High Efficiency Optical Phased Array Using Silicon Nitride Waveguide

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A high-efficiency grating antenna and a multimode interference beam splitter using a silicon-nitride waveguide have been studied for an optical phased array with an operating wavelength of 1550 nm. A waveguide grating antenna with patterned top cladding and a 1x2 multimode interference beam splitter with a tapered waveguide are considered. The optimized waveguide grating antenna and the multimode interference beam splitter offer above 70% directionality and 98% high single-mode transmission, respectively. These results indicate the possibility of using silicon nitride as a waveguide for a high-efficiency optical phased array.

Keywords: Silicon-nitride waveguide, Optical phased array, Solid-state LiDAR, Integrated optical device, Multimode beam splitter.

I. Introduction

Light detection and ranging (LiDAR) technology is a technology that can measure the properties of a substance such as temperature and concentration in addition to the distance from the laser to the target and the speed of the target by irradiating the laser to the target. LiDAR was attempted in the 1930s for the purpose of characterizing the atmosphere, but full-scale development was made with the development of lasers in the 1960s [1]. With the development of laser technology, riders have been spotlighted not only for analysing the characteristics of the atmosphere, but also for measuring the distance, shape, and speed of objects, especially for the implementation of unmanned vehicles [2–10].

In most LiDAR applications, beam steering technology is required. This technology has a wide range of applications in aerospace, laser communications, and other fields. The conventional mechanical beam steering system has high scanning efficiency and wide field of view.

However, because of the influence of mechanical motion and limited speed and so on, it has some problems such as scan speed, scan accuracy, and durability [11]. LiDAR devices based on optical phased arrays (OPAs) are being actively studied as an alternative to compensate for these problem [12–16]. OPA is attractive because it has a large out-of-plane emission conformal aperture, can operate in a solid-state, and utilizes an established semiconductor manufacturing infrastructure. The near-field pattern is defined by a coherent emitter array with individual phase control, and the far-field pattern is defined by Fraunhofer diffraction. The beam can be steered in the desired direction by controlling the phase of each emitter, which allows for an OPA aperture size of a few millimetres, allowing the generation of diffracted beams with a wide area receiver with a divergence angle of less than a millimetre. OPA system with photonic integrated circuit can realize a chip-scale beam steering system [17] and has wide various applications not only LiDAR, but optical communication system [18], projection systems [19], and 3-D imaging [20].

Figure 1 shows a schematic diagram of the OPA device. In this scheme, the beam is transmitted to the chip.
through the optical fiber is distributed to each channel through a multimode interference (MMI) beam splitter (region 1). The phase of each beam propagating through waveguides is controlled by metal heater (region 2) based on the thermo-optic effect, finally emitted as free-space through a waveguide grating antenna (WGA, region 3). Therefore, higher directionality is required because the intensity of the beam emitted to the free-space based on OPA is relatively weak compared to the case of the mechanical steering method. In order to solve this problem, the design of WGA where coupling between the chip and free space occurs is important. To increase the directionality of WGA, etched waveguide [21], photonic crystal [22], plasmonic grating coupler [23], Bragg reflectors [24], gold mirrors [25], and bottom grating [26] were attempted. These structures require complex processes and are particularly difficult to fabricate CMOS foundries by DUV lithography. In addition, in this structure, Fabry-Perot interference caused by downward radiation occurs, reducing the efficiency of the device [27, 28]. To solve this, a dual-layer waveguide structure [27] has been proposed, but such a structure is difficult to manufacture through a lithography process and is difficult to be compatible with existing devices. Recently, to solve this problem, a WGA structure with patterning applied to top cladding has been proposed, and through this, high directionality, as well as convenience of manufacturing through CMOS foundries, has been obtained [29]. The material constituting the waveguide of OPA determines the upper limit of the effective refractive index of WGA and in particular propagation loss due to optical absorption. In general, there are many studies using a waveguide using silicon with very low propagation loss in the OPA-operated short-wavelength infrared (SWIR) region, but due to the third-order nonlinearity characteristic of silicon, it is not suitable for high-optical power applications [15, 30, 31]. On the other hand, silicon nitride has attracted attention as a substitute for silicon because it has low nonlinearity and low propagation loss, high transmittance in the SWIR range, and relatively low refractive index [32–34]. In this paper, we propose the structure of fiber-chip coupler, MMI beam splitter, and WGA for OPA based on silicon nitride. Through 3D FDTD simulation, a tapered fiber-chip coupler and a tapered MMI beam splitter for an operating wavelength of 1550 nm were designed to minimize propagation loss, and WGA applied patterning to top cladding to maximize directionality. In this structure, we have obtained more than 90% chip-coupler efficiency and more than 98% MMI beam splitter efficiency and confirmed that the top cladding patterned WGA with silicon nitride waveguide has a high directionality of more than 70%.

II. OPA design and properties

The width and thickness of the silicon nitride waveguide were 2 μm and 0.5 μm, respectively, and the refractive index of silicon nitride for an operating wavelength of 1550 nm was set to 1.9963. The overall structure is in the form of a tapered fiber-chip coupler, waveguide, MMI beam splitter, and WGA on the SOI platform, as shown in Figure 2. We investigated the dimension that maximizes the efficiency of the tapered fiber-chip coupler, waveguide, MMI beam splitter, and WGA through 3D finite-difference time-domain (FDTD) simulation. The light propagating along the waveguide can form several modes. In the high order mode, the propagation loss is greater than in the low order mode [35]. We only considered the transmittance of 1st order TE mode in this study. Figure 3 (a) shows the top view of the tapered fiber-chip coupler. Light entering the chip through the tapered fiber proceeds from left to right. We study dimension of the tapered fiber-chip coupler to maximize the efficiency of the tapered fiber-chip coupler. First, while the length of the tapered fiber-chip coupler was fixed.
at 100 μm, the width of the tapered fiber-chip coupler was optimized and the length of the tapered fiber-chip coupler was again simulated using the obtained values. Figure 3 (b) and (c) show that the transmission of the tapered fiber-chip coupler is more affected by the width than the length of the tapered fiber-chip coupler. In figure 3 (b), the transmittance increases when wk is less than 0.34, but decreases when it is larger. Because there is no optical mode where wk is less than 0.28, and larger wk yields larger y-direction and z-direction propagation loss. This suggests that the accuracy of the fabrication process is very important when processing the width of the tapered fiber-chip coupler. From these results, we found that the tapered fiber-chip coupler has an efficiency of about 91% when the length of the tapered fiber-chip coupler is 70 μm and the width is 0.34 μm.

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Figure 4 shows the top view of the tapered MMI beam splitter. The MMI beam splitter consists of an MMI tapered input waveguide and a tapered output waveguide. We have investigated the width and length of each element, and the initial parameter values of the optimization are shown in Table 1. The study of the tapered MMI beam splitter is first optimized for the length of the MMI (L_{MMI}), then the width of the MMI (W_{MMI}), the width of the tapered output waveguide (W_{tow}), the
Fig. 4. (Color online) Top view of tapered multimode interference beam splitter. This structure consists of tapered input waveguide, multimode interferometer, and tapered output waveguide.

Table 1. Initial parameter for optimization of tapered multimode interference beam splitter.

<table>
<thead>
<tr>
<th>Structure</th>
<th>MMI</th>
<th>Tapered output waveguide</th>
<th>Tapered input waveguide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Length</td>
<td>Width</td>
<td>Width</td>
</tr>
<tr>
<td>Value</td>
<td>None</td>
<td>10 µm</td>
<td>5 µm</td>
</tr>
</tbody>
</table>

length of the tapered output waveguide ($L_{tow}$), and the tapered input waveguide width ($W_{tiw}$) and the length of the tapered input waveguide ($L_{tiw}$) were sequentially performed. Figure 5.1 and Figure 5.2 show the results for each parameter. Especially for figure 5.1 (b), under the influence of scattering at a small area surrounded by two output tapered waveguides, the transmission is noticeably decreased with an increase of $W_{MMI}$. It indicates that the width of the MMI, tapered output waveguide and tapered input waveguide has a greater effect on the efficiency of the tapered MMI beam splitter than other parameters. Besides, the results for the last optimization parameter $L_{tiw}$ show that suppression for the high order mode was successfully achieved in the tapered beam splitter. The value of each optimal parameter is $L_{MMI} = 37.2 \mu m$, $W_{MMI} = 10 \mu m$, $W_{tow} = 5 \mu m$, $L_{tow} = 9.5 \mu m$, $W_{tiw} = 6.4 \mu m$, $L_{tiw} = 11.2 \mu m$, where the efficiency of the tapered MMI beam splitter is 98.2%.

The light passing through the tapered beam splitter must have a curved path to reach each OPA channel. In this process, we study a circular arc waveguide with little propagation loss. The simulation structure and results are shown in Figure 6. Figure 6 (b) shows the transmittance of the 1st order TE mode for the radius curvature ($R_w$) of the circular arc waveguide. When $R_w$ is less than 16 µm, the transmittance tends to increase steeply as $R_w$ increases, but when $R_w$ is greater than 16 µm, peaks of similar size appear repeatedly as $R_w$ increases due to mode mismatch between straight rectangular waveguide and circularly bent rectangular waveguide. When $R_w$ is 16, 27, 37, and 47, the transmittance for each $R_w$ was 99.2%, 99.7%, 99.7%, and 99.7%, indicating that light was hardly lost while propagating along the circular arc waveguide.

One of the most important parts of OPA is WGA. The light propagating along each channel through the fiber-chip coupler and the tapered MMI beam splitter is emitted as free-space by WGA. We considered the top cladding-patterned WGA structure as shown in Fig-
ure 7 to obtain high directionality [26]. To measure the directionality in the z-direction, we set six monitors (±x-direction, ±y-direction, and ±z-direction) on each side of the simulation structure. The power of light propagating waveguide is collected in the x-direction by the monitor (+ x-direction), however, out-coupled power is collected by monitor placed at the other side (−x direction, ±y-direction, and ±z-direction). Directionality is defined as the power ratio collected by the monitor placed at z + direction to the power placed at the other side. The top cladding thickness, remained thickness, grating pitch, and fill-factor were considered as optimization parameters of the WGA structure. Table 2 shows the initial values of each parameter. Optimization for the WGA structure was performed in the order of top cladding thickness, remained thickness, grating pitch, and fill-factor, similar to the tapered MMI beam splitter mentioned above. Figure 8 (a) shows the change in normalized directionality according to the change in top cladding thickness. Compared to Figure 8 (b), (c), and (d), it can be seen that the effect on the directionality of the top cladding thickness is smaller than other parameters. While the top cladding thickness increased from 0.5 µm to 2 µm, the normalized directionality of WGA repeated increases and decreases between 0.92 and 1. However, for the retained thickness and grating pitch, it can be seen that the directionality of the WGA varies greatly from 0.2 to 1 while the value of each parameter increases from 0.05 µm to 1.2 µm, and from 0.5 µm to 1 µm. Optimization for the fill-factor (Figure 8 (d)) also shows a relatively large directionality change compared to the result for the top cladding thickness, but the change is relatively small compared to Figure 8 (b) and (c). Able to know. These results show that the remained thickness and grating pitch have the greatest influence on the directionality of the top cladding-patterned WGA structure. Table 3 shows the optimal values and directionality of each parameter obtained through the optimization process. The directionality is calculated to be above 70% at 1550 nm, the operation wavelength, as shown in Figure 9.

**Fig. 7.** (Color online) Side view of waveguide grating antenna structure. The grating is generated by etching of top SiO$_2$ cladding.

**Table 2.** Initial parameter for optimization of waveguide grating antenna.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Top cladding thickness</th>
<th>Remained thickness</th>
<th>Grating pitch</th>
<th>Fill-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>None</td>
<td>0.1 µm</td>
<td>0.8 µm</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Fig. 8.** Simulated normalized directionality with variations of (a) top cladding thickness, (b) remained thickness, (c) grating pitch, and (d) fill-factor.

**Table 3.** Optimal parameter and directionality for optimization of waveguide grating antenna.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Top cladding thickness</th>
<th>Remained thickness</th>
<th>Grating pitch</th>
<th>Fill-factor</th>
<th>Directionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.6 µm</td>
<td>0.1 µm</td>
<td>0.91 µm</td>
<td>0.55</td>
<td>72.60%</td>
</tr>
</tbody>
</table>

**III. Summary**

In this paper, we investigated the geometry of fiber-chip coupler, MMI beam splitter, and WGA for OPA based on silicon nitride waveguide. As a result of the optimization of the width and length of the fiber-chip coupler, we found the tapered fiber-chip coupler with 92% efficiency, and also the efficiency of the tapered fiber-
chip coupler to the efficiency of the tapered fiber-chip coupler and width had a greater effect than length. The optimal tapered MMI beam splitter, with an efficiency of 98.2% was found, and the width of the MMI, tapered output waveguide, and tapered input waveguide had a greater influence on the efficiency of the tapered MMI beam splitter than other parameters. From the optimization of the circular arc waveguide, the curvature radius of the circular arc waveguide having an efficiency of 99.7% was found. Finally, in case of the top cladding-patterned WGA, it was found that the remaining thickness and grating pitch had a greater effect on the directionality of the WGA than the top cladding thickness and fill-factor. Based on the results of this study, we will manufacture an OPA device based on a silicon nitride waveguide and experimentally investigate its optical properties. This work contributes to the study of the antenna for the LiDAR using a silicon nitride waveguide based on the OPA system.

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