Abstract—Silicon photonics wavelength-division-multiplexing filters are important building blocks in >100G transceivers and near future on-chip communications between many cores. The paper deals with four kinds of wavelength-division-multiplexing filters; they are, ring resonators, lattice-form filters, arrayed-waveguide gratings and planar Echelle gratings. Progress and technical challenges for these filter devices will be described.

Index Terms—Integrated optics, silicon photonics, wavelength filters.

I. INTRODUCTION

Silicon photonics based on silicon-on-insulator (SOI) technology is a promising technology to meet the requirements of rapid bandwidth growth and energy-efficient communications, while reducing cost per bit [1]. One of the most prominent advantages of photonics interconnection over metallic interconnects is higher bandwidth and signal routing functionality using wavelength division multiplexing (WDM) technology. There are mainly four kinds of devices capable of multi/demultiplexing tens of WDM signals; they are, ring resonators (RRs) [2], lattice-form filters (LFs) [3], arrayed-waveguide gratings (AWGs) [4] and planar Echelle gratings (PEGs) [5]. The former two are cascaded devices relying on temporal multi-beam interference effect and the latter two utilize spatial multi-beam interference effect. In order to achieve good crosstalk characteristics in the temporal and spatial multi-beam interference effects, uniformity of effective index \( n_e \) (\( \approx \beta / k \)), where \( \beta \) and \( k \) denote propagation constant and wave number, is critically important. Filter characteristics of four kinds of devices will be investigated and performance limitations of silicon photonics filters are discussed.

In the latter part of the paper, ultra-compact silicon reflective AWG (R-AWG) will be described. R-AWG enables us to achieve the smallest possible footprint when compared with the conventional transmission-type AWG (T-AWG) having the same AWG parameters. The size reduction of AWG contributes to minimize the total accumulated phase error and lead to lower the crosstalk of silicon AWGs.

II. BASIC CONFIGURATION OF WDM FILTERS

Basic configuration of the four kind of WDM filters are shown in Figs. 1-4. Coupled-resonator optical waveguide (CROW) [2] in Fig. 1 is intended to enlarge passband width of RRs. Free spectral range (FSR) of RR is given by FSR_{RR} = c/(N_c·L), where \( c \) is the light velocity in vacuum, \( L \) is a perimeter of the ring resonator and \( N_c \) (\( \approx n_e - \lambda \cdot dn_e / d\lambda \)) denotes group index of the waveguide. \( n_e \) is an effective index of the waveguide and \( k_0 \) and \( k \) are amplitude coupling coefficients of the directional couplers. The perimeter \( L \) is normally given by \( L = 2\pi R \), where \( R \) is a radius of the RR. The minimum radius of the bent waveguide in silica-based planar lightwave circuit (PLC) is typically \( R_{\text{Silica}} = 2 \) mm. Then, FSR of the silica-based RR becomes FSR_{RR(Silica)} = 16 GHz, where \( N_c = 1.46 \) has been used. FSR of InP-based RR is FSR_{RR(InP)} = 27 GHz, where \( R_{\text{InP}} = 500 \) \( \mu \)m and \( N_c = 3.55 \) are used. It is clear that the silica-based RR and InP-based RR are not practical devices because their FSRs are extremely narrow. On the other hand, the minimum bending radius in SOI-based waveguide can be as small as \( R_{\text{SOI}} = 3-5 \) \( \mu \)m [6]. FSR of the SOI-based RR becomes FSR_{RR(SOI)} = 3980 GHz, where \( R_{\text{SOI}} = 3 \) \( \mu \)m and \( N_c = 4.0 \) have been used. It is known that only SOI-based RR is the practical device for WDM filters. RR can (de-)multiplex only one spectral component among

Manuscript received September 24, 2013; revised October 30, 2013; accepted November 14, 2013. Date of publication July/August 2014.

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Wavelength-Division-Multiplexing Devices in Thin SOI: Advances and Prospects

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Nch signals. Then Nch RR should be concatenated in order to (de-)multiplex Nch channels.

LF consists of cascaded asymmetrical Mach-Zehnder interferometers (AMZIs) as shown in Fig. 2. FSR of LF is expressed as FSR_{LF} = c/(Nc·ΔL), where ΔL is the minimum path length difference in the cascaded AMZIs. c1 to c4 are power coupling coefficients in the directional couplers. Cascaded AMZI configuration enables us to achieve broadened passband width. Odd channels (λ1, λ3, ···, λ_{Nch}−1) and even channels (λ2, λ4, ···, λ_{Nch}) are separated by the single LF. In order to completely separate Nch (= 2^K) channels, K-stage LFs should be concatenated. Path length difference in the k-th (k = 1-K) stage LF is given by ΔL_k = ΔL/2^{k-1}.

Silica-based AWGs and PLCs are widely utilized in the current WDM, time division multiplexing (TDM) systems and fiber-to-the-home (FTTH) access networks. The most prominent feature of the silica PLCs is their well controlled waveguide core geometries and refractive-index uniformities. This allows us to fabricate multi-beam or multi-stage interference devices such as AWGs and LFs. FSR of AWG is prominent feature of the silica PLCs is their well controlled waveguide core geometries and refractive-index uniformities. This allows us to fabricate multi-beam or multi-stage interference devices such as AWGs and LFs. FSR of AWG is expressed as FSR_{RAWG} = c/(Nc·ΔL), where ΔL is the path length difference between adjacent array waveguides. ΔL can be made arbitrarily small (< 1 μm) by the layout design. The corresponding channel spacing of AWGs are S_{ch} = 37.5 nm at λ_0 = 0.51 μm and S_{ch} = 0.08 nm (1.0 GHz) at λ_0 = 1.55 μm, respectively. InP-based AWGs are also quite successful in commercial applications.

Although good crosstalk characteristics have been reported in PEGs at R&D stage, silica-based and InP-based PEGs have not been commercialized. The main reason for it is that crosstalks of the silica and InP AWGs are better than those of PEGs. It will be discussed more in detail in the following section.

Center wavelengths of RR, LF, AWG, and PEG are given by λ_0(RR) = n_{c,0}·L/m_{RR}, λ_0(LF) = n_{c}·ΔL/m_{LF}, λ_0(AWG) = n_{c}·ΔL/m_{AWG}, and λ_0(PEG) = n_{c}·ΔL/m_{PEG}, respectively, where m_{RR}, m_{LF}, m_{AWG}, and m_{PEG} are integers.

III. CROSSWALK CHARACTERISTICS OF WDM FILTERS

Accuracy of the channel center frequencies in the commercial silica AWGs to the International Telecommunication Union (ITU) specification is Δλ = ±2.5 GHz (ΔλL = ±0.02 nm) at λ = 1.55 μm region. Local effective-index fluctuation Δn_c, which is defined as the effective-index variation from place to place, is expressed by

\[ Δn_c = \frac{n_c}{\lambda_0}[Δλ], \]

where n_{c,0} has been used. Δn_c in silica AWG is then obtained as Δn_c ~ 1.8x10^{-5}. Here Δn_c is defined as the half of the peak-to-peak effective-index fluctuation.

On the other hand, an effective-index fluctuation in silica AWGs have been measured to be about δn_c ~ 10^{-6} by using Fourier transform spectroscopy. Difference between Δn_c and δn_c is explained as follows. Local effective-index along the ℓ-th array waveguide is expressed by \( n_c(ζ, ℓ) \) as shown in Fig. 5, where ζ is taken along the ℓ-th array waveguide. Phase retardation in the ℓ-th array waveguide is given by

\[ Θ_ℓ = \frac{2π}{\lambda} L_ℓ n_c(ζ, ℓ) dζ = \frac{2π}{λ} n_c(ℓ)L_ℓ, \]

where L_ℓ denotes geometrical length of the ℓ-th array waveguide and n_c(ℓ) is defined by

\[ n_c(ℓ) = \frac{1}{L_ℓ} \int_0^{L_ℓ} n_c(ζ, ℓ) dζ. \]

Here n_c(ℓ) is called as the path-averaged effective index which represents the mean value of n_c(ζ, ℓ) in the ℓ-th array waveguide. Figure 6 shows a typical variation of the local effective index n_c(ζ, ℓ) and its path-averaged effective index n_c(ℓ). Deviation of n_c(ℓ) from n_{c,0} is normally quite small (roughly 10 times smaller) compared to that of n_c(ζ, ℓ) from
\( n_{c0} \), where \( n_{c0} \) is a target value which is designed by the theory. \( \Delta n_c \) is the half of the peak-to-peak fluctuation in the local effective index \( n_c(\zeta, \ell) \). Path-averaged effective index \( n_c(\ell) \) also varies from waveguide to waveguide as shown in Fig. 7. Here \( \delta n_c \) is the half of the peak-to-peak fluctuation in the path-averaged effective index \( n_c(\ell) \).

It is understood that the path-averaged effective-index fluctuation \( \delta n_c \) is almost 10 times smaller than the local effective-index fluctuation \( \Delta n_c \). The relationship between \( \Delta n_c \) and \( \delta n_c \) holds to other WDM filters. Generally, accuracy of the center wavelength \( \lambda_0 \) depends on the local effective-index fluctuation \( \Delta n_c \) and the crosstalk of the filter is determined by the path-averaged effective-index fluctuation \( \delta n_c \). Both \( \Delta n_c \) and \( \delta n_c \) are caused by (a) the refractive index fluctuation in the core and cladding and (b) core size fluctuation in width and thickness. In addition to \( \delta n_c \), gap width error in directional couplers also brings crosstalk degradation to RRs and LFs.

Good crosstalk characteristics are obtained in silica-based AWGs as shown in Fig. 8. The relation between the effective-index fluctuation \( \delta n_c \) and crosstalk (XT) has been investigated theoretically and experimentally [13], [14]. Theoretical crosstalk was calculated for various kinds of AWGs by assuming random path-averaged effective index fluctuations. Randomness of the effective index fluctuation, in other words the spatial frequency of the effective index fluctuation, was obtained from the measured data [12]. Based on the investigations, the empirical expression for the relation between \( \delta n_c \) and XT has been obtained as

\[
XT_{AWG} \sim 10 \log \left( \frac{\delta n_c L_{ctr}}{\lambda_0} \right)^2,
\]

where \( L_{ctr} \) denotes array waveguide length in the middle waveguide of the array. The waveguide length of the \( \ell \)-th \( (\ell = 1 - N) \) array is expressed as \( L_\ell = L_{ctr} + (N/2 - \ell)\Delta L \). Then, \( L_{ctr} \) is known to be the average of the array waveguide length. It was shown in Ref. [14] that contribution of the thickness variation to \( \delta n_c \) in silica AWGs is less than about -45 dB and can be neglected for the crosstalk degradation. Based on the investigations on spatial multi-beam interference effects in PEGs, similar expression to Eq. (4) is obtained for the crosstalk of PEGs as

\[
XT_{PEG} \sim 10 \log \left( \frac{n_s 2\delta \zeta}{\lambda_0} \right)^2,
\]

where \( \delta \zeta \) denotes the position fluctuation in the reflection facet. It is known from Eq. (5) that \( \delta \zeta \) should be about 10 nm in order to obtain -35 dB crosstalk in silica PEGs (\( n_s \sim 1.45 \)). Such a small \( \delta \zeta \) would be possible in the laboratory experiments by using, for example, a focused ion beam (FIB) machine [5]. However, mask resolution in the commercial PLC products is normally about 25 nm - 50 nm without using
Dependence of the effective index $n_c$ to the core width $W$ and $n_m$ [27], respectively. and $d n_c / d T$ at the typical core thickness $T = 0.22$ μm is estimated to be ~9 nm by using Eq. (5), where $n_c = 2.85$. Except for 4ch-20nm Si PEG, crosstalk of SOI-based WDM filters are limited to -15~ -25dB.

Dependence of $n_c$ on the core thickness ($d n_c / d T$) is normally equal to $d n_c / d W$ because core shape of the silica-based waveguide is square in most cases. Core side-wall roughness measurements on the variation of resonant wavelengths in the RRs [23], [24] and Si AWGs [25]. Core side-wall roughness could not achieve sufficient crosstalk value to be used in the commercial WDM systems.

Table I summarizes the reported crosstalk characteristics of four kinds of WDM filters. All of the crosstalk values for Si photonics WDM filter in Table I is obtained by the laboratory experiments. Crosstalk of -30 dB was obtained only by 4ch-20nm Si PEG. $L_{ct}$ of the 4ch-20nm Si PEG is about 290 μm [18]. Facet position fluctuation $\delta \zeta$ is estimated to be ~9 nm from the measurements on the variation of resonant wavelengths in the Si-Wire AWG [17]. Local effective-index fluctuations in Si-wire waveguides have been evaluated to be about $\Delta n_c \sim 10^{-3}$ from the measurements on the variation of resonant wavelengths in the RRs [23], [24] and Si AWGs [25]. Core side-wall roughness of SOI waveguide is measured to be about $\sigma_w \sim 1$ nm [26] and top silicon thickness roughness is measured to be about $\sigma_T \sim 1$ nm [27], respectively.

Dependence of the effective index $n_c$ to the core width $W$ and thickness $T$ can be calculated by the vectorial finite element method [14]. Fig. 9 shows $n_c$ of silica-based waveguide against $W$ with thickness $T = 6.0$ μm (blue) and its dependence on the core width $d n_c / d W$ (red). $d n_c / d W$ at the typical core width $W = 6.0$ μm is $5.6 \times 10^{-5}$ μm$^{-1} = 5.6 \times 10^{-3}$ nm$^{-1}$. Dependence of $n_c$ on the core thickness ($d n_c / d T$) is normally equal to $d n_c / d W$ because core shape of the silica-based waveguide is square in most cases. Core side-wall roughness $\sigma_w$ and thickness fluctuation $\sigma_T$ of the silica waveguide is difficult to measure because core roughness caused by the reactive ion etching (RIE) is somewhat smoothed out by the high temperature consolidation process for the overcladding. When we assume $\sigma_w = \sigma_T \sim 20$ nm, we obtain local effective-index fluctuations as $\Delta n_c \sim 1.1 \times 10^{-5}$ which agrees with the experimental results.

Local effective-index fluctuations in Si-wire waveguides are about 2.5 times larger than that to the core width because core thickness is very thin compared to the width. It is made clear that stringent thickness uniformity is required to minimize $\Delta n_c$ [28] together with the improvement in the core width uniformity [29]. It is known that 1-nm core width and thickness fluctuation in silicon waveguides bring local effective-index fluctuations of the order of $\Delta n_c \sim$...
1.33-3.44x10^{-3}. Fluctuation of the path-averaged effective-index $\delta n_c$ in silicon waveguides has not been reported yet. However, $\delta n_c$ in silicon waveguides can be assumed to be about $\delta n_c \sim 3-5x10^{-4}$ based on the experimental results on the relationship between $\delta n_c$ and $\delta n_c$ in silica AWGs ($\delta n_c$ is about 10 times smaller than $\Delta n_c$).

Although the bending radius of the silicon waveguide (~3 $\mu$m) is about 700 times smaller than that of the silica waveguides (~2 mm), $L_{ct}$ of the silicon AWG cannot simply be 1/700 because the device size is normally determined by the path length difference $\Delta L$ and number of WDM channels $N_{ch}$. Typical $L_{ct}$ in the reported silicon AWGs is $L_{ct} = 200-500$ $\mu$m, which is roughly 50 times smaller than that of silica AWGs. On the other hand, $\delta n_c$ of silicon waveguide is about 300-500 times larger than that of silica waveguides. Then, $\delta n_c L_{ct}/\lambda_0$ in the silicon AWGs becomes 6-10 times larger than that of silica AWGs. This is the reason why crosstalk of silicon AWGs is about 15 ~ 20 dB worse than that of silica AWGs because the crosstalk is given by Eq. (4).

Waveguide loss is another important technical challenge when discussing scaling of WDM technology. Loss of silicon waveguide is about ~2 dB/cm [6], which is about 100 times larger than that of the silica waveguides (~0.02 dB/cm [4]). However, as described in the previous paragraph, propagation length ($L_{ct}$) is roughly 50 times smaller than that of silica AWGs. Then, insertion losses of the silicon photonics WDM filters are not so large compared to those of silica PLCs. The author believes that waveguide loss of silicon device would not be a critical issue.

PEG has been believed to be advantageous over AWG because only the facet position error causes crosstalk degradation. But, this is not true in SOI-based PEG since the effective-index fluctuation $\delta n_c$ caused by thickness nonuniformity in the slab region is substantially large in SOI slab. Then, Eq. (5) for silicon PEG should be modified to be more accurate form as

$$\frac{W}{H} < 0.3 + \frac{g/H}{\sqrt{1 - (g/H)^2}}, \quad \text{and} \quad 0.5 \leq \frac{g}{H} < 1.0. \quad (7)$$

It is known from Eq. (7) that core size of the Si-rib waveguide can be arbitrarily large as far as the above condition is maintained. 3-4 $\mu$m SOI thickness $H$ is used to fabricate various kinds of WDM devices [31], [32]. Crosstalk of -27 dB is obtained in the commercial 12 channel Si-rib PEG with 8-nm channel spacing by using 3-$\mu$m-thick SOI ($H = 3 \mu$m, $W = 3 \mu$m, and $g = 1.8 \mu$m) [33]. The minimum bending radius of the Si-rib waveguide is 5 mm which is not normally acceptable for silicon photonics because the advantage of the SOI-based device is the ultra compactness. Bending radius can be reduced by introducing deeply etched Si-wire waveguide at the curved section with tapered transitions before and after the bend. The minimum bending radius of 250 $\mu$m is achieved in [31]. It should be noted that the slab region with 3-$\mu$m thickness is highly multi-moded. Then, verticality of the etched reflection facet in PEG should be well maintained, otherwise crosstalk degradation takes place through higher-order mode excitation.

Sensitivity of the effective index $n_e$ in the large-core Si-rib waveguide to the core width $W$ and thickness $H$ becomes dramatically small. $dn_e/dW$ at the core width $W = 3 \mu$m is $3.0x10^{-6}$ nm^{-1} and $dn_e/dH$ at the core thickness $H = 3 \mu$m is $5.5x10^{-6}$ nm^{-1}. It is known that the sensitivity of $n_e$ in the large-core Si-rib waveguide is almost three orders of magnitude smaller than those of the Si-wire waveguides (Figs. 10(a) and (b)).

Flat-top passband characteristics are strongly required for WDM filters in most of the applications. Theoretical responses of CROW RRs and LFs have flat-top passband characteristics with zero insertion loss as shown by the dotted lines in Figs. 12 and 13. Here Fig. 12 and 13 show theoretical spectral responses of CROW RR (Fig. 1) and LF (Fig. 2) with and without effective-index fluctuations. $\delta n_e$'s in Fig. 12 are assumed to be $\delta n_e(1\text{st ring}) = -5x10^{-4}$, $\delta n_e(2\text{nd ring}) = -3x10^{-4}$, and $\delta n_e(3\text{rd ring}) = 3x10^{-4}$. The effective-index fluctuation $\delta n_e$'s in Fig. 13 are assumed to be $\delta n_e(1\text{st arm}) = -5x10^{-4}$, $\delta n_e(2\text{nd arm}) = -5x10^{-4}$, and $\delta n_e(3\text{rd arm}) = 5x10^{-4}$, respectively. Theoretically lossless and flat-top characteristics are great advantage in RRs and LFs. It is known from Figs. 12
and 13 that the through-port crosstalk in RR and crosstalk at both odd and even ports in LF are easily degraded down to ~ -15 dB by the probable effective-index fluctuations of $\delta_n \sim 3-5 \times 10^{-4}$. Through-port extinction in RR can be improved by the multistage design [34] where cleanup CROW filters are added to the through port. Tandem configuration as shown in Fig. 14 is quite effective to improve crosstalk characteristics in LFs [35]. Path length difference in the type-II filter should be $\Delta L_{II} = \Delta L + \lambda_0/2n_c$, where $\Delta L$ is the one in the type-I filter.

Fig. 12. Theoretical spectral responses of CROW RR (Fig. 1). Dotted lines are responses without effective-index fluctuations and solid lines are those with $\delta_n(1\text{st ring}) = -5 \times 10^{-4}$, $\delta_n(2\text{nd ring}) = -3 \times 10^{-4}$, and $\delta_n(3\text{rd ring}) = 3 \times 10^{-4}$.

Fig. 13. Theoretical spectral responses of LF (Fig. 2). Dotted lines are responses without effective-index fluctuations and solid lines are those with $\delta_n(1\text{st arm}) = -5 \times 10^{-4}$, $\delta_n(2\text{nd arm}) = -5 \times 10^{-4}$, and $\delta_n(3\text{rd arm}) = 5 \times 10^{-4}$.

Half-lambda ($= \lambda_0/2n_c$) difference in the path-length difference between the type I and II LFs are necessary because odd (even) spectral components pass cross (through) port of the type-I filter and through (cross) port in the type-II filter, respectively. Passband difference in the type I and II LFs can be adjusted by the half-lambda shift technique and thus signal extinction is doubled. With this elaborated configuration, chromatic dispersion caused by the filter themselves can be almost completely eliminated.

There are two possible origins for the performance degradation in SOI-based RRs and LFs; they are gap width error in directional couplers and effective-index fluctuation $\delta_n$ in the waveguides. However, effective-index fluctuation is considered to be the dominant factor because the crosstalk was improved from -10 dB to less than -35 dB by the thermal tuning of the ring waveguides [36]. If the original -10-dB crosstalk level was caused by the gap width error, crosstalk cannot be improved by the thermal tuning because the heat treatment does not correct the physical gap errors.

AWGs and PEGs having CROW cleanup filter at every output waveguide [14] will be attractive to improve the crosstalk characteristics. Center wavelength fluctuation of Si AWGs have been measured to be $\Delta \lambda = \pm 1.0$ nm ($\Delta f = \pm 125$ GHz) at $\lambda = 1.55 \mu$m region [25]. Then channel spacing of AWGs should be wider than ~ 500 GHz in order to have better matching between the pass wavelengths of AWG and cleanup filters.

Flat-top AWGs & PEGs have intrinsic excess losses [4]. Fig. 15(a) shows a schematic relation between the focused light beam $E(\lambda)$ and local normal mode (LNM) in a flat-top AWG or PEG. LNM is an eigen mode in the output waveguide. Along with the change of $\lambda$, $E(\lambda)$ moves on the interface between slab and output waveguide. Demultiplexing property of the flat-top AWG.

Fig. 14. Tandem LF configuration to improve crosstalk characteristics.
channel center wavelength $\lambda_0$ cannot be obtained because the focused beam is broadened in order to achieve flat-top spectral characteristics. Fig. 15(b) shows a typical demultiplexing property of the flat-top AWG. 3-5 dB loss includes fiber-coupling losses at input/output facets (~0.3 dB/facet). 1-dB-down bandwidth ($B_{1\text{dB}}$) and 3-dB-down bandwidth ($B_{3\text{dB}}$) are typically half and three-quarter of the channel spacing $S_{\text{ch}}$. Fig. 16(a) shows a schematic relation between the focused light beam $E(\lambda)$ and LNMs in flat-top AWG or PEG with multimode output waveguides. Theoretically, 100 percent (lossless) coupling efficiency is obtainable because the focused beam couples with either one of the eigen modes in the multimode output waveguide [37]. Fig. 16(b) shows a typical demultiplexing property of the multimode-output AWG [38]. 1.5-1.7 dB loss including fiber-coupling losses was obtained with $B_{1\text{dB}} \sim 0.7S_{\text{ch}}$ and $B_{3\text{dB}} \sim 0.8S_{\text{ch}}$, respectively. Flat-top technique using multimode output waveguide was also applied to Si-rib PEG and achieved ~25 dB crosstalk [33]. Multimode-output AWGs and PEGs are applicable as the demultiplexers at the receiver end because light beam in the multimode output waveguide can be directly coupled to the photodetector. However, AWGs and PEGs with single-mode output waveguides as shown in Fig. 15 are prerequisite when they are used in the single-mode fiber repeater systems.

IV. SOI-BASED REFLECTIVE AWG

It is shown in the previous section that (a) an improvement in core width and thickness uniformity to reduce $\delta_n$ and (b) size reduction of the device to make $L_{\text{ctr}}$ small are strongly required in order to achieve good crosstalk characteristics in SOI-based WDM filters. Reflective AWG (R-AWG) has a unique property that array waveguides can consist of all straight waveguides. Straight array waveguides and the length reduction both contribute to minimize the total accumulated phase error and lead to lower the crosstalk of AWGs. R-AWG was first proposed in silica AWG [39] and fabricated in InP AWG [40] and Si-wire AWG [41]. However, insufficient crosstalk (~ -13 dB in [40] and ~ -12 dB in [41]) have been obtained, probably due to the imperfection in Au-metal facet verticality in [40] and long and bent Si-wire array waveguides in [41].

Here, fabrication of silicon R-AWG using distributed Bragg reflector (DBR) facets [42] will be described. It enables us to achieve the smallest possible footprint when compared with the conventional transmission-type AWG (T-AWG) as shown in Fig. 3. Straight array waveguides and the length reduction both contribute to minimize the total accumulated phase error and lead to lower the crosstalk of AWGs [14].

R-AWG configuration using DBR facet would be difficult for silica- and InP-based AWGs because the minimum achievable gap width is normally 2-3 $\mu$m in silica AWGs and 1.0-1.5 $\mu$m in InP AWGs. The vertical requirement of less than ±1 degree and metal absorption loss are another difficulties for silica and InP R-AWGs using metal at the reflecter. Crosstalk of ~30 dB was obtained by the reflective silica AWG where straight reflecting surface was provided by cutting and polishing the array waveguides and depositing a Cr-Au film on it [43]. However, cutting and polishing each chip adds extra cost and is not acceptable even for the commercial silica-based AWGs.

R-AWGs were fabricated on 200 nm SOI wafers having a 220 nm thick silicon core layer on a 2 $\mu$m buried oxide layer. Figures 17(a) and (b) show the schematic configuration and photograph of the silicon R-AWG which consists of input/output (I/O) Si-wire waveguides, a slab region with arc length of 91.7 $\mu$m, and 40 Si-rib straight array waveguides with successive $\Delta L/2$ ($\Delta L = 13.2 \mu$m) geometrical path-length difference [42]. The width of the Si-wire waveguide is 480 nm and that of the Si-rib waveguide is 650 nm with 150 nm peripheral heights, respectively.

Fig. 16. (a) Schematic relation between the focused light beam $E(\lambda)$ and LNMs in multimode-output AWG or PEG. (b) Typical demultiplexing property of the flat-top AWG with multimode output waveguides.
Si-wire I/O waveguides are adiabatically transformed to Si-rib waveguides before reaching the slab interface so as to reduce reflections. The array waveguide spacing at the slab interface is 1.55 μm and I/O waveguide spacing is 2.2 μm, respectively. Deeply etched (220 nm) second-order DBR is used as a reflection facet which was demonstrated in a silicon PEG [44]. DBRs are fabricated using the stepper. The period is 620 nm, the gap width is 130 nm and the number of periods is \( N_{\text{DBR}} = 10 \), respectively. Different from the surface relief grating [45], the mode-coupling coefficient of the deeply etched grating does not strongly depend on the diffraction order and more than 90 % (< 0.5 dB loss) power reflectivity can be obtained for \( N_{\text{DBR}} > 8 \). On the other hand, the reflection bandwidth of the second-order DBR is 160 nm which is almost the half of that of the first-order DBR. A 1x1 multimode interference (MMI) mode filter was added to every array waveguide to suppress the higher-order mode because the Si-rib waveguide with a 650 nm width is slightly multi-moded [46]. The MMI mode filter was 1.3 μm in width and 3.0 μm in length. Simulated insertion loss of the mode filter for the fundamental mode is ~0.04 dB, while loss for the higher-order mode is larger than 50 dB.

Array waveguides in the R-AWG can be entirely weakly-guiding waveguides such as Si-rib waveguides because bent waveguides are not required. Effective-index fluctuation \( \delta n_c \) of the Si-rib waveguide with respect to the core-width fluctuation is ~2 times smaller than that of the Si-wire waveguide [14]. In addition to that, the average array waveguide length \( L_{\text{cw}} \) of the R-AWG can be 3-4 times shorter than that of the T-AWG having the same AWG parameters. Smaller \( \delta n_c \) and shorter \( L_{\text{cw}} \) in the R-AWG both contribute to reduce crosstalk of AWG as shown in Eq. (4).

In the measurement, light from the broadband source is coupled through an input single-mode fiber (SMF) to the central (no. 8) Si-wire waveguide. Output SMF is stepwise connected to the waveguide from no. 1 [the uppermost port in Fig. 17(a)] to nos. 7 and 9 to no. 15 [the lowermost port in Fig. 17(a)]. The other end of the output SMF is introduced to the bulk spectrometer. Spacing of the I/O waveguides is enlarged from 10 μm to 127 μm so as to allow SMF butt coupling to the waveguides [the fanout region is not shown in Figs. 17(a) and (b)]. Measurement results of 14 channel 400GHz Si-RAWG for TE polarization is shown in Fig. 18. Fiber coupling loss was about 3.0 dB by using a spot-size converter. These results are normalized by the transmission of a straight Si-wire waveguide so that the coupling loss between SMF and R-AWG is excluded.

On-chip loss of 3.0 dB and crosstalk of -20 dB have been obtained in Fig. 18. Insertion loss of Si DBR itself was reported to be ~1.5 dB for \( N_{\text{DBR}} = 200 \) [47]. The loss of DBR facet in our Si R-AWG is then expected to be ~0.1 dB for \( N_{\text{DBR}} = 10 \). Propagation loss in the array waveguides is the major source of the excess loss of AWG. Excess loss of the Si R-AWG should be smaller than other configurations because array waveguide length of the R-AWG is several times shorter than that of the T-AWG. The central channel at \( \lambda \sim 1594 \) nm is not available because it comes back to the input port. Figure 18 was obtained by the light excitation to the central input waveguide. The farfield radiation field is expected to excite only the fundamental mode in the array waveguide because every array waveguide is directed to the central input waveguide. In order to investigate the functionality of the MMI mode filter, the light input and output relation is reversed. We coupled light into the original output port (nos. 1–7 and nos. 9–15) and measured at the original input port (no. 8) as shown in Fig. 19(a) in order to investigate whether the standard layout of I/O waveguides [Fig. 19(b)] is possible. The measurement was repeated by shifting the coupling position through the entire (original output port) positions. In this off-center light coupling, the farfield radiation field is expected to excite higher-order modes in the array waveguide and degrade the crosstalk characteristics.

![Fig. 18. Measurement results of 14ch-400GHz Si reflective AWG.](image_url)

![Fig. 19. Relation of I/O waveguides which is reversed from that in Fig. 17(a). (b) Standard layout of I/O waveguides where input and output waveguides are placed oppositely.](image_url)

However, almost no substantial crosstalk degradation was
observed as shown in Fig. 20. Black lines in Fig. 20 show transmission spectra for the center input as shown in Fig. 18 and colored lines show those for the off-centered light excitation. Slight deviations in the insertion losses may be due to the coupling loss variations from port to port because fixed coupling loss value was used. It is confirmed that the MMI mode filter can sufficiently suppress the higher-order modes. MMI mode filter allows us to implement a standard layout of I/O waveguides as shown in Fig. 19(b).

Fig. 21 shows a transmission spectrum of one of the 14 channels of the eight AWGs on the different die. Four dies are located in the central region of the 200 mm wafer and other dies are picked up from the peripheral regions of the four quadrants. The center wavelength fluctuation is measured to be ~0.6 nm, which is about 3 times smaller than the previously reported value [25]. It suggests that the effective-index fluctuation $\delta n_e$ is also 3 times smaller because $\delta n_e$ is proportional to $\delta \lambda$ and the crosstalk of less than -20 dB should have been obtained. Several factors are considered to be the origin by which crosstalk is limited to around -20 dB; they are, irregularities in DBR periodicity, size fluctuations in MMI mode filters, and SOI thickness fluctuations. The former two factors can be reduced by the improvement of the fabrication process. Crosstalk degradation by the SOI thickness fluctuations can be reduced by using thicker core layer, for example, with 0.5 μm [14]. $\delta n_c/\delta T$ for both of the Si-rib waveguide and slab region with 0.5-μm-thick cores are calculated to be ~5 times smaller than those of 0.22-μm-thick cores.

Although R-AWG resembles planar concave grating, the major difference is that the delay arms (array waveguides) and the light interference region (slab region) are clearly separated in the R-AWG. Then, athermal R-AWG can be fabricated by using two different kinds of SOI-based cores (without using polymer material), such as Si-rib and Si-slot waveguides, in the array waveguide region [48].

Several temperature compensation techniques have been demonstrated for AWGs; they are the polymer-filled technique [49]-[50], and mechanical athermalization technique [51]. Different from silica AWGs, the methods mentioned above cannot simply be applied to silicon AWGs, mainly due to their extremely small size and large diffraction loss in the polymer-filled groove. Athermal AWG employing two different core materials in the array waveguide was demonstrated in InP-based AWG [52]. This athermalization technique is quite advantageous for silicon AWG because the array waveguides can entirely consist of SOI-based materials.

Figure 22 shows a schematic configuration of the proposed athermal Si R-AWG consisting of Si-rib and Si-slot waveguides [48]. The overall Si-slot waveguide is 500 nm wide and 220 nm tall, with a 150 nm wide silica slot region.

The thermo-optic coefficient of the Si-slot waveguide is calculated to be $dn_c/dT = 5.7 \times 10^{-5}$/°C, which is about 3 times smaller than that of the Si-rib waveguide ($dn_c/dT = 1.83 \times 10^{-4}$/°C), where $n_c (= 1.6068)$ and $n_e (= 2.7054)$ are effective indices of the Si-slot waveguide and Si-rib.
waveguide. The center wavelength of the athermal R-AWG is expressed as \[ \lambda = \frac{2}{m} \left( \frac{n_c \Delta s - n_c \Delta \ell}{n_c} \right), \]

where \(\Delta s\) and \(\Delta \ell\) are path-length differences in the Si-slot and Si-rib waveguides, respectively. The rightmost equation in Eq. (8) is given by the requirement that the athermal R-AWG should satisfy 14 output channels with 400-GHz spacing because \(\Delta L\) is determined by the system specifications independently of the athermal conditions. The athermal condition is derived from Eq. (8) as

\[ \frac{d\lambda}{dT} = \frac{2}{m} \left( \frac{dn_c}{dT} \delta s - \frac{dn_c}{dT} \delta \ell \right) = 0. \]

Path-length differences \(\Delta s\) and \(\Delta \ell\) in the Si-slot waveguides and Si-rib waveguides are obtained from Eqs. (8)-(9) by

\[ \Delta s = \frac{\Delta L}{2 \left( \frac{n_c}{\delta n_c} \left( \frac{dn_c}{dT} \right) - \frac{dn_c}{dT} \right)}, \quad \Delta \ell = \frac{\Delta L}{2 \left( \frac{n_c}{\delta n_c} \left( \frac{dn_c}{dT} \right) - 1 \right)}. \]

\(\Delta s\) and \(\Delta \ell\) are calculated to be 23.37 µm and 7.28 µm, respectively. A waveguide transformer between Si-rib and Si-slot waveguides consists of several pairs of complementary tapers [53]. It is capable of converting Gaussian-like modes in the Si-rib waveguide to complicated non-Gaussian-like Si-slot waveguide modes, and vice versa.

V. CONCLUSION

Four kinds of silicon photonics WDM filters have been investigated in comparison with the silica-based filter devices. It is made clear that core width and thickness fluctuations of the order of 0.5 nm ~ 1 nm limits the crosstalk of SOI-based waveguides and PEGs having CROW cleanup filters (tandem configuration) will be attractive to achieve crosstalk better than -30 dB.

A compact SOI-based reflective 1x14 R-AWGs with 400-GHz channel spacing has been demonstrated. Good crosstalk value of -20 dB was achieved with the on-chip loss of 3 dB. R-AWG configuration allows us to achieve the smallest possible footprint when compared with the conventional transmission-type AWG having the same parameters. The ultra-compactness of the Si R-AWG and its athermalization will be quite advantageous not only for on-chip CMOS applications but for transceiver applications in data communications beyond 100Gb/s.

REFERENCES


Katsunari Okamoto (M'85–SM'98–F'03) received the B.S., M.S., and Ph.D. degrees in electronics engineering from Tokyo University, Tokyo, Japan, in 1972, 1974, and 1977, respectively. He joined Ibaraki Electrical Communication Laboratory, Nippon Telegraph and Telephone Corporation (NTT), Ibaraki, Japan, in 1977, and was engaged in the 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 (DIFF) and succeeded in fabrication of DIFF that had chromatic dispersion less than +/−1 ps/km/m in a wide spectral range. From September 1982 to September 1983, he worked as a guest researcher at Optical Fiber Group, Southampton University, England, where he was engaged in the research on birefringent optical fibers. At NTT Photonics Laboratories, he has developed various kinds of AWGs and integrated-optic reconfigurable add/drop multiplexers (ROADM). From July 2006, he worked as Professor of Electrical and Computer Engineering at the University of California at Davis (UC Davis). His research at UC Davis includes passive and active photonics devices and silicon photonics. He is currently working as CTO at SiPhX Corporation on the silica- and SOI-based AWGs and miniature PLC spectroscopic sensors for environmental sensing and health diagnostics. He has published more than 294 papers in technical journals and international conferences. He authored and co-authored 8 books including “Fundamentals of Optical Waveguides (Elsevier”). Dr. Okamoto is a member of the Institute of Electrical and Electronics Engineers (Fellow), Optical Society of America and the Institute of Electronics Information and Communication Engineers of Japan.