Ultra-Compact Silicon Photonic 512 × 512 25 GHz Arrayed Waveguide Grating Router

Stanley Cheung, Tiehui Su, Katsunari Okamoto, Fellow, IEEE, and S. J. B. Yoo, Fellow, IEEE

Abstract—This paper discusses design, fabrication, and characterization of a 512 × 512 arrayed waveguide grating router (AWGR) with a channel spacing of 25 GHz. The dimensions of the AWGR is 16 mm × 11 mm and is fabricated on a 250 nm silicon-on-insulator platform. The measured channel crosstalk is approximately −4 dB without any compensation for the phase errors in the arrayed waveguides. The AWGR spectrum in the arrayed waveguide grating arms were characterized by using an optical vector network analyzer. Fabrication details of obtaining low loss silicon ridge waveguides are also discussed.

Index Terms—Integrated optical devices, waveguide filters, optical interconnects, data centers, wavelength-division-multiplexing (WDM).

I. INTRODUCTION

There has been extensive research on silicon photonics as a promising future technology to meet the demands of high-capacity, energy-efficient, and cost-effective on-chip communications [1], [2]. In most applications, it is widely recognized that wavelength-division-multiplexing (WDM) techniques are critical in achieving high aggregate bandwidth for optical communications [3], [4]. In the WDM scheme, multiple sources are modulated and encoded to carry optical signals [5], [6]. The data rate for each channel is limited by the modulations speed, however the total bandwidth is scaled by the wavelength number (channels) used in the optical communication system via the arrayed waveguide grating (AWG) [5], [7]. Typically the channel count (spectral resolution) of an AWG can be increased by increasing the interference order of the grating or the number of arrayed waveguides and so therefore, AWGs have been used not only for WDM applications, but optical sensing [8], [9] and optical spectrometers [10] as well. Significant work has been done to develop high-performance AWGs based on a number of various material platforms such as buried InP/InGaAsP ridge waveguides [3], [4], [11]–[13], silicon-on-insulator (SOI) ridge waveguides [14], SOI nanowires [15]–[19], silica-on-Si buried waveguides [20]–[22], polymer waveguides [23], and nano-core Si$_3$N$_4$ waveguides [5], [7], [24]. Silica AWGs have reached commercialization owing to its high performance; however, the bending radius is usually very large because of its low index-contrast (∼1.5%) [25] compared to SOI (>40%). For this reason, high density integration on a small footprint is problematic. SOI-nanowires have an ultra-high index contrast, which enable several tens of micron-scale bending radius to be implemented on-chip. However, the drawback of SOI-nanowires are the phase-errors that cause channel crosstalk degradation and on-chip losses. On the other hand, Dai et al. have demonstrated a low loss Si$_3$N$_4$ 16 channel-200 GHz AWG with a reported loss of 0.03 dB/cm for a 2 mm bend radius, and we have demonstrated high-contrast 40 channel-100 GHz AWG based on silicon rib waveguides on SOI [26].

Aside from WDM communications, the unique wavelength routing characteristics of arrayed waveguide grating routers (AWGRs) have been proposed and demonstrated as a viable optical interconnect architecture for future high-performance computing (HPC) due to its wavelength parallelism, dense interconnectivity, and all-to-all connectivity [27]–[31]. HPC architectures based on AWGR include LIONS (formally DOS) [32], Petabit, and IRIS [33] have shown that limiting factors that prevent such systems from being deployed on a large scale is the port count on a single AWGR [27].

In this work, we design, fabricate, and demonstrate a high port count 512 × 512 AWGR on a SOI material platform. First, we present AWGR based design parameters. Detailed fabrication steps are discussed to realize low-loss silicon waveguides followed by experiments. Table I shows the current state-of-the-art high resolution AWGs on various material platforms.

II. AWG FUNDAMENTAL CONCEPTS AND DESIGN

The theory of AWG can be found in [37]–[39] and is reviewed here to define parameters used in designs later in this paper. As Fig. 1 illustrates, the AWG consists of input and output waveguides, each with a separate field profile. No power is coupled away from the input waveguide. The output waveguide is the primary field guide in a broadening mode, which is the end of the AWG. Power is coupled from the input waveguide to the output waveguide by the interference of coupled guides with the same propagation constant, Ω. The coupling efficiency is controlled by the phase error between the two channels, ΔΦ. The monomial Ω is the product of the propagation constant, Ω = k 512, where k is the waveguide propagation constant. Each channel is separated from the next channel by a value of Δk = k = 25 GHz. The channel number is given by n = (Ω − Δk)/Δk, which is the order of the diffraction in the grating. The maximum number of channels that can be supported is given by N = 1/2 Δk Δk. The total bandwidth is scaled by the number of channels, N. The channel count is inversely proportional to the channel spacing, Δk, which is the product of the propagation constant, Ω = k 512.

The channel count of the AWG is determined by the design parameters, which are the number of arrayed waveguide arms, N, and the number of waveguides per arm, M. The total number of waveguides per AWG is given by M × N. The channel spacing is determined by the number of waveguides per arm, M, which is inversely proportional to the channel count, N. The total bandwidth is scaled by the number of channels, N. The channel count is inversely proportional to the channel spacing, Δk, which is the product of the propagation constant, Ω = k 512.

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output waveguides, two free-propagation slab regions, and arrayed waveguides where each neighboring waveguide have a constant path length difference of \( \Delta L \). The input light is launched into the first slab region from the left where the beam diffracts and excites the arrayed waveguides. After traveling though the arrayed waveguides, the light beam constructively interferes at a particular focal point in the second slab region. The location of the focal points depend on the signal wavelength \( \lambda_0 \) due to the relative phase delay in each arrayed waveguide [37], [38].

After traversing the arrayed waveguide arms, the signal in each arm should theoretically acquire a constant linear phase increment from the adjacent waveguide by \( \Delta L/\lambda \). The path length difference of two adjacent light beams in the arrayed waveguide arms must be an integer multiple of \( 2\pi \) for constructive interference at the output slab region location denoted as \( x \). This interference condition is given by [37], [38]:

\[
\beta_\alpha (\lambda_0) \left( f_1 - \frac{d_1 x_1}{2 f_1} \right) + \beta_\epsilon (\lambda_0) [L_c + (i - 1) \Delta L] + \beta_\epsilon (\lambda_0) [L_c + (i - 1) \Delta L] + \beta_\epsilon (\lambda_0) \left( f - \frac{d x}{2 f} \right) - 2m\pi 
\]

(1)

where \( \beta_\alpha \) is the propagation constant in the slab region, \( \beta_\epsilon \) is the propagation constant in the arrayed waveguide arms, \( \lambda_0 \) is the center wavelength, \( f \) is the radius of curvature in the slab region, \( L_c \) is the minimum length of the arrayed waveguide arm, and \( m \) is an integer. The phase matching condition can further be reduced as follows [38]:

\[
\beta_\alpha (\lambda_0) \frac{d_1 x_1}{f_1} - \beta_\epsilon (\lambda_0) \frac{d x}{f} + \beta_\epsilon (\lambda_0) \Delta L = 2m\pi. \tag{2}
\]

The relationship between the light input position at \( x_1 \) and \( x \) is such that:

\[
\frac{d_1 x_1}{f_1} = \frac{d x}{f} \tag{3}
\]

when the phase term \( \beta_\epsilon (\lambda_0) \Delta L = 2m\pi \) and the center wavelength:

\[
\lambda_0 = \frac{n_\epsilon \Delta L}{m}. \tag{4}
\]

Dispersion at each location of the second slab at \( x \) is found by differentiating (2) and results in the following [37]:

\[
\frac{\Delta x}{\Delta \lambda} = -\frac{N_s f_1 \Delta L}{n_\epsilon d_1 \lambda_0} \tag{5}
\]

where \( n_\epsilon \) is the effective index of the slab and \( N_s = n_\epsilon - \lambda (dn_\epsilon/d\lambda) \) is the group index of the effective index of the arrayed waveguide arm. Similarly, the dispersion at the input side of the first slab region \( x_1 \) is given as [37]:

\[
\frac{\Delta x_1}{\Delta \lambda} = -\frac{N_s f_1 \Delta L}{n_\epsilon d_1 \lambda_0}. \tag{6}
\]

The amount of available wavelength channels can therefore be determined by dividing the FSR value by the output waveguide separation \( D \) and is given as [37], [38]:

\[
N_{ch} = \frac{X_{FSR}}{D} = \frac{\lambda_0 f}{n_\epsilon d}. \tag{11}
\]

However, high-resolution AWGs on SOI require very long lengths such that any slight non-uniformity in the waveguide refractive index or dimension due to fabrication, will result in non-uniformity of the propagation constant for the different arms [22], [40], [41]. This in turn, induces non-uniform phase distortions at the output slab region known as phase errors. The phase errors cause de-focusing of a clean focal point at the output slab region and they are the main source of channel crosstalk [4], [16], [18], [42], [43].

The 512 × 512 25 GHz AWGR design is outlined in Table II above. The device structure uses a SOI layer structure with a 250 nm thick top silicon layer and a 2 μm buried oxide (BOX) which results in a total chip footprint of 11 mm × 16 mm. The input, output and arrayed waveguide gratings are partially etched with an etch depth of 100 nm. Fig. 2 illustrates the waveguide structure and optical mode field.

AWG design starts with the system parameters, including number of channels \( N_{ch} \), center wavelength \( \lambda_0 \), and channel
### TABLE II
**SUMMARY OF 512 × 512 AWGR DESIGN PARAMETERS**

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Symbol</th>
<th>Design values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of channels</td>
<td>(N_{ch})</td>
<td>512</td>
</tr>
<tr>
<td>Center wavelength</td>
<td>(\lambda_0)</td>
<td>1.55 (\mu)m</td>
</tr>
<tr>
<td>Channel spacing</td>
<td>(\Delta\lambda)</td>
<td>0.2 nm</td>
</tr>
<tr>
<td>Number of arms</td>
<td>(N_{ac})</td>
<td>1200</td>
</tr>
<tr>
<td>Arrayed WG pitch</td>
<td>(d)</td>
<td>450 nm</td>
</tr>
<tr>
<td>Arrayed WG width</td>
<td>(w)</td>
<td>950 nm</td>
</tr>
<tr>
<td>Input WG pitch at slab region</td>
<td>(D)</td>
<td>450 nm</td>
</tr>
<tr>
<td>Input WG width at slab region</td>
<td>(w_{\text{in}})</td>
<td>1.55 (\mu)m</td>
</tr>
<tr>
<td>Input/output WG width</td>
<td>(W_e)</td>
<td>3 (\mu)m</td>
</tr>
<tr>
<td>Path length difference</td>
<td>(\Delta L)</td>
<td>6.011 (\mu)m</td>
</tr>
<tr>
<td>Grating order</td>
<td>(m)</td>
<td>11</td>
</tr>
<tr>
<td>AWG slab(lens) radius</td>
<td>(f)</td>
<td>2796.531 (\mu)m</td>
</tr>
<tr>
<td>Bend radius</td>
<td>(R_{\text{min}})</td>
<td>85 (\mu)m</td>
</tr>
<tr>
<td>Waveguide height</td>
<td>(R_{H})</td>
<td>250 nm</td>
</tr>
<tr>
<td>Waveguide slab height</td>
<td>(S_{H})</td>
<td>150 nm</td>
</tr>
<tr>
<td>Buried oxide (BOX) height</td>
<td>(B_{H})</td>
<td>2 (\mu)m</td>
</tr>
</tbody>
</table>

*WG* = waveguide.

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Fig. 2. (a) SOI waveguide cross-section and associated parameters. (b) Half-field simulation of optical mode in arrayed waveguide arm.

Fig. 3. Simulated TE-polarized mode of a SOI ridge waveguide and associated effective index versus waveguide width versus sidewall angle from etching.

### Fig. 4
(a) Mask layout of a single 512 × 512 25-GHz AWGR device. (b) Fabricated device on SOI with footprint of 11 mm × 16 mm.

### TABLE III
**HBR PLASMA BASED TCP ETCH RECIPE**

<table>
<thead>
<tr>
<th>Step</th>
<th>Oxide etch step</th>
<th>Silicon etch step</th>
<th>Si overetch step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure [mTorr]</td>
<td>13</td>
<td>12</td>
<td>80</td>
</tr>
<tr>
<td>TCP RF [watt]</td>
<td>200</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>Bias RF [watt]</td>
<td>40</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Electrode gap [cm]</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>HBr [scm]</td>
<td>0</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>CF(_3) [scm]</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>He clamp [scm]</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Time [sec]</td>
<td>10</td>
<td>vary</td>
<td>10</td>
</tr>
</tbody>
</table>

---

The optical mode simulations are performed with a full-vectorial-eigenmode solver that computes the complex propagation constant that includes the propagation loss associated with radiation into the silicon substrate. Fig. 3 shows the simulated mode profiles that covers and range of widths that are used in the AWGR design. The simulations also examine the realistic case of effective index dependence on sidewall angle due to our plasma dry etching. This will be discussed in the fabrication section. Fig. 4 shows the waveguide mask
Fig. 6. De-multiplexing properties of $512 \times 512$ 25 GHz AWGR (a) in $C$-band, (b) in $S$-band, and (c) in $L$-band.

III. FABRICATION

Fabrication begins with a 6′′ SOI wafer from SOITEC which consists of a 250 nm thick top silicon layer and a 2 μm BOX. The wafer goes through initial RCA-1 and RCA-2 cleaning and is then coated with 900 nm of Rohm Haas UV210-0.6 photoresist, soft-baked at 130 °C for 60 s and then exposed with a ASML DUV stepper using a 248 nm-KrF light source at 18 mJ/cm$^2$ with appropriate focus correction. The sample goes through a 130 °C post-exposure bake for 1 min and then developed in Rohm Haas MF26A developer for 60 s at 20 °C. In order to reduce the photoresist roughness due to the standing wave interference from the DUV exposure, we employ photoresist reflow at 156 °C for 120 s on a hotplate. Next, a LAM TCP plasma etcher is used to etch the silicon with an optimized hydrogen bromide (HBr) recipe as shown in Table III. After plasma dry etching, the photoresist is removed using oxygen plasma at a pressure of 3.75 torr, RF power = 400 W at a chuck temperature of 250 °C for 120 s on a hotplate. Next, a LAM TCP plasma etcher is used to etch the silicon with an optimized hydrogen bromide (HBr) recipe as shown in Table III. After plasma dry etching, the photoresist is removed using oxygen plasma at a pressure of 3.75 torr, RF power = 400 W at a chuck temperature of 250 °C for 120 s on a hotplate. Next, dry thermal oxidation is performed to further reduce sidewall roughness in a horizontal furnace at 1000 °C. The wafers are then dipped in a HF : H$_2$O (1:25) solution to remove thermal oxidation. Next, the wafer is coated with a 1 μm thick low temperature LPCVD oxide, and the samples are then cleaved and the input and output facets are polished to a mirror finish for subsequent optical testing.

Fig. 5 shows the generalized fabrication flow discussed. Near isotropic etching was achieved by using a pure HBr etch which reduces the passivation layer by exposing the silicon atoms to Br radicals [44], [45].

IV. EXPERIMENTAL RESULTS

The spectral response of the fabricated devices were characterized with an optical vector network analyzer (OVNA). The OVNA is capable of high spectral resolution and uses a continuously swept mode-hop-free laser to measure transmission intensity of the AWG [46]. We first evaluated the waveguide loss for a width of 750 nm based on the Fabry–Perot-loss equation [47], and it was determined to be 2.78 dB/cm. The waveguide loss is on the high side compared to e-beam-based resist (hydrogen silsesquioxane) fabrication which yields 0.92 ± 0.14 dB/cm [48]. However, the waveguide loss is low enough to observe the transfer function of various devices. The facet power reflection was determined to be 31% based on 3D-FDTD simulations. The estimated coupling loss at each facet is calculated to be 11.3 dB. Fig. 6 shows the measured spectrum across the 512 channels. The measured channel is spacing is 25 GHz with an estimated channel cross-talk of approximately −4 dB. The measurement was done at input port #323, close to the center of all AWG inputs. We believe that the phase errors caused by accumulation of the non-uniformity in the effective refractive index in the arrayed waveguides due to fabrication tolerance is the source of major phase errors giving rise to the relatively high channel cross-talk [10], [18], [41]. We believe that channel cross-talk performance can be further improved by optimizing our fabrication process through oxide sidewall smoothening [49].

V. CROSSTALK VERSUS PHASE ERRORS

The challenge of high resolution and high channel count silicon photonic AWGRs is phase errors and resulting crosstalk. Especially in high contrast waveguides like silicon photonic waveguides, even a small amount of fabrication tolerance...
induced by waveguide thickness or width variations will give rise to relatively large effective index variations and large phase errors compared to low contrast waveguides like doped silica waveguides [22], [37], [50]. Fig. 7 shows calculated passband errors derived from the waveguide sidewall roughness.

Fig. 7. Simulation of the relation between phase errors and crosstalk characteristics.

VI. CONCLUSION

This paper demonstrates the design, fabrication, and optical characterization of $512 \times 512$ SOI AWGR with 25 GHz channel spacing. The overall device footprint is 11 mm × 16 mm. We believe, this is the highest channel count SOI AWGR reported so far alongside with the highest resolution. The measured channel crosstalk was approximately −4 dB. Although the present device has high channel crosstalk, we believe this can be further improved with optimized fabrication process to lower the phase errors derived from the waveguide sidewall roughness.

We have also presented a fabrication process to realize low-loss silicon waveguides with a measured loss value of 2.78 dB/cm for a silicon waveguide height and width of 250 nm and 750 nm respectively. With further improvement on high resolution and high channel-count AWGRs, chip-scale HPC systems can be realized.

REFERENCES

was born in Sacramento, CA, USA. He is currently working toward the Ph.D. degree in electrical engineering at the University of California, Davis, CA. His research interests include InP/InGaAsP semiconductor mode-locked lasers, silicon photonic integrated circuits, and hybrid Si/III–V active devices.

Tiembui Su is currently working toward the Ph.D. degree in electrical engineering at the University of California, Davis, CA, USA. His research interests include orbital angular momentum (OAM) and AWG devices on various material platforms.
Katsunari Okamoto (M’85–SM’98–F’03) was born in Hiroshima, Japan, on October 19, 1949. He received the B.S., M.S., and Ph.D. degrees in electronics engineering from the University of Tokyo, Tokyo, Japan, in 1972, 1974, and 1977, respectively. In 1977, he was with Ibaraki Electrical Communication Laboratory, Nippon Telegraph and Telephone Corporation (NTT), Ibaraki, Japan, and was engaged in research on transmission characteristics of multimode, dispersion-flattened single-mode single polarization (PANDA) fibers, and fiber-optic components. He proposed for the first time the dispersion-flattened fiber (DFF) and succeeded in the fabrication of DFF that had chromatic dispersion less than ±1 ps/km/nm over a wide spectral range. From September 1982 to September 1983, he was a Guest Researcher with the Optical Fiber Group, Southampton University, Southampton, U.K., where he was engaged in research on birefringent optical fibers. From October 1987 to October 1988, he was an Associate Professor with the Research Center for Advanced Science and Technology (RCAST), University of Tokyo, with Dr. E. A. J. Marcatili from AT&T Bell Laboratories. He was a Guest Professor of the endowed chair at RCAST. They studied the influence of nonlinear optical effects on propagation characteristics of optical fibers. Along with research activities, they taught electromagnetic theory, optoelectronics, and fiber optics at the Electronics and Applied Physics Department. Since 1990, he has been working on the analysis and the synthesis of guided-wave devices and the computer-aided-design (CAD) and fabrication of silica-based planar lightwave circuits (PLCs) at Ibaraki R&D Center, NTT Photonics Laboratories. He developed a CAD tool based on the beam propagation method and a FEM waveguide and stress analyses. The design tool for arrayed waveguide grating (AWG) filter is widely utilized in the NTT Photonics Laboratory and its subsidiary company (NEL). He has developed a 256 × 256 star coupler, various kinds of AWGs, ranging from eight-channel 300-nm spacing AWGs to 128-channel 25-GHz AWGs, flat spectral response AWGs, and integrated-optic reconfigurable add/drop multiplexers. Two hundred to fifty-gigahertz-spacing AWGs are now widely used in commercial WDM systems. In 2003, he started Okamoto Laboratory Ltd. Okamoto Laboratory is an R&D consulting company that deals with the custom design of optical fibers and functional planar lightwave circuits. Since July 2006, he has been a Professor of electrical and computer engineering at the University of California, Davis (UC Davis). He has published more than 220 papers in technical journals and international conferences. He authored and coauthored eight books including *Fundamentals of Optical Waveguides*. His research interests include passive and active photonics devices for high-performance all-optical networks. He is a member of the Optical Society of America and the Institute of Electronics, Information, and Communication Engineers of Japan.

S. J. Ben Yoo (S’82–M’84–SM’97–F’07) received the B.S. degree in electrical engineering (with Distinction), the M.S. degree in electrical engineering, and the Ph.D. degree in electrical engineering with a minor in physics, all from Stanford University, Stanford, CA, USA, in 1984, 1986, and 1991, respectively. He is the Director of Institute of Intelligent and Integrated Information Technology (I4 T) and Professor of Electrical Engineering at University of California at Davis (UC Davis), CA. His research at UC Davis includes high-performance optical switching systems, nanophotonic–electronic systems integration for next generation networking and computing systems. His recent demonstrations included CMOS photonic lattice filter systems, optical label switching routers scalable to 42 Petabit/sec aggregate capacity with 1000 times improvement in performance/power efficiency. Prior to joining UC Davis in 1999, he was a Senior Research Scientist at Bellcore, leading technical efforts in optical networking research and systems integration. His research activities at Bellcore included optical-label switching for the next-generation Internet, reconfigurable optical networks, wavelength interleaving cross connects, wavelength converters, vertical-cavity lasers, and high-speed modulators. He also participated in the advanced technology demonstration network/multiwavelength optical networking (ATD/MONET) systems integration, and a number of standardization activities. Prior to joining Bellcore in 1991, he conducted research on nonlinear optical processes in quantum wells, a four-wave-mixing study of relaxation mechanisms in dye molecules, and ultrafast diffusion-driven photodetectors at Stanford University. He served as an Associate Editor for IEEE PHOTONIC TECHNOLOGY LETTERS, Guest Editors for IEEE/OSA JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE JOURNAL OF SPECIAL TOPICS IN QUANTUM ELECTRONICS. He is Fellow of the IEEE, OSA, and NIAC, and a recipient of the DARPA Award for Sustained Excellence in 1997, the Bellcore CEO Award in 1998, the Mid-Career Research Faculty Award (UC Davis) in 2004, and the Senior Research Faculty Award (UC Davis) in 2011. Prof. Yoo is a Cochair of Photonics in Switching conference 2007, 2008, and 2010.