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**Cantilever Inverse Taper Coupler With SiO2 Gap for Submicrometer Silicon Waveguides**

**对于亚微米硅波导二氧化硅间隙悬臂倒锥形耦合器**

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Abstract— In this letter, we present a cantilever inverse taper coupler with Si O2 gap for coupling optical beam between an optical fiber and a sub-micron Si waveguide. // The result shows that the input spot size of 5 m can be coupled to 500 nm×240 nm silicon waveguide with a coupling loss less than 0.49 dB/facet and a 3-dB misalignment tolerance larger than 1.8 m for both TE and TM modes.The coupling loss for a standard cleaved fibre with the input spot size of 10.5 m is 3.72 dB/facet (TE) and 2.12 dB/facet (TM). // The couplers have shown improvement in misalignment tolerance for the input spot size of 5 m and in coupling loss for the input spot size of 10.5 m due to the introduction of Si O2 gap in comparison with other reported taper coupler designs.These improvements are achieved without compromising the other performance parameter (coupling loss or misalignment tolerance) and requiring complicated design and fabrication process.

摘要——在这封信中，我们提出了一个悬臂倒锥形耦合器与硅氧间隙耦合光束之间的光纤和亚微米硅波导。结果表明，5 μm的输入光斑可以耦合到500 nm×240 nm的硅波导，耦合损耗小于0.49 dB/面，TE和TM模式的3 dB失调容差大于1.8 m。输入光斑尺寸为10.5米的标准解理光纤的耦合损耗为3.72分贝/面(TE)和2.12分贝/面(TM)。与其他报道的锥形耦合器设计相比，耦合器在输入光斑尺寸为5米时的失调容差和输入光斑尺寸为10.5米时的耦合损耗方面有所改善，这是因为引入了二氧化硅间隙。这些改进是在不损害其他性能参数(耦合损耗或失调容差)的情况下实现的，并且需要复杂的设计和制造过程。

Index Terms— Taper coupler, misalignment tolerance, coupling loss.

索引术语——锥形耦合器、失调容差、耦合损耗。

I. INTRODUCTION

一.导言

PHOTONIC Integrated Circuits (PICs) on Silicon-On-Insulator (SOI) substrate have been attracting a lot of attention and developing fast in the last two decades. // The unique advantages of SOI substrate include excellent optical properties of silicon, significant device scaling due to sili-con's high refractive index and CMOS fabrication process compatibility. // Launching light into a sub-micron silicon waveguide (SiW) from a standard single-mode fiber with minimal coupling loss is highly desirable as the traditional butt-coupling approach introduces a significant coupling loss due to large Mode Field Diameter (MFD) mismatch between the SiW and standard single-mode fiber.

近二十年来，绝缘体(SOI)衬底上的硅基光子集成电路引起了人们的广泛关注，发展迅速。SOI衬底的独特优势包括硅的优异光学性能、李思-康的高折射率和CMOS制造工艺兼容性导致的显著器件缩放。从标准单模光纤以最小的耦合损耗将光发射到亚微米硅波导(SiW)中是非常理想的，因为传统的对接耦合方法由于SiW和标准单模光纤之间的大模场直径(MFD)失配而引入了显著的耦合损耗。

Grating and inverse taper couplers are the main approaches that have been employed to improve the coupling efficiency between a SiW and a single-mode optical fiber. // Grating couplers exhibit a narrow bandwidth when designed for high coupling efficiency and their fabrication process is relatively complex [1].In contrast, inverse taper couplers have been demonstrated with wider bandwidth and higher coupling efficiency [2]. // But they are prone to non-smooth coupling facet and fiber-to-coupler misalignment that result in substantial loss. // A short SiO2 gap defined photo-lithographically and reactive ion etched in front of the taper waveguide has been used to achieve a smooth coupling facet.However, the gap is required to be as short as possible to prevent additional loss due to beam divergence in the Si O2 gap [2]. // To further reduce MFD mismatch, lensed fibers with input spot size of 2.5 0.5 m have also been used to demonstrate an inverse taper coupler with a loss of 0.7dB/facet [2].Although the small spot size from the lensed fiber improves the coupling efficiency, such couplers suffer from misalignment tolerance.Misalignment introduced during packaging process, for exam-ple, can easily lead to significant loss.A comprehensive sim-ulation shows that a 3 dB horizontal misalignment tolerance for a single stage linear inverse taper with a 2.5 m spot size lensed fiber is 1.27 m and 0.93 m for TE and TM mode, respectively [3].

光栅和倒锥形耦合器是用来提高SiW和单模光纤之间耦合效率的主要方法。当设计用于高耦合效率时，光栅耦合器表现出窄带宽，并且它们的制造过程相对复杂[1]。相反，反向锥形耦合器已经被证明具有更宽的带宽和更高的耦合效率[2]。但是，它们容易出现非平滑耦合面和光纤到耦合器的错位，从而导致大量损耗。 在锥形波导前面光刻和反应离子刻蚀了一个短的二氧化硅间隙用于实现平滑的耦合面。然而，该间隙要求尽可能短，以防止由于二氧化硅间隙[2]中的光束发散引起的额外损耗。为了进一步减少MFD失配，输入光斑尺寸为2.5±0.5m的透镜光纤也被用于演示损耗为0.7分贝/分面[2]的倒锥形耦合器。尽管透镜光纤的小光斑尺寸提高了耦合效率，但这种耦合器存在失调容差。例如，在包装过程中引入的错位很容易导致重大损失。一个全面的模拟表明，对于2.5 m光斑尺寸的透镜光纤，单级线性倒锥的3 dB水平失准容差对于TE和TM模式分别为1.27 m和0.93 m，[3]。

Cantilever inverse taper couplers have been proposed to confine a beam in a cladding material in order to improve coupling efficiency and misalignment tolerance [4]-[6].However, the improvement in misalignment tolerance was limited because most couplers were designed for small input spot size of 2.5 m. Although larger spot size can provide better misalignment tolerance, the coupling loss is higher than 4dB/facet for a standard cleaved fibre due to large MFD mismatch.A coupler for larger spot size has been reported in order to improve misalignment tolerance with a coupling loss of about 2dB/facet and 4dB/facet for 5 m and 9.2 m, respectively [5].However, the coupling structure requires a relatively complicated design and fabrication process.A coupler that reduces coupling loss to 2dB/facet for TE mode input from a standard cleaved fibre with a 10.5 m spot size has been demonstrated [6], but the coupler has to be surrounded by index-matching oil.Therefore, a coupler that reduces coupling loss for large input spot sizes and increase misalignment tolerance for small input spot sizes without requiring index-matching oil or complicated fabrication process is highly desirable.In this letter, we report such a coupler consisting of an inverse taper silicon structure embedded in a Si O2 cantilever waveguide with a Si O2 gap.

为了提高耦合效率和失调容限，已经提出了悬臂倒锥形耦合器来将光束限制在包层材料中，[4]-[6]。然而，未对准容差的改善是有限的，因为大多数耦合器是为2.5 m的小输入光斑尺寸而设计的。尽管较大的光斑尺寸可以提供更好的未对准容差，但是对于标准解理光纤，由于大的MFD失配，耦合损耗高于4dB/刻面。报道了一种用于较大光斑尺寸的耦合器，以提高失调容限，其耦合损耗分别为约2dB/刻面和4dB/刻面，分别为5 m和9.2 m[5]。然而，耦合结构需要相对复杂的设计和制造过程。[6号已经演示了一种耦合器，对于来自10.5米光斑尺寸的标准解理光纤的TE模式输入，该耦合器将耦合损耗降低到2dB/刻面，但是耦合器必须被折射率匹配油包围。因此，非常需要一种耦合器，其对于大的输入光点尺寸减少耦合损耗，并且对于小的输入光点尺寸增加未对准容差，而不需要折射率匹配油或复杂的制造工艺。在这封信中，我们报道了这样一种耦合器，它由嵌入在具有二氧化硅间隙的二氧化硅悬臂波导中的倒锥形硅结构组成。

II.DESIGN

二、设计

The proposed cantilever inverse taper coupler consists of a 100 m long SiO2 cantilever waveguide, an inverse linear taper SiW embedded in the middle of the SiO2 waveguide and a SiO2 gap between the SiO2 waveguide facet and the taper end. // Figure 1(a) and (b) show the top and side views of the coupler, respectively. // The SiW is 500nm wide and 240nm high rectangular structure formed from a 240nm thick active layer of an SOI substrate with the BOX acting as a lower cladding and covered with an identically thick PECVD Si O2 on top as upper cladding. // The waveguide is terminated by the inverse linear taper structure from the initial width of 500nm to 80nm in a length of 100 m. // The taper portion of SiW is located in the middle of the 100 m long SiO2 cantilever waveguide consisting of the BOX and the deposited PECVD oxide. // The SiO2 gap represents the portion of the SiO2 cantilever waveguide between the taper end and SiO2 waveguide facet. // The SiO2 waveguide has identical width and height of either 6 m or 8 m depending on the design for input spot sizes of 5 m or 10.5 m, respectively.

所提出的悬臂倒锥形耦合器由100米长的二氧化硅悬臂波导、嵌入在二氧化硅波导中间的倒线性锥形SiW以及二氧化硅波导面和锥形端之间的二氧化硅间隙组成。图1(a)和(b)分别显示了耦合器的俯视图和侧视图。 // SiW是500纳米宽、240纳米高的矩形结构，由240纳米厚的SOI衬底有源层形成，BOX作为下包层，顶部覆盖有相同厚度的PECVD二氧化硅作为上包层。 // 波导管的终端是在100米中从初始宽度500纳米到80纳米的反向线性锥形结构。 // SiW的锥形部分位于100米二氧化硅悬臂波导的中间，该波导由BOX和沉积的PECVD氧化物组成。 // 二氧化硅间隙代表二氧化硅悬臂波导在锥形端和二氧化硅波导面之间的部分。 // 根据输入设计，二氧化硅波导的宽度和高度相同，为6米或8米斑点大小分别为5米或10.5mi

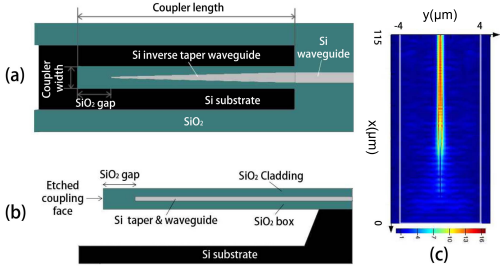


Fig. 1.(a) Coupler schematic top view.(b) Coupler schematic side view.(c) Simulated field distribution along XY plane.

图1。耦合器示意俯视图。耦合器示意侧视图。沿XY平面的模拟场分布。

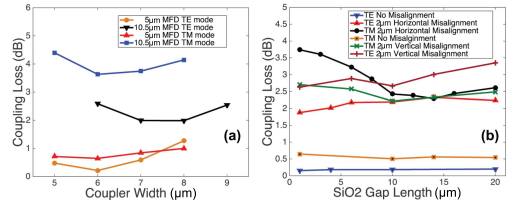


Fig. 2.(a): Coupling loss for 5 m and 10.5 m MFD input source as a function of SiO2 waveguide width with 1 m SiO2 gap in TE mode.(b): The coupling loss of 6 m×6 m coupler for input spot size of 5 m for various SiO2 gap lengths.

图2。(a):在TE模式下，5米和10.5米MFD输入源的耦合损耗与1米二氧化硅间隙的二氧化硅波导宽度的函数关系。(b):对于不同的二氧化硅间隙长度，输入光斑尺寸为5米时，6米×6米耦合器的耦合损耗。

Fig. 3.Misalignment tolerance of 6 m× m coupler with 5 m MFD input

图3。具有5米MFD输入的6米×米耦合器的失调容差

source: (a) TE mode.(b) TM mode.

资料来源:(a)技术教育模式。(二)商标模式。

III.SIMULATION

三、模拟

The cantilever coupler is investigated using a 3D Finite Difference Time Domain simulation. // A 1550nm Gaussian mode source is launched at the coupler facet and acts as an input source. Figure 1(c) shows the field distribution along XY plane for 8m wide coupler with 10 m long SiO2 gap. The coupling loss of the coupler is calculated from the input power at the source and power measurement in the SiW.Misalignment tolerances are investigated by launching the input source at various positions in vertical and horizontal directions. Both TE and TM modes have been studied with input spot sizes of 5 m and 10.5 m.

使用三维时域有限差分模拟来研究悬臂耦合器。1550纳米高斯模式光源在耦合器面发射，并作为输入源。图1(c)显示了具有10米SiO2间隙的8米宽耦合器沿XY平面的场分布。耦合器的耦合损耗由源端的输入功率和SiW的功率测量值计算得出。通过在垂直和水平方向的不同位置启动输入源来研究失调容差。在输入光斑尺寸为5米和10.5米的情况下，对热电模式和热电模式进行了研究。

In order to obtain optimal SiO2 waveguide width (same as height), the coupling loss as a function of SiO2 waveguide with 1m long SiO2 gap is simulated and plotted in figure 2(a). // The optimal widths for 5 m input spot sizes are 6 m for both TE and TM modes. For 10.5 m input spot size, the optimal widths are 6 m and 8 m for TM and TE, respectively. // However, as the SiO2 gap length is further increased from 1 m, the 6 m wide coupler starts to produce more coupling loss in TM mode than 8 m wide coupler. For example, the simulated loss for 8 m wide coupler is 1.8dB and smaller than 3.4dB for 6 m wide coupler for SiO2 gap length of 22 m. Coupler width wider than 8 m can be expected to provide better coupling in TM mode.However, the coupling loss in TE mode will increase as the width is made larger than 8 m. // Therefore, the width of 8 m is chosen as the optimal width for 10.5 m input spot size.

为了获得最佳的二氧化硅波导宽度(与高度相同)，在图2(a)中模拟并绘制了耦合损耗与具有1 mSiO2间隙的二氧化硅波导的函数关系。对于TE和TM模式下5米长的输入光斑尺寸的最佳宽度为6米。对于10.5米的输入光斑尺寸，最佳宽度分别为6米和8米。然而，随着硅氧间隙长度从1米进一步增加，6米宽的耦合器开始产生比8米宽的耦合器更多的耦合损耗。例如，对于宽度为8米的耦合器，模拟损耗为1.8分贝，对于宽度为6米的耦合器，模拟损耗小于3.4分贝，对于宽度为22米的二氧化硅间隙长度，模拟损耗小于3.4分贝。然而，当宽度大于8 m时，TE模式中的耦合损耗将增加。因此，选择8 m的宽度作为10.5 m输入光斑尺寸的最佳宽度。

The 6 m×6 m coupler designed for an input spot size of 5 m is simulated for various lengths of SiO2 gap to investigate their effect on coupling loss with 0 m and 2 m horizontal misalignments. The result is presented in figure 2(b) and indicates that the coupling loss is relatively constant with the Si O2 gap length between 1 m and 20 m for both TE and TM mode when there is no misalignment. With a 2 m horizontal misalignment, the coupling loss drops down from 3.7dB to 2.4dB for TM mode when the SiO2 gap is increased from 1 m to 10 m, which indicates the SiO2 gap allows improvement in misalignment tolerance. Further increase in the length of SiO2 gap above 10 m does not provide any significant advantage as the coupling loss is either maintained or increased. // Figure 3 (a) and (b) show the coupling loss as a function of misalignment in both vertical and horizontal directions with Si O2 gaps of 1 m and 10 m for TE and TM mode, respectively. For TM mode, the 3dB misalignment tolerance in vertical direction for 10m long SiO2 gap improves to 2.5 m as compared to 2 m for 1 m long SiO2 gap. However, the improvement of misalignment tolerance for TE mode due to SiO2 gap is not observed from figure 3 (a).

为了研究不同长度的硅氧间隙对0米和2米水平失调耦合损耗的影响，模拟了为5米输入光斑尺寸设计的6米×6米耦合器。结果如图2(b)所示，表明耦合损耗相对恒定当没有错位时，硅氧间隙长度在1米和20米之间。对于2米水平失准，当硅氧间隙从1米增加到10米时，耦合损耗从3.7分贝下降到2.4分贝，这表明硅氧间隙允许提高失准容限。当耦合损耗保持不变或增加时，进一步增加10米以上的氧化硅间隙长度不会提供任何显著的优势。 图3 (a)和图3(b)显示了在垂直和水平方向上耦合损耗作为失准的函数，其中硅氧间隙分别为1米和10米。对于TM模式，10米SiO2间隙在垂直方向上的3dB失调容差提高到2.5米，相比之下，1米SiO2间隙为2米。然而，从图3 (a)中没有观察到由于二氧化硅间隙导致的热电模式失调容差的改善。

The coupling behavior and misalignment tolerance of the proposed coupler are also examined for an input spot size of 10.5 m. The input spot size of 10.5 m represents the use of a standard single mode optical fiber.Such fibers are significantly cheaper than lensed fibers and their use is appealing from cost perspective.The coupler width for 10.5 m input spot size is increased from 6 m to 8 m in order to ensure minimal coupling loss. The coupling loss as a function of SiO2 gap length is obtained and presented in figure 4 for 0 m and 2 m horizontal misalignments. It can be seen from the plot that the coupling loss goes down as the length of SiO2 gap is increased until it reaches an optimal value.The optimal length for TE mode is 15 m at which the coupling loss is 1.4dB. The coupling loss is higher at 1.8dB for TM mode at the optimal length of 22 m. Figure 5(a) and (b) show the coupler misalignment tolerance for TE and TM mode, respectively, for 1 m and 10 m long Si O2 gaps.Coupling loss of 1.7dB for 3 m misalignment in both vertical and horizontal direction can be observed for both 1 m and 10 m long Si O2 gaps in TE mode.This behavior is fairly similar for TM mode with 1.8dB coupling loss for 3 m misalignment in both directions.The result indicates the misalignment tolerance is not affected significantly by the Si O2 gap in both TE and TM modes for 10.5 m input spot size.However, significant improvements in coupling losses can be observed from figure 5 when 10 m long SiO2 gap is introduced.

针对10.5米的输入光斑尺寸检查了所提出的耦合器的耦合行为和失调容差。10.5米的输入光斑尺寸代表了标准单模光纤的使用。这种光纤比透镜光纤便宜得多，从成本角度来看，它们的使用很有吸引力。10.5米输入光斑尺寸的耦合器宽度从6米增加到8米，以确保最小的耦合损耗。获得了耦合损耗与硅氧间隙长度的函数关系，并在图4中给出了0米和2米水平失调的情况。从图中可以看出，耦合损耗随着氧化硅间隙长度的增加而降低，直到达到最佳值。TE模式的最佳长度为15米，耦合损耗为1.4分贝。TM模式的最佳长度为22米，耦合损耗在1.8分贝时更高。图5(a)和(b)分别显示了TE和TM模式的耦合器失调容差。对于1米和10米SiO2间隙。在TE模式中，对于1米和10米SiO2间隙，可以观察到在垂直和水平方向上3米未对准的1.7分贝的耦合损耗。对于在两个方向上3 m未对准时耦合损耗为1.8dB的TM模式，这种行为非常相似。结果表明，对于10.5米的输入光斑尺寸，硅氧间隙对失调容差没有显著影响。然而，当引入10米长的二氧化硅间隙时，从图5中可以观察到耦合损耗的显著改善。

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王等:用于亚微米硅波导的带二氧化硅间隙的悬臂倒锥形耦合器1409

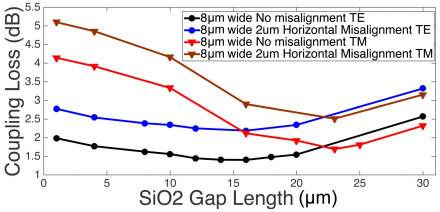
Fig. 4.The coupling loss of 8 m×8 m coupler for input spot size of 10.5 m for various SiO2 gap lengths.

图4。对于不同的二氧化硅间隙长度，输入光斑尺寸为10.5米时，8米×8米耦合器的耦合损耗。

Fig. 5.Misalignment tolerance of 8 m×8 m coupler with 10.5 m MFD input source: (a) TE mode;(b) TM mode.

图5。具有10.5米MFD输入源的8米×8米耦合器的失调容差:(a) TE模式；(二)商标模式。

IV.FABRICATION

四.制造

The inverse taper silicon waveguides are fabricated on an SOI wafer with a 3 m thick buried Si O2 and 240nm thick active silicon layer.PMMA was spin-coated on the wafer and patterned by electron-beam lithography.Chromium film is evaporated and lifted off to form a pattern that defines the inverse tapered silicon waveguides.Subsequently, the pattern was transferred to the active Si layer using Inductively Coupled Plasma (ICP) reactive ion etching with chromium as a mask.The chromium is removed by wet etch and the SiWs are coated with a 3 m PECVD Si O2 and 1.5 m thick PECVD amor-phous silicon.Photoresist is then spun on top of the amorphous silicon and photo-lithographically patterned to define the Si O2 waveguide and grooves.The pattern is transferred to the amorphous Si using ICP-RIE with photoresist as a mask.After removing the remaining photoresist in O2 plasma, the pattern is subsequently transferred to the Si O2 layer in ICP-RIE system using SF6/C4F8 chemistry.The grooves for the fiber are then deep etched using the Bosch process to 70 m depth with patterned Si O2 as mask.The silicon underneath the Si O2 waveguide is removed via Si isotropic etch in ICP-RIE system using SF6 chemistry to form the Si O2 cantilever waveguide.Using this fabrication approach, we have fabricated a number of devices consisting of input and output couplers connected with a short silicon waveguides.For 5 m spot size input, the input couplers are 6 m wide, 100 m long Si O2 waveguide cantilever with 1 m and 10 m long Si O2 gap.For 10.5 m spot size input, 8 m wide and 6 m thick input couplers are fabricated, as the coupler thickness is limited by the SOI box, with a 15 m long Si O2 gap.The output couplers for all the devices are 6 m wide, 100 m long Si O2 waveguide cantilever with 1 m long Si O2 gap.

反锥形硅波导制作在具有3米厚的掩埋氧化硅和240纳米厚的活性硅层的SOI晶片上。将聚甲基丙烯酸甲酯旋涂在晶片上，并通过电子束光刻形成图案。铬膜被蒸发并剥离以形成限定倒锥形硅波导的图案。随后，使用铬作为掩模的电感耦合等离子体(ICP)反应离子蚀刻将图案转移到活性硅层。通过湿法蚀刻去除铬，并且用3 μm的PECVD二氧化硅和1.5 μm厚的PECVD非晶硅涂覆SiWs。然后将光致抗蚀剂旋涂在非晶硅上，并光刻构图以限定二氧化硅波导和凹槽。以光刻胶为掩膜，用等离子体刻蚀将图形转移到非晶硅上。在去除O2等离子体中剩余的光致抗蚀剂之后，随后使用SF6/C4F8化学将图案转移到等离子体-离子刻蚀系统中的硅O2层。然后使用博世工艺，以图案化的二氧化硅为掩模，将光纤的凹槽深度蚀刻至70米。硅氧波导下面的硅通过电感耦合等离子体刻蚀系统中的硅各向同性刻蚀去除，利用SF6化学形成硅氧悬臂波导。使用这种制造方法，我们制造了许多由连接的输入和输出耦合器组成的器件带有短硅波导。对于5 m光斑尺寸输入，输入耦合器为6 m宽、100 m斯隆O2波导悬臂，带1 m和10 m斯隆O2间隙。对于10.5米的光斑尺寸输入，制作了8米宽和6米厚的输入耦合器，因为耦合器厚度受到SOI盒的限制，具有15米的SiO2间隙。所有设备的输出耦合器为6米宽、100米SiO2波导悬臂，带有1米SiO2间隙。

V.MEASUREMENT

V.尺寸

Measurements of coupling loss and misalignment tolerance have been conducted on the fabricated couplers.The input beam to the coupler is obtained from the output of a polar-ization maintaining (PM) lensed fiber that is connected to a polarization controller (Agilent 11896A) coupled to a laser source (Agilent 8164B) generating a beam at a wavelength of 1550nm.The PM lensed fiber is used to produce the required input spot size of 10.5 m and 5 m, respectively, for the measurements.After launching the input beam into the input coupler, the beam propagates through a short silicon waveguide to an output coupler to be collected by the output PM lensed optical fiber which is coupled to an optical power meter.The coupling loss is obtained from the difference in optical power at the input and output ends.The PM fiber at the input side is positioned at various vertical and horizontal locations using micro aligners(Ultralign M561) to measure misalignment tolerance.The TE and TM modes are set by the polarization controller.

对制作的耦合器进行了耦合损耗和失调容差的测量。耦合器的输入光束来自偏振保持(PM)透镜光纤的输出，该光纤连接到偏振控制器(安捷伦11896A)，该偏振控制器耦合到产生1550纳米波长光束的激光源(安捷伦8164B)。永磁透镜光纤用于产生测量所需的输入光斑尺寸，分别为10.5米和5米。在将输入光束发射到输入耦合器中之后，光束通过短硅波导传播到输出耦合器，由耦合到光功率计的输出永磁透镜光纤收集。耦合损耗由输入端和输出端的光功率差获得。输入侧的预防性维护光纤使用微对准器(Ultralign M561)定位在不同的垂直和水平位置，以测量失调容差。模式和模式由偏振控制器设置。

The coupling loss and misalignment tolerance measure-ments for 1 m and 10 m long Si O2 gap couplers with input spot size of 5 m are plotted in figure 6(a) and (b) for TE and TM mode, respectively.The coupling losses are 0.51dB (TE) and 0.57dB(TM) for 1 m long Si O2 gap and 0.49dB (TE) and 0.46dB(TM) for 10 m long Si O2 gap.The coupler with 10 m long Si O2 gap show a similar coupling loss with 1 m Si O2 gap, which is well match the simulation result.Furthermore, significant improvement in misalignment tol-erance with 10 m long Si O2 gap as compared to 1 m long Si O2 gap can be observed and agrees with simulation results.For example, the 3dB vertical misalignment tolerance increases from 1.2 m (1 m gap) to 1.8 m (10 m gap) for TE mode.This demonstrates the benefit of introducing the optimal length of Si O2 gap.Certain asymmetric characteris-tics observed in the result are due to fabrication imperfections such as alignment accuracy between masks at various litho-graphy stages.This leads to the difference in misalignment tolerance characteristics in the positive and negative offset directions.Despite the asymmetric characteristics, the coupler with 10 m long Si O2 gap shows better misalignment toler-ance and hence, better tolerance to fabrication imperfections.

输入光斑尺寸为5米的1米和10米斯隆O2间隙耦合器的耦合损耗和失调容差测量值分别在TE和TM模式的图6(a)和(b)中绘制。对于1 m斯隆O2间隙，耦合损耗为0.51分贝(TE)和0.57分贝(TM)，对于10 m斯隆O2间隙，耦合损耗为0.49分贝(TE)和0.46分贝(TM)。具有10 m斯隆氧隙的耦合器显示出与1 m硅氧隙相似的耦合损耗，这与模拟结果很好地匹配。此外，可以观察到与1 mSiO2间隙相比，10 mSiO2间隙的失调容限有显著改善，并且与模拟结果一致。例如，对于TE模式，3dB垂直失调容差从1.2 m (1米间隙)增加到1.8 m (10米间隙)。这证明了引入最佳长度的二氧化硅间隙的好处。结果中观察到的某些不对称特征是由于制造缺陷造成的，例如不同光刻阶段掩模之间的对准精度。这导致了正负偏移方向上的失调容差特性的差异。尽管具有非对称特性，但具有10 mSiO2间隙的耦合器显示出更好的失调容限，因此，对制造缺陷具有更好的容限。

Measurements on similar couplers and with 8 m (wide) × 6 m (thick) couplers using input spot size of 10.5 m have also been conducted.The measured coupling loss with 1 m and 15 m Si O2 gap are given in figure 6(c) and (d) for TE and TM mode, respectively.Note 15 m Si O2 gap is chosen as it is found to be the optimal length for 8 m × 6 m coupler from simulation that gives 2.5dB and 2.1dB coupling losses for TE and TM modes, respectively.The coupling

还对类似耦合器和使用10.5米输入光斑尺寸的8米(宽)× 6米(厚)耦合器进行了测量。在图6(c)和(d)中，分别给出了TE模式和TM模式下，在1 m和15 m硅氧间隙下测得的耦合损耗。注:选择15米硅氧间隙，因为从模拟中发现它是8米× 6米耦合器的最佳长度，分别给出了2.5分贝和2.1分贝的耦合损耗。联轴器

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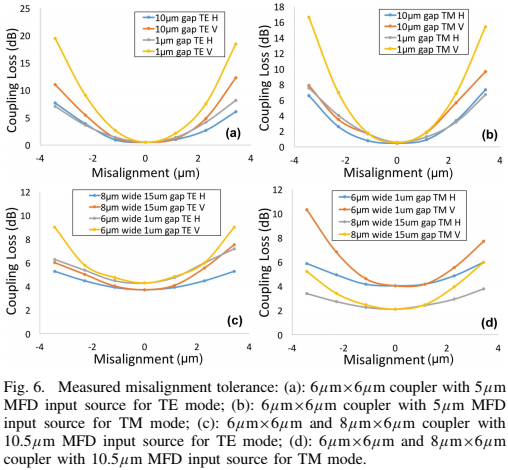
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《美国电气和电子工程师学会光子技术通讯》，第29卷，第16期，2017年8月15日

range for both fabricated 6 m×6 m and 8 m×6 m coupler.The simulation and measurement results agree quite well as seen from the 6 m×6 m coupler.For symmetric coupler dimensions of 8 m×8 m, simulation shows that the coupling loss is constant over the wavelength range with slight decrease for TM mode as the wavelength increases.

制造的6 m×6 m和8 m×6 m耦合器的范围。从6 m×6 m耦合器的情况看，模拟和测量结果吻合得很好。对于8米×8米的对称耦合器尺寸，模拟表明耦合损耗在整个波长范围内是恒定的，随着波长的增加，TM模的耦合损耗略有降低。

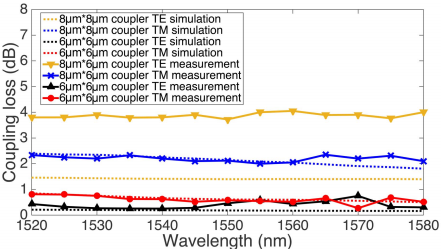


VI.CONCLUSION

六.结论

In this letter, we demonstrate that misalignment tolerant and low loss cantilever inverse taper couplers can be designed by introducing a Si O2 gap with an optimal length and width in front of a tapered end of silicon waveguide for a desired input spot size.A 6 mx6 m coupler with 10 m Si O2 gap shows that coupling loss less than 0.49dB and misalignment tolerance larger than 1.8 m for 3 dB additional loss with a 5 m input spot size can be achieved in both TE and TM modes.Introduction of the 15 m Si O2 gap with 8 m wide coupler improves TM mode coupling loss from 4.05dB/facet to 2.12dB/facet while maintaining large misalignment tolerance for input spot size of 10.5 m. The proposed couplers are superior in comparison to other reported couplers in that they improve misalignment tolerance or coupling loss without significantly compromising the other, requiring complicated design and fabrication process.

在这封信中，我们证明了通过在硅波导的锥形端前引入具有最佳长度和宽度的二氧化硅间隙，可以设计出容许失调和低损耗的悬臂倒锥形耦合器，以获得所需的输入光斑尺寸。具有10米二氧化硅间隙的6米x6米耦合器显示，在TE和TM模式下，耦合损耗小于0.49分贝，失调容差大于1.8米，附加损耗为3分贝，输入光斑尺寸为5米。15米硅氧间隙和8米宽耦合器的引入将TM模式耦合损耗从4.05分贝/刻面提高到2.12分贝/刻面，同时对于10.5米的输入光斑尺寸保持较大的未对准容差。与其他报道的耦合器相比，所提出的耦合器更优越，因为它们提高了未对准容差或耦合损耗，而不会显著损害其他耦合器，需要复杂的设计和制造工艺。



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承认

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Fig. 7.Measured and simulated Coupling losses of the fabricated and designed couplers over the wavelength range of 1520nm to 1580nm.

图7。在1520纳米到1580纳米的波长范围内测量和模拟制造和设计的耦合器的耦合损耗。

loss is 4.29dB/facet and 4.05dB/facet with 1 m Si O2 gap and 6 m wide coupler for TE and TM mode, respectively.However, the coupling loss decreases to 3.72dB/facet (TE) and 2.12dB/facet (TM) for 8 m wide coupler with 15 m long Si O2 gap.The significant decrease in coupling losses with TM mode agrees with the simulation result and represents a superior coupling efficiency in comparison to other reported couplers.Hence, the results clearly demonstrate improvement in coupling loss while maintaining similar large misalignment tolerance when Si O2 gap is introduced into a cantilever inverse taper coupler.

TE和TM模式的损耗分别为4.29分贝/刻面和4.05分贝/刻面，1米硅氧间隙和6米宽耦合器。然而，对于具有15 m斯隆O2间隙的8 m宽耦合器，耦合损耗降低到3.72分贝/刻面(TE)和2.12分贝/刻面(TM)。与其他报道的耦合器相比，采用TM模式的耦合损耗的显著降低与模拟结果一致，并且表现出优越的耦合效率。因此，当硅氧间隙被引入悬臂倒锥形耦合器时，结果清楚地证明了耦合损耗的改善，同时保持了相似的大的未对准容差。

Figure 7 shows the simulation and measurement of the coupling loss for the designed and fabricated couplers over the wavelength range of 1520nm to 1580nm.It can be seen that the coupling loss is almost constant over the 60nm wavelength

图7显示了设计和制造的耦合器在1520nm至1580nm波长范围内耦合损耗的模拟和测量。可以看出，耦合损耗在60nm波长上几乎是恒定的

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