扩散,钛离子在充满氩气、氮气或空气等气体的高温环境中从金属薄膜扩散至晶体表面;最后,观察扩散情况,如果没有达到预期效果,则再次进行高温扩散,钛扩散的典型扩散深度为几微米。不同的钛离子浓度会导致不同的光折射率增加量,范围为 $0.001\sim 0.04$ ^[13]。通过钛扩散工艺制作的光波导晶格结构不会发生变化,能保持铌酸锂晶体的电光特性,因此钛扩散是使用最为广泛的可改变铌酸锂晶体折射率的方法。同时,经过钛扩散制备的波导不仅允许 TE 和 TM 模式传播,且具有较低的传输损耗,还能够很好地耦合到单模光纤中^[14]。

1982年,Jackel等^[15]在实验中发现氢离子与铌酸锂中的锂离子发生置换反应,能够改变晶体的非寻常光折射率 n_e ,因此提出可使用质子交换法制备铌酸锂光波导。该团队基于这个思路提出一种较为完整的质子交换方案,其工艺流程包括清洗材料基底、在基底上附着掩模、通过光刻将图案转移至掩模、质子交换、退火、抛光等。

质子交换的主要步骤是在高温环境下将铌酸锂晶体浸入含有氢离子的质子源中,质子源通常为含有苯甲酸(BA)和苯甲酸锂(LB)的混合溶液。相比于钛扩散,质子交换能够带来更大的 n_e 改变量,这主要取决于质子源中锂离子的浓度。 n_e 增大随着质子源中锂离子浓度的增大而减小。当锂离子浓度低于阈值时, n_e 改变量大于 0.08 ,但较为完全的质子交换会破坏铌酸锂晶体的晶相;当锂离子浓度在阈值附近时, n_e 改变

值迅速降低;当锂离子浓度大于阈值时, n_e 改变量低于 0.04 。在苯甲酸和苯甲酸锂混合溶液中发生质子交换,会导致铌酸锂晶体的电光或声光系数急剧减小,影响晶体电光性能。传统的退火质子交换(APE)通过退火恢复一定的电光系数和非线性光学系数,同时也能减小传输损耗。对于非线性光学应用,通常采用软质子交换(SPE)制备光波导,因为这种质子交换方式的质子源锂离子浓度较高,以较低的 n_e 改变量为代价保持了晶体的电光和非线性特性。

除了上述几种质子交换方法外,研究发现当控制苯甲酸熔体中的锂离子物质的量分数为 $2\%\sim 2.4\%$ 时,所制备的波导具有不同的晶相^[16],既保持了晶体的非线性,对模场产生很强的束缚作用,又能获得相对较大的 n_e 改变量。该种工艺方案发生在封闭的金属容器内,将晶体放入容器后将容器抽至真空,熔化熔体后使得铌酸锂样品渗入到熔体中,以此实现质子交换。气相质子交换(VPE)利用气体作为质子源,展示了制备具有非线性的高折射率波导的可能性^[17]。然而,该工艺对制备条件极为敏感,质子交换时间与质子在铌酸锂晶体表面的扩散深度没有线性关系,因此无法利用这种技术制备光学器件。除了锂离子浓度外,质子交换环境是否完全真空也会影响质子交换的效果。高真空质子交换可以通过控制质子源中的水分来提高所制备波导的质量^[18]。

铌酸锂材料属于惰性材料,因此无法在没有预处理的情况下对其进行刻蚀。此外,由于铌酸锂材料具有高硬度和耐磨性,很难直接对其进行工艺加工。需要注意的是,在质子交换反应中,氢离子扩散到铌酸锂衬底中来代替锂离子,导致铌酸锂晶体发生相变,并产生晶体结构缺陷,使得质子交换区域能够被直接刻蚀。通过这种方法可以在薄膜铌酸锂上制备表面光滑的高质量脊波导^[19-20]。因此,本实验提出一种将质子交换和蚀刻结合的工艺方案,如图1所示,用于在体铌酸锂

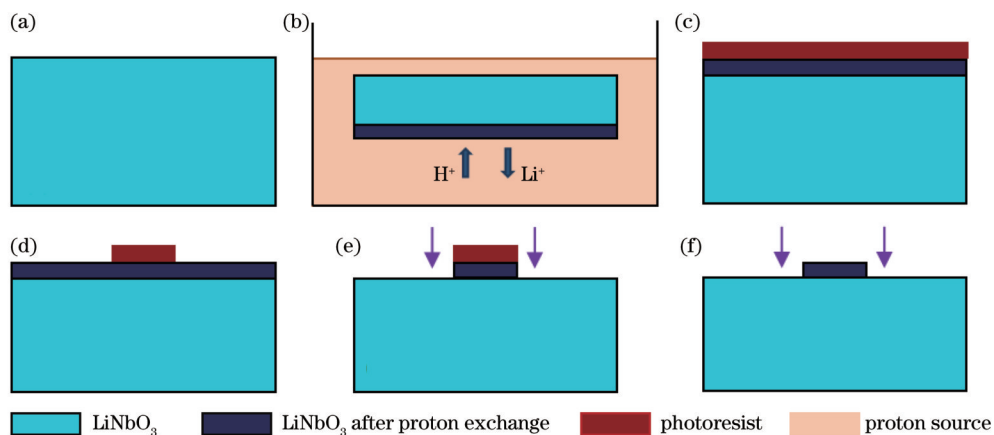


图1 工艺流程。(a)体铌酸锂基底;(b)质子交换;(c)旋涂光刻胶;(d)光刻;(e)刻蚀;(f)去除光刻胶

Fig. 1 Fabrication process. (a) LiNbO_3 substrate; (b) proton exchange; (c) photoresist spin-coating; (d) photolithography; (e) etching; (f) removal photoresist

平台制备波导。该工艺先将铌酸锂衬底在高温环境下浸没在质子源中足够长时间,确保质子交换深度达到波导所需的高度;在质子交换后,在晶体表面旋涂光刻胶并通过光刻将图案转移至光刻胶层,再采用湿刻蚀、等离子体刻蚀等工艺进行刻蚀,将图案转移至质子交换部分,最后洗去光刻胶。

3 铌酸锂波导优化设计

通过仿真实验分析该工艺方案能否减小波导宽度。实验结果^[21]表明,当铌酸锂晶体在 300 °C 的条件下浸入锂离子物质的量分数为 1% 的质子源中进行 72 h 的质子交换后, Δn_e 与波长 λ 的关系可以描述为

$$\Delta n_e = 0.0847376 + \frac{2862.93}{\lambda^2} + \frac{1.57563 \times 10^9}{\lambda^4} \quad (1)$$

由式(1)可知,当波长为 1550 nm 时,质子交换区的 Δn_e 约为 0.08。此时,不同扩散深度的有效模场面积如图 2 所示。当扩散深度为 2.4 μm 时,若波导没有进行刻蚀,波导的最小模场面积为 14.5 μm^2 。

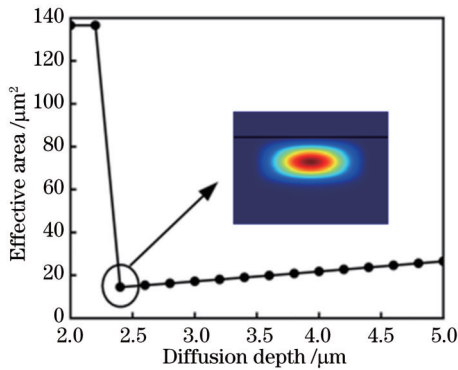


图 2 当 Δn_e 为 0.08 时,不同质子交换深度下的有效模场面积
Fig. 2 Effective area under different diffusion depths of waveguides when Δn_e is 0.08

当对波导进行刻蚀后,如图 3 所示,波导的最小有效模场面积可以降低到 6.7 μm^2 ,验证了所提出的工艺方案能够有效减小波导尺寸。当波导的有效模场面积最小时,波导宽度降低到 4.2 μm ,相比于其他材料,利用铌酸锂晶体制作的波导宽度仍较大。

通过增大 Δn_e 来进一步减小波导的尺寸。根据理论研究结果,质子交换可以获得的最大 Δn_e 为 0.12。当 Δn_e 为 0.1 时,可以得到图 4 所示的扩散深度与模场有效面积的关系。当扩散深度为 2 μm 时,最小有效模场面积为 7 μm^2 。为了验证所提工艺方案能够减小波导尺寸,将波导高度设置为 2.8 μm ,得到图 5 所示的波导宽度和有效模场面积的关系。当波导宽度为 2.4 μm 时,波导对光场的约束能力最强。与未经刻蚀的波导相比,增加刻蚀流程可以有效减小波导的宽度,从而减小器件尺寸。

此外,由于可优化参数较多,采用粒子群优化

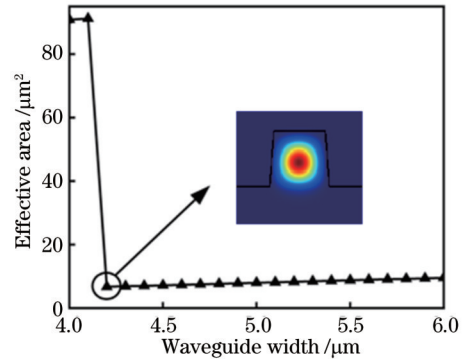


图 3 当 Δn_e 为 0.08 时,不同波导宽度下的有效模场面积
Fig. 3 Effective area under different widths of waveguides when Δn_e is 0.08

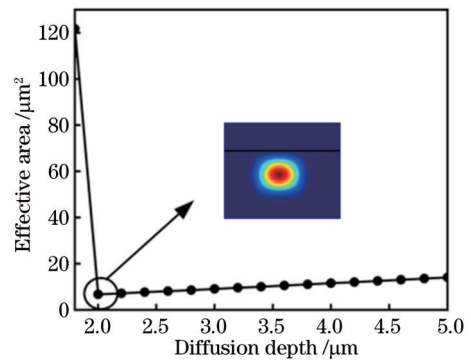


图 4 当 Δn_e 为 0.1 时,不同质子交换深度下的有效模场面积
Fig. 4 Effective area under different diffusion depths of waveguides when Δn_e is 0.1

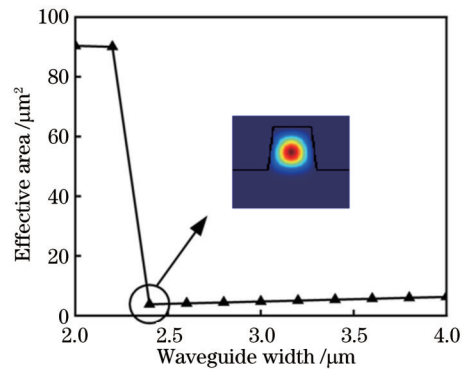


图 5 当 Δn_e 为 0.1 时,不同波导宽度下的有效模场面积
Fig. 5 Effective area under different widths of waveguides when Δn_e is 0.1

(PSO)算法对波导尺寸进行逆向设计。PSO 算法本质上是一种随机搜索算法,优化速度快,能以较快速度得到全局最优解,其迭代优化过程如图 6 所示,有 3 个变量需要调整优化,包括质子交换时间、侧壁倾角和波导的刻蚀宽度。将优化目标(FOM)设定为有效模场面积,选择的优化停止准则为达到最大迭代次数就停止搜索,将迭代次数设定为 20,群体大小设定为 20。综合前文扫描结果来设定粒子的位置范围,将质子交

换深度变化范围约束在 $2\sim 4\ \mu\text{m}$, 将波导刻蚀宽度约束在 $1.5\sim 3.5\ \mu\text{m}$, 将侧壁倾角约束在 $80^\circ\sim 90^\circ$ 。图 7 所示为不同迭代次数下有效模场面积的变化趋势, 可以看到, 经过多次迭代后, 3 个参数将保持稳定, 波导的有效模场面积最小, 可以作为最终的优化结果。此时对应的质子交换深度为 $2.48\ \mu\text{m}$, 波导宽度为 $2.78\ \mu\text{m}$, 侧壁倾角为 80.5° 。考虑到工艺精度的限制, 认为当侧壁倾角为 80.5° , 波导宽度为 $2.8\ \mu\text{m}$, 波导高度为 $2.5\ \mu\text{m}$ 时, 有效模场面积最小。

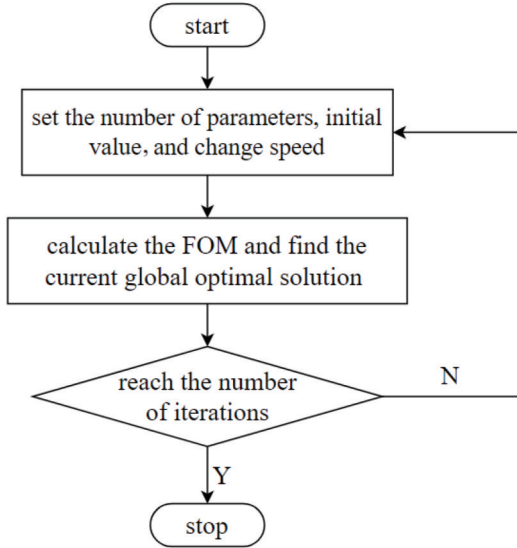


图 6 PSO 算法流程

Fig. 6 Flow of PSO algorithm

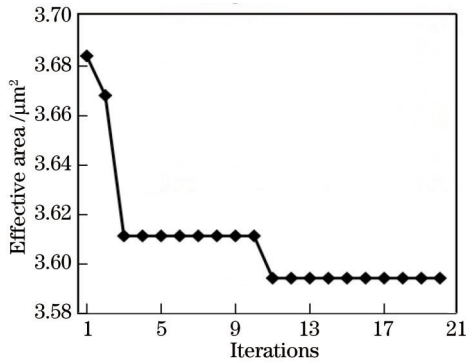


图 7 不同迭代次数下有效模场面积的变化趋势

Fig. 7 Trend of effective mode field area under different iterations

4 铌酸锂阵列波导光栅设计

阵列波导光栅波分复用/解复用器的整体结构如图 8(a) 所示, 它由输入/输出波导、平板波导、阵列波导构成。其中, 输入/输出平板波导一般采用罗兰圆结构, 如图 8(b) 所示, 且输入/输出波导和阵列波导由输入/输出平板波导连接。光从输入波导进入, 在输入平板波导中形成高斯远场衍射, 并以相同的相位进入阵

列波导中。阵列波导的作用是引入长度差, 以此形成相位差, 使得不同波长的光在输出平板波导中聚焦在罗兰圆的不同位置, 即对应从不同的输出波导输出, 从而实现波长的解复用功能。由于整个器件呈对称结构, 当将器件输出端作为输入端时, 器件能够实现波长的复用功能。

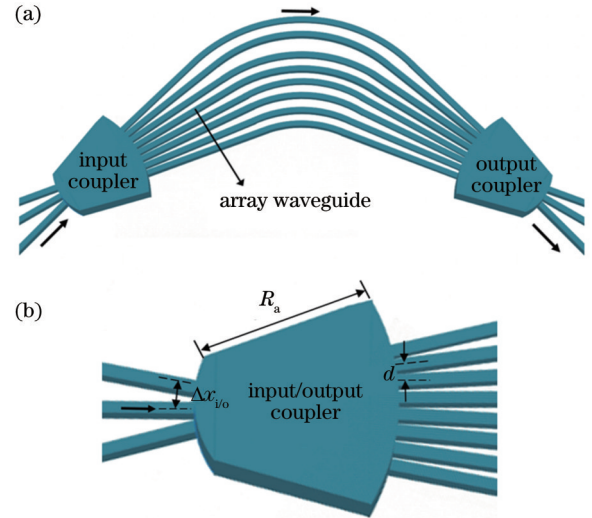


图 8 阵列波导光栅结构图。(a) 阵列波导光栅整体结构图; (b) 输入平板波导俯视图

Fig. 8 AWG structure diagram. (a) Schematic of AWG; (b) top view of the coupler

阵列波导光栅满足的光栅方程为

$$n_{s, \text{eff}} d \sin \theta_i + n_{s, \text{eff}} d \sin \theta_o + n_{c, \text{eff}} \Delta L = m \lambda_0, \quad (2)$$

式中: $n_{s, \text{eff}}$ 为平板波导的有效折射率; $n_{c, \text{eff}}$ 为波导有效折射率; θ_i 和 θ_o 分别为阵列波导与中心输入/输出波导的夹角; ΔL 为相邻阵列波导的长度差; m 为衍射级数; λ_0 为中心波长; d 为相邻阵列波导的间距。

采用优化后的波导尺寸设计阵列波导光栅。由于刻蚀过程是各向异性的, 波导存在一定的侧壁倾角, 设定波导的侧壁倾角为 85° , 通过仿真可得, 当波导宽度为 $2.4\ \mu\text{m}$, 波导脊高为 $2.8\ \mu\text{m}$ 时, 波导的群折射率 n_g 为 2.218, $n_{c, \text{eff}}$ 为 2.155。选择足够大的阵列波导间距来保证相邻阵列波导之间没有串扰, 但较大的阵列波导间距会导致罗兰圆的直径增大, 从而导致器件尺寸增大, 本实验最终将波导间距选定为 $4\ \mu\text{m}$ 。粗波分复用阵列波导光栅的波长间隔为 $20\ \text{nm}$, 自由光谱范围 (FSR) 越大, 器件的均匀性越好, 但会增大器件尺寸; FSR 越小, 芯片尺寸越小, 但器件的均匀性会下降。同时, 为了避免通道混叠, FSR 应大于 $80\ \text{nm}$, 因此, 本实验将衍射级数设定为 11。根据阵列波导光栅设计的基本原理^[22], 可以对器件其他结构参数进行确认, 最终得到器件尺寸约为 $850\ \mu\text{m} \times 620\ \mu\text{m}$ 。

由于整个阵列波导光栅器件尺寸较大, 对器件整体进行仿真将会耗费较长时间和大量内存, 因此将器件简化为输入/输出平板波导两部分分别进行仿真。

由于光在阵列波导中的传播损耗较小,可以忽略不计,因此在仿真模型中将光在阵列波导中传输的过程转换为数学模型。通过控制光进入每根波导的顺序来代替阵列波导的效果,用时间差来代替长度差,以简化仿真模型,提升仿真效率。时延 Δt 与相邻波导长度差 ΔL 的关系可表示为

$$\Delta t = \frac{\Delta L}{v_g}, \quad (3)$$

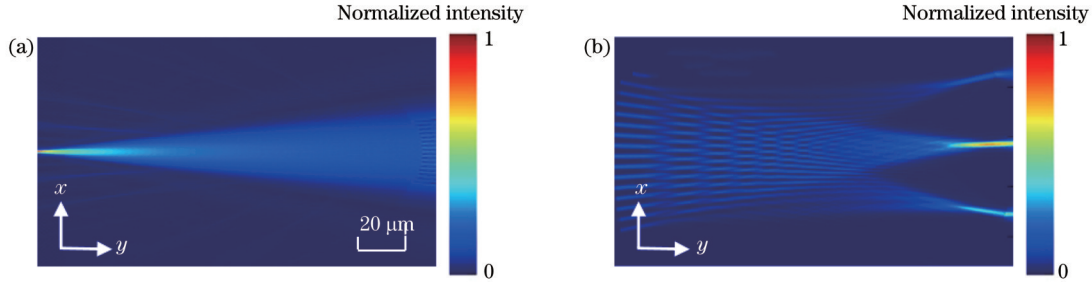


图 9 耦合器光场图。(a)输入耦合器的光场;(b)输出耦合器的光场

Fig. 9 Coupler light field diagrams. (a) Optical field profile of input coupler; (b) optical field profile of output coupler

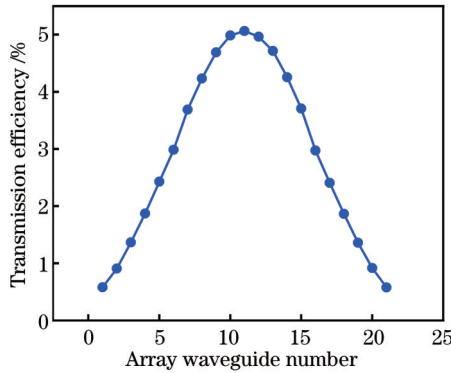


图 10 每根阵列波导的传输效率

Fig. 10 Transmission efficiency of each array waveguide

图 11 所示为阵列波导光栅的输出光谱。可以看出,通道间距为 20 nm,每个通道的插入损耗为 6 dB 左右,串扰均低于 -22 dB,如表 1 所示。

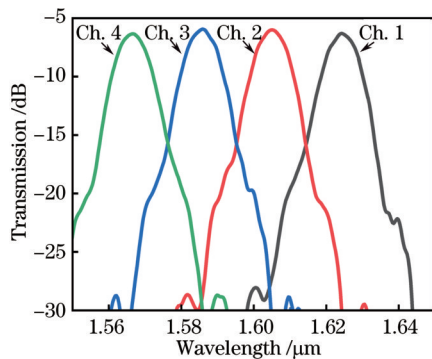


图 11 阵列波导光栅的传输频谱图

Fig. 11 Transmission spectra of AWG

5 结 论

质子交换会使铌酸锂发生相变,并产生结构缺陷,

式中: v_g 表示群速度。

图 9 所示分别为阵列波导光栅的输入耦合光场和 1517 nm 波长光在输出耦合器的光场,图 10 所示为从输入耦合器进入到每根阵列波导的传输效率。可以看出,由于相邻阵列波导间距较大,光从输入耦合器进入阵列波导时因波导形状突变而无法全部进入下一个波导结构,即输入耦合器的平板模式与阵列波导的模式耦合时产生反射和散射,带来了部分损耗。

表 1 每个通道的插入损耗和串扰

Table 1 Insert loss and crosstalk of each channel

Channel No.	Insert loss /dB	Crosstalk /dB
Ch. 1	6.31	-23.66
Ch. 2	6.01	-23.00
Ch. 3	5.94	-22.80
Ch. 4	6.34	-22.27

使得铌酸锂可以被直接刻蚀。因此,提出一种将质子交换和刻蚀工艺结合的波导制备工艺。通过仿真验证了该工艺的可行性。通过改变质子交换的深度、波导的刻蚀宽度和由铌酸锂的各向异性所导致的刻蚀不完全带来的侧壁倾角,结合 PSO 算法优化了体铌酸锂平台的波导宽度。采用优化后的波导设计了一种阵列波导光栅,相邻通道的串扰均低于 22 dB,进一步验证了所提工艺的可行性。未来的工作将集中在利用由这种工艺方案制备的波导设计其他光学器件,并通过实验验证该工艺方案对波导尺寸的优化效果。

参 考 文 献

- [1] Smit M, Williams K, Jos V. Past, present, and future of InP-based photonic integration[J]. APL Photonics, 2019, 4: 050901.
- [2] Weis R S, Gaylord T K. Lithium niobate: summary of physical properties and crystal structure[J]. Applied Physics A, 1985, 37 (4): 191-203.
- [3] 孙祺. 钛扩散铌酸锂光波导光学性质的实验研究[D]. 天津: 天津大学, 2020.
Sun Q. Experimental studies on optical properties of titanium-diffused lithium niobate optical waveguides[D]. Tianjin: Tianjin University, 2020.
- [4] Chen G Y, Li N X, Da Ng J, et al. Advances in lithium niobate photonics: development status and perspectives[J]. Advanced Photonics, 2022, 4(3): 034003.
- [5] Bazzan M, Sada C. Optical waveguides in lithium niobate:

- recent developments and applications[J]. Applied Physics Reviews, 2015, 2(4): 040603.
- [6] Cheng R S, Chen W L, Wang W S. Mach-Zehnder modulators with lithium niobate ridge waveguides fabricated by proton-exchange wet etch and nickel indiffusion[J]. IEEE Photonics Technology Letters, 1995, 7(11): 1282-1284.
- [7] Vazimali M G, Fathpour S. Applications of thin-film lithium niobate in nonlinear integrated photonics[J]. Advanced Photonics, 2022, 4(3): 034001.
- [8] 乔玲玲, 汪旻, 伍荣波, 等. 超低损耗铌酸锂光子学[J]. 光学学报, 2021, 41(8): 0823012.
- Qiao L L, Wang M, Wu R B, et al. Ultra-low loss lithium niobate photonics[J]. Acta Optica Sinica, 2021, 41(8): 0823012.
- [9] 原荣. 阵列波导光栅(AWG)器件及其应用[J]. 光通信技术, 2010, 34(1): 1-5.
- Yuan R. Arrayed waveguide grating component and its applications[J]. Optical Communication Technology, 2010, 34(1): 1-5.
- [10] Prost M, Liu G Y, Yoo S J B. A compact thin-film lithium niobate platform with arrayed waveguide gratings and MMIs [C]//2018 Optical Fiber Communications Conference and Exposition (OFC), March 11-15, 2018, San Diego, CA, USA. New York: IEEE Press, 2018.
- [11] Li J Y, Yin R, Ji W, et al. AWG optical filter with tunable central wavelength and bandwidth based on LNOI and electro-optic effect[J]. Optics Communications, 2020, 454: 124445.
- [12] Ji W, Gong Z S, Yin R, et al. Tunable arrayed waveguide grating optical filter based on lithium niobate-on-insulator and electro-optic effect[J]. Optical Engineering, 2018, 57(7): 077102.
- [13] Zhu D, Shao L B, Yu M J, et al. Integrated photonics on thin-film lithium niobate[J]. Advances in Optics and Photonics, 2021, 13(2): 242-352.
- [14] Zhang D L, Wong W H, Pun E Y B. Near-stoichiometric LiNbO₃ optical waveguides fabricated using vapor transport equilibration and Ti co-diffusion[J]. Applied Physics Letters, 2004, 85(15): 3002-3004.
- [15] Jackel J L, Rice C E, Veselka J J. Proton exchange for high-index waveguides in LiNbO₃[J]. Applied Physics Letters, 1982, 41(7): 607-608.
- [16] Stepanenko O, Quillier E, Tronche H, et al. Crystallographic and optical properties of Z-cut high index soft proton exchange (HISoPE) LiNbO₃ waveguides[J]. Journal of Lightwave Technology, 2016, 34(9): 2206-2212.
- [17] Masalkar P J, Fujimura M, Suhara T, et al. Vapour phase proton-exchange: technique for waveguide fabrication in LiNbO₃ [J]. Electronics Letters, 1997, 33(6): 519-520.
- [18] Rambu A P, Apetrei A M, Doutre F, et al. Analysis of high-index contrast lithium niobate waveguides fabricated by high vacuum proton exchange[J]. Journal of Lightwave Technology, 2018, 36(13): 2675-2684.
- [19] Li Y, Lan T, Yang D C, et al. Fabrication of ridge optical waveguide in thin film lithium niobate by proton exchange and wet etching[J]. Optical Materials, 2021, 120: 111433.
- [20] Li X P, Chen K X, Hu Z F. Low-loss bent channel waveguides in lithium niobate thin film by proton exchange and dry etching [J]. Optical Materials Express, 2018, 8(5): 1322-1327.
- [21] El Hadi K, Rastogi V, Shenoy M R, et al. Spectral measurement of the film-substrate index difference in proton-exchanged LiNbO₃ waveguides[J]. Applied Optics, 1998, 37(27): 6463-6467.
- [22] Smit M K, Van Dam C. PHASAR-based WDM-devices: principles, design and applications[J]. IEEE Journal of Selected Topics in Quantum Electronics, 1996, 2(2): 236-250.

Arrayed Waveguide Grating Fabricated over Bulk Lithium-Niobate Substrate Based on Proton Exchange and Etching

Yuan Jiayi, Liu Jiacheng, Du Jiangbing*, He Zuyuan

State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China

Abstract

Objective Lithium niobate (LN), as a key material in the photonic industry, exhibits a strong electro-optic (EO) effect, a large nonlinear optical coefficient, and chemical stability. Traditional LN waveguides are usually prepared through titanium (Ti) diffusion or proton exchange. Ti diffusion exchange causes an increase of 0.001–0.04 in the refractive index, which depends on Ti density, diffusion time, and temperature. Proton exchange can give rise to a change in the refractive index of up to 0.12. These waveguides have the disadvantage of low refractive index contrast between waveguide and cladding, which leads to weak optical constraints, a large mode area, and a millimeter-level bending radius. This is the major limitation of conventional bulk LN for broad applications with a large amount and a small size of LN chips. Therefore, it is necessary to develop a method with a low-cost wafer and high-index-contrast waveguide, which is also the main objective of this work.

Methods This study mainly presents the theory and simulation. The LN material is chemically inert, and therefore, it can hardly be etched without any pre-treatment. In addition, mechanical processing of the LN material is also difficult to proceed due to its high hardness and wear resistance. It is worth noting that during the proton exchange reaction, ions diffuse into the LN substrate to exchange ions, which leads to the occurrence of phase transition and structural defects, and thus, the proton exchange region can be easily etched. Therefore, we present a process scheme combining proton

exchange technology with etching technology. The LN substrate is submerged in the proton source at a high temperature for a long time to assure that the depth of the proton exchange should be equal to the required height of the waveguide at least. After the proton exchange, samples are etched by methods such as wet etching and plasma etching, and the waveguide is retained. The feasibility of the process is verified by simulations. Moreover, the proton exchange depth, etching width, and sidewall angle are changed to optimize the waveguide width of the bulk LN platform.

Results and Discussions The experimental result demonstrates that the waveguide prepared with 1% diluted melt at 300 °C for 72 h can increase n_e by 0.08 at 1550 nm. We initially set the Δn_e to 0.08. The effective mode area under different diffusion depths is shown in Fig. 2. The minimum area is about $14.5 \mu\text{m}^2$ when the diffusion depth is $2.4 \mu\text{m}$. The etched waveguide shows its superiority in reducing width (Fig. 3), and the effective mode area in the waveguide can be reduced to $6.7 \mu\text{m}^2$ by etching. Although the waveguide is decreased to $4.2 \mu\text{m}$, it is still large compared to that of other material platforms. We can further reduce the waveguide size by increasing Δn_e . Δn_e of LN after proton exchange is set to 0.1 at 1550 nm according to theoretical research. With the growth of the diffusion depth, the effective mode area also changes (Fig. 4). The minimum effective mode area is about $7 \mu\text{m}^2$ when the diffusion depth is $2 \mu\text{m}$. To verify the advantage of the fabrication process mentioned above, we set the height of waveguides to $2.8 \mu\text{m}$. Under the same temperature, the proton exchange depth we set can be realized by proton exchange time expansion. Considering the non-vertical sidewalls produced by the etching of LN, the angle of the tilted sidewall is 85° . When the width of the waveguide is $2.4 \mu\text{m}$, the waveguide has the strongest ability to confine the light field (Fig. 6). Compared with the case of an unetched waveguide, increased etching can effectively reduce the width of the waveguide. In addition, as many parameters can be optimized, we use particle swarm optimization (PSO) to design the waveguide size reversely. A set of these parameters that can realize the strongest confinement of the optical field is selected with the assistance of PSO. Here, the figure of merit (FOM) is defined as the effective mode area. The optimization is conducted via Lumerical Mode Solutions. The simulations show that the lowest waveguide width is $2.5 \mu\text{m}$, and the bending radius is reduced to the level of hundreds of microns, which greatly lessens the size of bulk LN devices. Wavelength-division multiplexing (WDM) devices are one of the key components for optical communications. As a planar waveguide component based on optical integration technology, an arrayed waveguide grating (AWG) has the advantages of high integration and low loss compared with the traditional dielectric filter. Hence, it is widely used in the optical interconnection of data centers. On the basis of the proposed process scheme, an AWG with a center wavelength of 1550 nm, four channels, and channel spacing of 400 GHz is designed. The footprint of the device is $850 \mu\text{m} \times 620 \mu\text{m}$, and the transmission loss of the AWG is about 6 dB, as shown in Fig. 10. Since the waveguide spacing is set to be larger than $4 \mu\text{m}$ to avoid the crosstalk from the adjacent waveguides, light cannot enter the arrayed waveguides from the input coupler completely, which causes loss (Fig. 10). The crosstalk between adjacent channels is all lower than 22 dB, which further verifies the feasibility of this scheme.

Conclusions In this paper, a method for fabricating AWGs over the bulk LN substrate is presented. The design of a four-channel CWDM AWG is investigated with a reduced cost due to the use of bulk LN, which proves that this process can reduce the size of the optical devices on the bulk LN platform.

Key words gratings; lithium niobate; proton exchange; coarse wavelength division multiplexing; arrayed waveguide grating