Tapered Self-Written Waveguide between Silicon Photonics Chip and Standard Single-Mode Fiber

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Abstract: The first self-written waveguide applied to silicon photonics with a spot-size converter using a SiON waveguide achieves low coupling loss and high alignment tolerance between a standard single-mode fiber and silicon photonics chip. © 2020 The Authors.

1. Introduction

Silicon photonics (SiPh) is opening up new opportunities for optical communications. A remaining challenge of SiPh technology is how to achieve a low-loss and high-throughput optical connection between standard single-mode fiber (SSMF) and SiPh chip. A promising approach for achieving such high-throughput connection is utilization of passive alignment method instead of conventional active alignment method. To apply the passive alignment method, a connection method is required that provides low-loss connection with high-alignment tolerance because the accuracy of mechanical passive alignment methods is μm order at most. There are two fiber-coupling methods commonly used for conventional SiPh technology, grating coupling and edge coupling. The grating coupling can directly couple to the SSMF and has an advantage of high lateral alignment tolerance that meets passive alignment. On the other hand, the grating coupling still poses some challenges that include polarization dependence, wavelength dependence and high coupling loss compared to the edge coupling. The edge coupling can provide a low-loss, high-bandwidth, and polarization-independent connection by using a spot-size converter (SSC) [1] integrated in the SiPh chip facet. One reported approach of the edge coupling is to use high-numerical aperture fiber (HNAF) as a bridge between a SiPh chip and SSMF [2]. However, the alignment tolerance of this approach is sub-μm order due to each of them having a small mode-filed diameter (MFD) (≈ 4 μm). It also requires additional process for thermally expanded core splicing between HNAF and SSMF. Another approach of edge coupling is to use an on-chip SSC to expand the MFD at a SiPh facet so that it is equal to that of the SSMF [3]. The alignment tolerance at this MFD (≈ 10 μm) is greater than that in the HNAF method. However, the SSC fabrication process is complicated because it involves undercutting the Si substrate and 3D device fabrication.

To cope with the problem, an optical self-alignment technique that realizes low coupling loss even with the existence of lateral offset and gap is a key factor. A low-loss optical self-alignment technology is the self-written waveguide (SWW). SWW is fabricated by filling the gap between waveguides with photo-curable resins and curing the resin with light emitted from each core [4]. In addition, this method can create tapered SWW between waveguides with different core diameter [5]. Consequently, it has potential to achieve low-loss and high alignment tolerance between SiPh chip and SSMF without an HNAF and complex chip fabrication processes. However, SWW is not applicable to fiber-coupling method to SiPh chip. This is because strong curing light absorption ranging from the visible to ultra-violet region occurs in semiconductor waveguides, which is an obstacle to obtaining the light emission from the SiPh chip that necessary for SWW. To overcome this problem, recent studies have investigated by changing the curing wavelength of resin to near-infrared wavelength that can propagate the Si waveguide [6,7]. However, the SWW from SiPh chip has not been reported. We speculate that it was difficult to create SWW by this approach, because the high optical power for SWW by this wavelength light can break Si waveguide.

In this paper, we propose novel structure for SWW to a SiPh chip. To the best of our knowledge, this is the first SWW created by using radiation from a SiPh chip. The bi-directional curing light emission from an SSMF and SiPh chip create the tapered SWW, which provides coupling loss equivalent to that for HNAF butt-coupling. Moreover, the alignment tolerance with the tapered SWW is drastically improved from that with the HNAF approach.

2. A concept for SWW connection between SiPh chip and SSMF with passive alignment

We propose a novel approach for SWW by using widely used waveguide structures. We focus on the second-core materials in SSC for SWW connection between the SiPh chip and SSMF [1]. Fig. 1(a) shows a schematic of the waveguide structure. The SiON portion of this structure can confine visible light because SiON is transparent in this region. Fig.1 (a) shows the propagation mode of 405 nm wavelength is calculated by a finite difference eigenmode solver in commercial software. The result indicates confinement of the 405 nm light in the SiON portion and its propagation. In addition, the SWW has to couple the curing light to the SiON portion. As shown in Fig. 1(b), we devised Y-junction-like wavelength combiner to combine curing light. In addition, this structure does not affect to SSC function for 1.55 μm when it is made in the Si waveguide region. This is because the 1.55 μm light is strongly confined in the Si waveguide and thus does not feel the SiON structure. The coupling efficiency with and without this structure was calculated by a commercial finite-difference time-domain method to quantify the influence. The results indicated that the difference in the coupling efficiency from the SiON waveguide to Si waveguide is less than 0.1 dB from 1.5 to 1.6 μm. Moreover, with this structure and SiON waveguide, the curing light can be coupled to a chip during the process for fibers connection and multiple channels can be connected simultaneously as shown Fig 1(c). Consequently, this structure is suitable for combining passive alignment and an SWW.

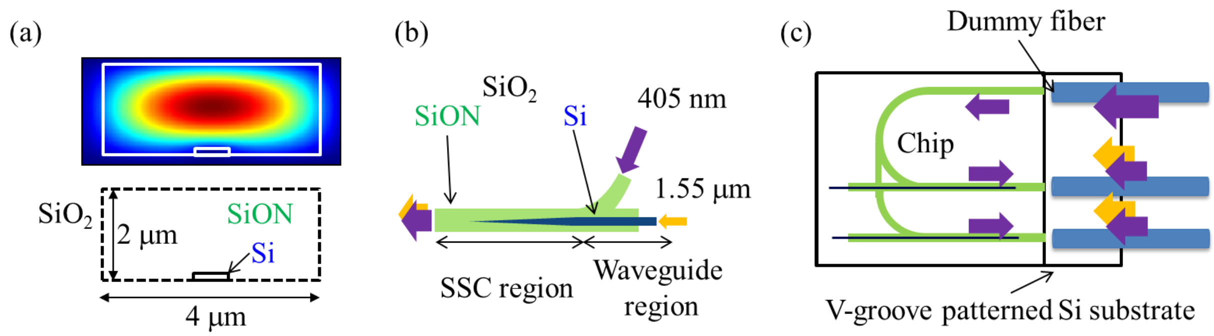

Fig. 1: (a) The schematic of SSC and calculated 405 nm light propagation mode, (b) Y-junction like structure for SWW, and (c) schematic of the method for SWW connection with passive alignment.

3. Experimental result of tapered SWW connection between SiPh chip and SSMF

The structure for the SWW was fabricated. As shown in the chip layout in Fig. 2(a), the structure makes the curing light radiate from SiPh chip. The insertion loss of the chip, measured by single-mode fibers at the wavelength of 405 nm, was about 10 dB. Although this loss value is as high as that of a conventional waveguide, the power needed for the SWW is less than 100 μW. Therefore, the loss value is sufficient for the SWW. Furthermore, a measurement of the Y-junction influence revealed that the difference between the average insertion loss of several chips with and without the Y-junction is lower than 0.3 dB. We consider that the difference was not caused by the Y-junction but by chip-to-chip variation.

An SWW connection experiment was carried out using this chip. Coupling loss with the tapered SWW between different cores depends on SWW formation conditions, gap G between the waveguides, the power of curing light from each chip, P_1 and P_2, and exposure time T [5]. To accomplish the low-loss coupling, we used an in-situ experimental setup, which enables us to monitor the loss during the measurement of the tapered SWW as shown as Fig. 2(b). The normalized loss is measured by filtered amplified spontaneous emission (ASE) source whose wavelength is from 1548 to 1552 nm. We used acrylic resin to create a tapered SWW core with n = 1.49 after polymerization.

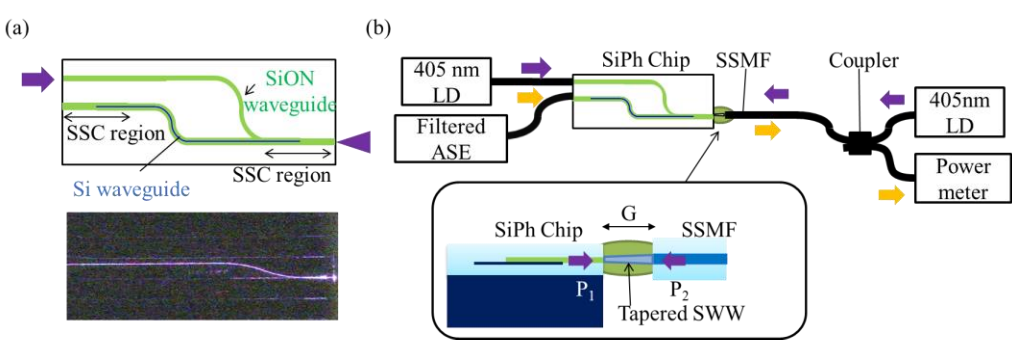

Fig. 2: (a) Chip layout and fabricated chip coupled curing light from fiber, (b) experimental setup.

The conditions for low connection loss after condition had been specified were T = 1.0 second, P_1 = −14 dBm, P_2 = −18 dBm, and G = 40 μm. Fig. 3 (a) shows the steps of the SWW process and Table 1 shows the coupling losses at each step. The fabricated tapered SWW at the condition is shown in Fig. 3(b). The excess loss due to the

MFD mismatch and gap was improved by forming the tapered SWW. The normalized coupling loss measured in this SWW condition from HNAF butt-coupling with index matching oil is about 0.7 dB. The measured coupling loss between the HNAF and chip was estimated at about 2.9 dB. This loss is larger than the maximum excess loss of 2.2 dB between same type SSC reported in [1,8] and HNAF. Therefore, it can be improved by optimizing design and process condition.

Table 1. the normalized losses at each step (gap and lateral offset were 40 and 0 μm)

Process steps	Normalized loss (dB)
1. Align SSMF to SiPh chip in air	5.2
2. Set gap and lateral offset and fill the gap with resin	4.8
3. After tapered SWW	0.7

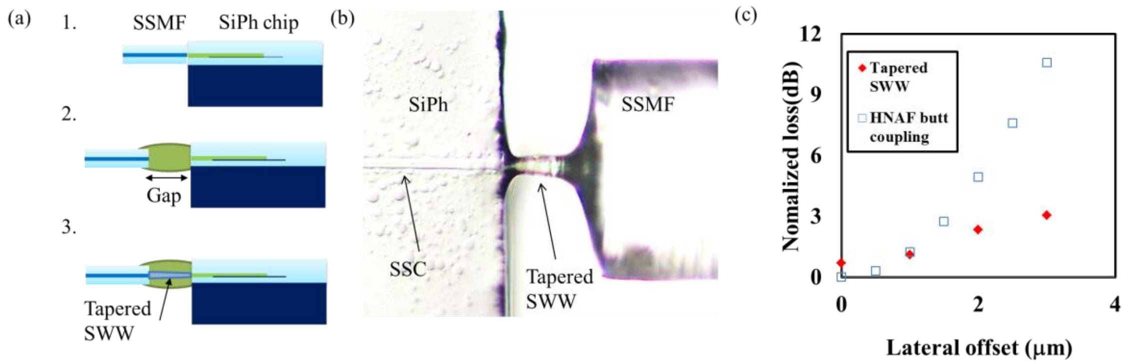

Fig. 3: (a) Schematic of SWW process steps, (b) tapered SWW between SiPh chip and SSMF after removing unpolymerized resin, (c) alignment tolerance of tapered SWW and HNAF butt-coupling.

Next, we measured the alignment tolerance of the tapered SWW connection in the low-loss condition. Fig. 3(c) shows the normalized loss of the tapered SWW when there is a lateral offset. The alignment tolerance is remarkably improved compared to HNAF butt-coupling. Although the coupling loss is higher than that for HNAF butt-coupling, the tapered SWW loss can be improved by optimizing the tapered SWW process condition, because the inevitable loss due to material absorption and Fresnel loss is lower than 0.1 dB. From a practical viewpoint, the tapered SWW clad should be cured as an adhesive. Although the clad of the tapered SWW was unpolymerized resin of the core in this experiment, we succeeded in replacing the unpolymerized region with other clad materials that function as an adhesive after washing out the unpolymerized resin. The excess loss after replacing the clad material was 0.2 dB because the refractive index of the clad resin is 1.46, which is lower than the 1.48 of the unpolymerized resin in the core. Consequently, the excess loss can be improved by choosing the optimal material for the clad region of the tapered SWW.

4. Conclusion

We achieved an SWW connection between a SiPh chip and SSMF. To the best of our knowledge, this is the first SWW enabled by radiation from a SiPh chip. Moreover, our tapered SWW drastically improved alignment tolerance with loss equivalent to that of HNAF. Our SWW method has great potential for high-throughput packaging.

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