同行专家业内评价意见书编号: 20240854227

附件1

浙江工程师学院（浙江大学工程师学院）
同行专家业内评价意见书

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申报工程师职称专业类别（领域）： 电子信息

浙江工程师学院（浙江大学工程师学院）制

2024年03月27日

一、个人申报

（一）基本情况【围绕《浙江工程师学院（浙江大学工程师学院）工程类专业学位研究生工程师职称评审参考指标》，结合该专业类别(领域)工程师职称评审相关标准，举例说明】

1. 对本专业基础理论知识和专业技术知识掌握清况

本人在专业基础理论知识和专业技术知识方面，已熟练掌握相关光波导器件的设计理论与设计方法，相关专业课程取得优异成绩，同时熟悉光波导器件的加工流程并掌握了多种加工方式，明晰了多种加工方式各自的优缺点，并且能熟练运用相关仪器测试光波导器件及系统的基本性能。总而言之，经过几年的研究生培养，本人熟练掌握了光波导器件的调研、设计、加工、测试、封装等各方面工作。

2. 工程实践的经历

2022-2023年期间，本人在江苏尚飞光电科技股份有限公司开展了为期一年左右的工程实践，参与了应用型课题研究项目：低损耗延迟线的设计，应用先进的展宽波导截面设计和曲率渐变的S型弯曲解决了大规模集成光芯片中光波导传输损耗大的问题，实现了目前基于多项目晶圆的低损耗光波导。

3. 在实际工作中综合运用所学知识解决复杂工程的实例

在这次深入到企业的工程实践中，不管是在专业上、团队合作上还是科研和企业的关系上，我都收获了很多，通过在学校学的知识解决工程中的实际问题，这种感觉很奇妙。损耗是光波导的基本特性，降低光波导的损耗对于硅基光电子芯片的大规模集成具有重要影响。低损耗延迟线项目中设计制作的延迟线是在绝缘体上硅上实现的，主要突破点在于降低光波导损耗并降低器件尺寸，在实验室成果的基础上，同时经过工业生产角度的思考，进一步实现既能在工业上大批量生产、损耗又远低于单模波导并且不引入高阶模的低损耗光波导。项目的主要工作内容可以分为波导截面设计、延迟线版图设计、与流片加工厂对接、延迟线后续性能测试四部分，本人承担波导截面设计、延迟线版图设计、延迟线后续性能测试等3部分工作内容。

考虑实际产品并不像实验室成果一样，制作出了一个性能优良的样品就可以出成果，我们要考虑生产方式的稳定性和良品率；要考虑制作方式是否有大规模的生产线，是否能够支持大批量生产；要考虑生产成本和经济效益等等。出于上述考虑，我们更倾向于流片加工厂生产，而不是自己加工，并且首选多项目晶圆流片，而不是电子束曝光，后者并不适合大批量制作。

常用的降低损耗的方法有：基于工艺改进的湿法刻蚀、无刻蚀光波导、化学机械研磨（Chemical Mechanical Polishing, CMP）等；基于截面设计的超薄波导、脊型波导、展宽波导等。尽管湿法刻蚀、无刻蚀光波导、CMP等工艺可以有效降低光波导的传播损耗，但它们与流片标准工艺不兼容，因此难以实现系统集成、批量生产和技术产业化。超薄光波导虽然能够将损耗值降至相对较低水平，但除光波导外，超薄薄膜上的其他器件尚未成熟，而且在设计上存在困难，不适用于整体系统的研发。同时，薄膜厚度的降低需要用更大的光波导弯曲半径来进行补偿，这不利于器件与系统的小型化，脊型光波导也面临类似的问题。而展宽光波导会增大器件体积，容易引入多模，难以保持单模传输。为推动硅基片上集成光学系统的研究，在追求低损耗的同时，必须兼顾器件体积，以及低损耗光波导与系统、流片工艺之间的兼容性。

为了解决上述问题，我们引入了展宽光波导与欧拉S型弯曲相结合的方法，设计了结构紧凑

的基于阿基米德螺旋线的螺旋线圈，曲率渐变的欧拉S型弯曲通过合理设计可以避免激发高阶模，并降低曲率失配引入的模式失配损耗，而且宽度渐变，中间从多模展宽波导缩窄成单模波导宽度，这也可以过滤掉可能激发的高阶模式。曲率渐变的阿基米德螺旋曲线也是同理，即降低曲率突变引起的模式失配损耗。在降低损耗的同时减小器件的尺寸。

基于上述工艺方案和设计，我们在常用的通信波段实现了0.12dB/cm的超低传播损耗，与损耗为2.5dB/cm的单模波导相比，其损耗降低至单模波导的1/20，并且结构紧凑，曲率渐变的欧拉S型弯曲和阿基米德螺旋曲线极大地降低了延迟线的结构体积，节约了流片面积，降低了生产成本。相关可调延迟线阵列可以实现0.635 ns的大范围延时，最小延时步进为5ps。

光芯片可以实现大信息量、高传输速率的信息传输需求，突破当前电芯片集成度受限的瓶颈，具有抗电磁干扰、大带宽、高传输速率等优点，并且硅基底可以CMOS工艺相兼容。许多光子集成电路应用需要低损耗片上波导来实现更高性能，例如延迟线、片上集成光学陀螺仪、超高Q值微腔、微波光子相控阵波束整形、光学相干断层扫描系统。因此，降低波导损耗至关重要，高密度以及低损耗的特性对实现微型化硅基器件和片上大规模集成系统有着举足轻重的意义。

（二）取得的业绩（代表作）【限填3项，须提交证明原件（包括发表的论文、出版的著作、专利证书、获奖证书、科技项目立项文件或合同、企业证明等）供核实，并提供复印件一份】

1.
公开成果代表作【论文发表、专利成果、软件著作权、标准规范与行业工法制定、著作编写、科技成果获奖、学位论文等】

成果名称	成果类别 [含论文、授权专利（含发明专利申请）、软件著作权、标准、工法、著作、获奖、学位论文等]	发表时间/授权或申请时间等	刊物名称/专利授权或申请号等	本人排名/总人数	**备注**
Ultra-low-loss Silicon Waveguides covering a very large band	会议论文	2023年11月04日	2023 Asia Communications and Photonics Conference	1/5	

2.**其他代表作【主持或参与的课题研究项目、科技成果应用转化推广、企业技术难题解决方案、自主研发设计的产品或样机、技术报告、设计图纸、软课题研究报告、可行性研究报告、规划设计方案、施工或调试报告、工程实验、技术培训教材、推动行业发展中发挥的作用及取得的经济社会效益等】**

（三）在校期间课程、专业实践训练及学位论文相关情况	
课程成绩情况	按课程学分核算的平均成绩： 84 分
专业实践训练时间及考核情况(具有三年及以上工作经历的不作要求)	累计时间： 1 年（要求1年及以上） 考核成绩： 96 分（要求80分及以上）
本人承诺	
个人声明：本人上述所填资料均为真实有效，如有虚假，愿承担一切责任，特此声明！ **申报人签名：**李钢敏	

22160447

二、日常表现考核评价及申报材料审核公示结果

日常表现考核评价	非定向生由德育导师考核评价、定向生由所在工作单位考核评价： ☑优秀　　□良好　　□合格　　□不合格 德育导师/定向生所在工作单位分管领导签字（公章）：　2024 年 3 月 28 日
申报材料审核公示	根据评审条件，工程师学院已对申报人员进行材料审核（学位课程成绩、专业实践训练时间及考核、学位论文、代表作等情况），并将符合要求的申报材料在学院网站公示不少于5个工作日，具体公示结果如下： □通过　　□不通过（具体原因：　　　　　　） 工程师学院教学管理办公室审核签字（公章）：　　　年　月　日

浙江大学研究生院

攻读硕士学位研究生成绩表

学号：22160447	姓名：李钢敏	性别：女	学院：光电科学与工程学院	专业：电子信息	学制：2.5年
毕业时最低应获：24.0学分		已获得：27.0学分		入学年月：2021-09	毕业年月：2024-03
学位证书号：1033532024302007			毕业证书号：103351202402300033		授予学位：电子信息硕士

学习时间	课程名称	备注	学分	成绩	课程性质	学习时间	课程名称	备注	学分	成绩	课程性质
2021-2022学年秋季学期	集成平面光波导器件		2.0	88	跨专业课	2021-2022学年秋冬季学期	工程前沿技术讲座		2.0	82	专业学位课
2021-2022学年秋季学期	人工智能算法与系统		2.0	80	专业学位课	2021-2022学年夏季学期	微光学技术及微系统		2.0	94	专业学位课
2021-2022学年秋季学期	科技写作		2.0	88	专业学位课	2021-2022学年夏季学期	先进传感技术		2.0	85	专业学位课
2021-2022学年秋季学期	研究生英语基础技能		1.0	免修	公共学位课	2021-2022学年夏季学期	自然辩证法概论		1.0	81	公共学位课
2021-2022学年秋季学期	电子信息工程中数学模型与方法		2.0	88	专业学位课	2021-2022学年春夏季学期	工程伦理		2.0	84	公共学位课
2021-2022学年秋冬季学期	中国特色社会主义理论与实践研究		2.0	82	公共学位课	2022-2023学年春季学期	游泳		1.0	优	公共选修课
2021-2022学年秋冬季学期	光学电磁理论		3.0	94	专业学位课	2022-2023学年夏季学期	“四史”专题		1.0	93	公共选修课
2021-2022学年冬季学期	研究生英语		2.0	免修	公共学位课						

说明：1. 研究生课程按三种方法计分：百分制，两级制（通过、不通过），五级制（优、良、中、及格、不及格）。

2. 备注中“*”表示重修课程。

学院成绩校核章：

成绩校核人：张梦依

打印日期：2024-04-02

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Ultra-low-loss Silicon Waveguides covering a very large band

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Abstract— **We present an ultra-low-loss silicon waveguide covering a very large band. Additionally, we investigate the waveguide wavelength-dependent scattering losses. Remarkably, we achieve loss reductions of (0.1663, 0.1226, 0.0742) dB/cm around (1310, 1550, 1910) nm, respectively.**

Keywords-silicon – photonics; ultra-low-loss; multi-mode waveguide; very large-band

I. INTRODUCTION

In recent years, silicon photonics has emerged as a highly popular technology due to its CMOS compatibility, high integration density, and cost-effectiveness compared to bulk fiber optic systems [1,2]. Notably, on-chip optical waveguides with ultra-high refractive index contrast (Δn≈2) confine the mode field within a compact size [3]. However, this high contrast also increases the interaction of the mode field with the rough sidewalls and surfaces of the waveguide, leading to enhanced scattering losses [2]. Many applications of photonics integrated circuits (PICs) now require long on-chip waveguides for functional unit interconnections, such as true-time delay lines [4] and optical gyroscopes [5]. Therefore, it is crucial to reduce silicon waveguide propagation losses across very large wavelengths.

The roughness of interfaces is the primary source of propagation loss in waveguides. Currently, there are two main approaches to effectively reduce waveguide loss. One involves improving the fabrication process to reduce waveguide sidewall roughness. Techniques such as chemo-mechanical polishing (CMP) have been used to achieve smoother waveguide interfaces [6], and wet chemical etching is also commonly employed [7]. However, these processes may not be suitable for mass production in multi-project wafer (MPW) foundries. The second approach involves reducing the mode field's contact with the sidewall through mode field modulation. Careful optimization of the waveguide's cross-sectional shape is an effective means of reducing scattering losses [5].

Additionally, we observed a negative correlation between the scattering loss of the mode field in multimode waveguides and the wavelength. In this paper, we conducted a systematic comparison of multimode waveguide losses across different wavelength bands. Notably, we achieved an ultra-low-loss silicon-on-insulator (SOI) waveguide with a loss of 0.1663 dB/cm at 1310 nm, utilizing the MPW foundry approach, and a cross-section of 220 nm × 3000 nm. The same structure demonstrated reduced losses of 0.1226 dB/cm at 1550 nm and 0.0742 dB/cm at 1910 nm.

II. DESIGN AND SIMULATION COMPARISON

The cross-section of the ultra-low-loss waveguide is carefully chosen as 220 nm×3000 nm. Figure 1(a) illustrates the design of the proposed SOI waveguide spiral, featuring single-mode input/output waveguides with width of 450 nm. The central part of the spiral, depicted in red in Fig. 1(b), is specially designed with four Euler curves followed by two sections of Archimedean spiral. A gap of 2 µm is judiciously selected. To suppress and eliminate higher-mode excitation, we determine the Euler curve parameters ($R_{\max}$, $R_{\min}$) using the approach described in [8] and [9], and the S-bend narrows to a 600 nm wide waveguide in the middle from 3 µm.

For silicon waveguide, the total propagation loss is the sum of many contributions and the interfacial scattering induced by sidewall and interface roughness is the main source for the total loss. Here we introduce the three-dimensional volume current method (TDVCM), a method modeling the radiation loss due to scattering from the refractive index inhomogeneity at this rough interface as an equivalent polarization volume current density, to calculate the propagation loss due to interfacial scattering and has observed a negative correlation between scattering loss and wavelength.

We conducted extensive calculations of the propagation loss attributed to interfacial scattering across the studied wavelength range of 1200 - 2000 nm. Here, we analyzed and compared the propagation loss of the 220 nm thick SOI wave-

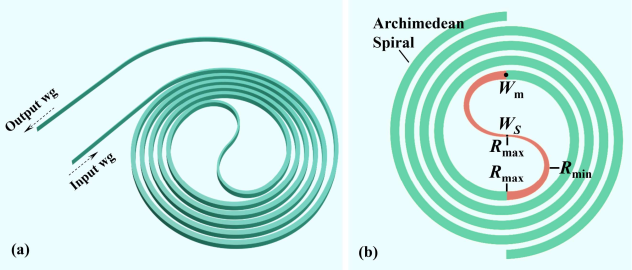

Figure 1. (a) Spiral 3D diagram featuring single-mode input/output waveguides with width of 450 nm; (b) Composition of spiral with tapered Euler curve S-bend and Archimedean spiral.

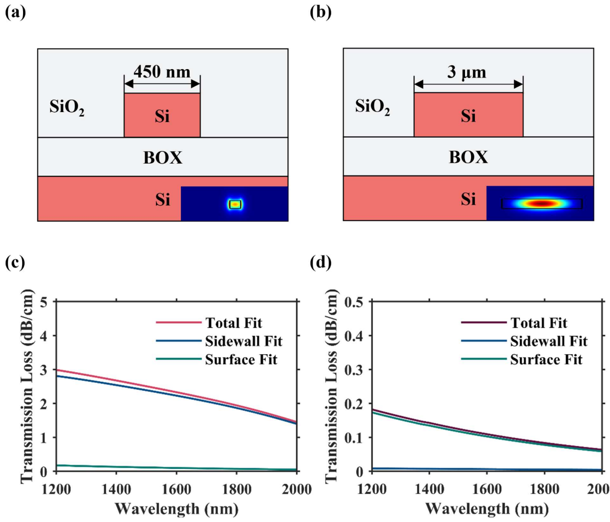

Figure 2. (a) The cross-section and TE$_0$ mode field distribution at 1910 nm with the waveguide with of 450 nm; (b) the cross-section and TE$_0$ mode field distribution at 1910 nm with the waveguide with of 3 μm; (c) the variation of three types of losses in a 450-nm-wide waveguide with increasing wavelength range of 1200-2000 nm; (d) the variation of three types of losses in a 3-μm -wide waveguide with increasing wavelength range of 1200-2000 nm.

guide with width of 3 μm and 450 nm, encompassing the scattering losses induced by the sidewall, surface, and the total propagation loss. The sidewall and surface roughness used were 3 nm and 0.25 nm according to the modern fabrication technology [10].

Figures 2(a)-(b) show the waveguide cross-section and TE$_0$ mode field distribution simulated by MODE of the waveguide with width of 450 nm and 3 μm, and we can find that the contact area between the mode field and interface of the wider waveguide is less. Figures 2(c)-(d) present the calculations results, demonstrating that propagation loss attributed to interfacial scattering of the waveguide with width of 450 nm and 3 μm gradually decrease with increasing wavelength, including the scattering loss due to the sidewall, surface, and the total loss. Notably, the scattering loss induced by the sidewall is too small to exhibit a discernible trend. Besides, the loss of the wider waveguide is much lower than the narrower waveguide. Specifically, the total simulated propagation loss of the waveguide with width of 3 μm is calculated to be 0.1591 dB/cm at 1310 nm, 0.1169 dB/cm at 1550 nm, and further reduces significantly to 0.0721 dB/cm at 1910 nm, contrast to the 2.8233 dB/cm at 1310 nm, 2.4201 dB/cm at 1550 nm, and 1.6877 dB/cm at 1910 nm of the waveguide with width of 450 nm.

III. EXPERIMENT

We experimentally fabricated the spiral waveguide on a 220 nm SOI platform with a length of 23 cm and a width of 3 μm, thereby validating the simulation findings. The fabrication was carried out using MPW foundry, demonstrating the compatibility of the ultra-low-loss waveguide with CMOS technology for scalable mass production. To assess the losses of the same structure across a very large band, we employed inverse taper coupling instead of grating couplers to couple optical signals at different wavelength. The test results, presented in Fig.3 (a)-(c), showed that the average loss of the spiral was 0.1663 dB/cm at 1310 nm, 0.1226 dB/cm at 1550 nm, and further reduced to 0.0742 dB/cm at 1910 nm. Remarkably, the experimental results aligned closely with the simulation outcomes, as depicted in Fig.3 (d), indicating a strong correlation between them. Slight discrepancies observed can be attributed to the effects of sidewall and surface roughness, which are inherent to the fabrication process. The successful verification of the ultra-low-loss waveguide's performance in practical implementation reinforces its potential for advanced photonic integrated circuits.

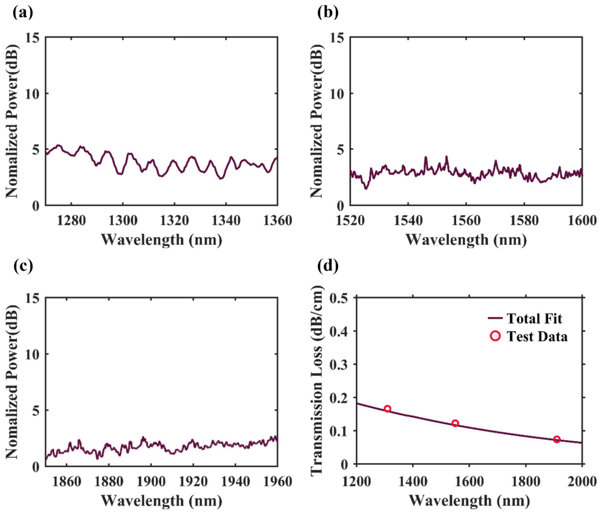

Figure 3. (a) 23 cm long spiral loss at 1310 nm; (b) 23 cm long spiral loss at 1550 nm; (c) 23 cm long spiral loss at 1910 nm; (d) matching between test results and simulation results.

IV. SUMMARY

In this paper, we demonstrate an ultra-low-loss silicon waveguide covering the entire spectral band and reveal the relationship of waveguide scattering loss with wavelength. achieving an ultra-low-loss SOI waveguide with a loss of 0.1663 dB/cm for the TE$_0$ mode at 1310 nm based on MPW foundry, which cross section is chosen as 220 nm × 3000 nm. The loss of the same structure is 0.1226 dB/cm at 1550 nm, and can be greatly reduced to 0.0742 dB/cm at 1910 nm. The ultra-low-loss waveguide mentioned is compatible with CMOS technology and can be mass-produced.

ACKNOWLEDGMENT

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