Elimination of Polarization Sensitivity in Silica-Based Wavelength Division Multiplexer Using a Polyimide Half Waveplate

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***Abstract*—This paper proposes a low-loss technique for eliminating polarization sensitivity in a silica-based planar lightwave circuit (PLC) which uses a polarization mode converter formed at the center of the circuit. This converter consists of a waveguide gap housing a polyimide half waveplate. The excess loss of the converter was drastically reduced to 0.26 dB with a $\Delta =$ 0.75% waveguide by employing an 18 μm-wide waveguide gap and a 14.5 μm-thick polyimide half waveplate. A polarization mode conversion crosstalk of -37 dB was achieved at 1.55 μm. Using this converter, we successfully eliminated the polarization sensitivity in some silica-based PLC-type wavelength division multiplexers. The converter is also insensitive to temperature and offers long term stability.**

***Index Terms*—Arrayed-waveguide grating multiplexer, planar lightwave circuit, polarization dependent loss (PDL), polarization sensitivity, polyimide waveplate, wavelength division multiplexing (WDM), silica-based waveguide.**

I. Introduction

OPTICAL wavelength division multiplexing (WDM) is an attractive way of increasing transmission capacity and network flexibility. Recently, many WDM systems have been demonstrated and they employed various kinds of wavelength-division multiplexer. Silica-based planar lightwave circuits (PLC's) have lately attracted considerable attention as wavelength-division multiplexers. This is because silica-based PLC's offer great design flexibility, low insertion loss, good reproducibility, and long term reliability. However, polarization dependence is a crucial problem with these devices.

Several approaches have been reported for eliminating the polarization dependence in PLC-type multiplexers as shown in Table I [1]–[14]. The first approach involves controlling waveguide birefringence with stress releasing grooves formed beside the waveguide [1], but this technique requires precise fabrication reproducibility for the grooves, so it does not meet the demands of mass production. Waveguide birefringence control with a thin Si_3N_4 film under the waveguide core [2] and polarization dependence compensation with two different birefringent waveguides [3] are considered to pose similar difficulties in terms of fabrication reproducibility. Waveguide birefringence control by laser trimming an amorphous silicon (a-Si) stress applying film deposited on the surface of the waveguide [4] is more practical, because the responses of the TE and TM modes can be adjusted after the a-Si film has formed, which means that precise a-Si film formation is not required. Photoinduced birefringence control [5] can also be employed after the device has been fabricated. However, these trimming processes take considerable time, so they are also unsuitable for mass production. The array order trick [6], [7] is an ingenious way of eliminating the polarization sensitivity in InP waveguides, but in general, it cannot be applied to silica-based PLC's. This is because the silica-based waveguide has a birefringence of around 10^{-4}. This value restricts the free spectral range (FSR) to around 0.1 nm, in other words, silica-based PLC's using the array order trick are incapable of realizing multiplexers with a channel spacing of a few nm. A reduction in the intrinsic birefringence seems a promising way to realize such multiplexers. Recently polarization insensitive multiplexers have been reported with low birefringent waveguides [9]–[12]. However, these waveguides still have a birefringence of about 10^{-5}, which corresponds to a wavelength shift of a few GHz between the TE and TM modes. This means that these waveguides cannot be applied to multiplexers with channel spacings of less than a few ten GHz.

We proposed and demonstrated a polarization mode conversion technique with a 92-μm-thick quartz half waveplate [8], but the excess loss of 5 dB caused by the converter was considered too large for practical use. We developed a narrow 18-μm waveguide gap and a thin 14.5-μm polyimide half waveplate to reduce the excess loss, and successfully achieved a polarization insensitive multiplexer with a low excess loss of 0.26 dB [13], [14]. This method is extremely useful in silica-based PLC's and is suitable for mass production, because the fabrication process is simple and it can be applied to any birefringent waveguide or channel spacing device.

In this paper, we describe a polarization mode conversion technique for eliminating the polarization dependence in silica-based WDM devices especially that in arrayed-waveguide grating (AWG) multiplexers. Section II describes the principle behind the elimination of polarization dependence in a multiplexer using the converter. The first part of Section III

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TABLE I
APPROACHES FOR ELIMINATING POLARIZATION DEPENDENCE

Approaches		Materials	Features	Ref.
Birefringence Control	Stress Releasing Groove	SiO_2 on Si	Precise fabrication reproducibility required	[1]
	Si_3N_4 Film	SiO_2 on Si		[2]
	Waveguide with different birefringence	InP		[3]
	a-Si Stress Applying Film	SiO_2 on Si	Trimming process is required	[4]
	Photoinduced Birefringence			[5]
Array Order Trick (FSR $= \lambda_{\mathrm{TE}} - \lambda_{\mathrm{TM}}$)		Al_2O_2 on Si	FSR is fixed by waveguide birefringenced	[6]
		InP		[7]
Polarization Conversion with Half Waveplate		SiO_2 on Si	92 μm-thick quartz waveplate	[8]
			15 μm-thick polyimide waveplate	[14]
Reduction of Waveguide Bifringence		InP	Waveguide material is limited	[9]
		SiO_2 on SiO_2		[10], [11]
		Polymer on Si		[12]

estimates the converter specification in terms of the excess loss and the polarization mode conversion crosstalk for a 0.8 nm-spaced AWG multiplexer. Then it describes the fabrication of a polyimide half waveplate and a polarization mode converter. The fundamental characteristics of the converter are reported in the last part of Section III. Section IV describes polarization insensitive WDM multiplexers which use this converter, focusing particularly on the AWG multiplexer. The temperature independence and long term stability of the polarization insensitive operation is also presented. Finally, we summarize our results in Section V.

II. PRINCIPLE OF ELIMINATING POLARIZATION DEPENDENCE

The polarization dependence in a silica-based AWG multiplexer fabricated on a silicon substrate is caused by the waveguide birefringence ($B = n_{\mathrm{TM}} - n_{\mathrm{TE}}$), which is the refractive index difference between the TE and TM modes. Residual thermal stress between a silica-glass layer and a silicon substrate induces this waveguide birefringence and results in a wavelength response shift in the TE and TM modes. The center wavelength of $\lambda_{\mathrm{TE(TM)}}$ transmitted from the central input port to the central output port in an AWG multiplexer is given by

$$\lambda_{\mathrm{TE(TM)}} = \frac{n_{\mathrm{TE(TM)}} \cdot \Delta L}{m} \tag{1}$$

where $n_{\mathrm{TE(TM)}}, m$ and ΔL represent the effective refractive index in the TE (TM) mode, the diffraction order and the path difference between neighboring arrayed waveguides, respectively. The center wavelength is, therefore, shifted with $\Delta\lambda$ in the TE and TM modes by the waveguide birefringence as follows:

$$\Delta\lambda = \frac{B \cdot \Delta L}{m} \tag{2}$$

where B is the birefringence.

This polarization dependent wavelength shift can be simply eliminated by converting the polarization modes at the center of the circuit. Fig. 1 shows the configuration of our proposed polarization insensitive AWG multiplexer with a polarization mode converter, which consists of a waveguide gap housing a half waveplate. The input TE light travels in the TE mode in the first half of this circuit, it is then converted to the TM mode at the center, and travels in the TM mode in the second half. The center wavelength of λ_0 is, therefore, the average of those of the TE and TM modes as follows:

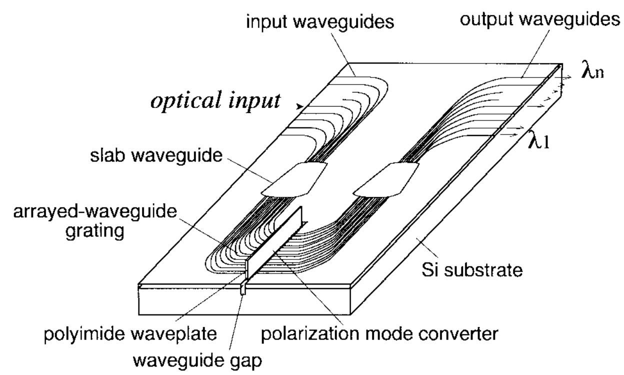


Fig. 1. Configuration of the proposed polarization insensitive AWG multiplexer with a polarization mode converter formed at the center of the circuit.

$$\lambda_0 = \frac{(n_{\mathrm{TE}} + n_{\mathrm{TM}}) \cdot \Delta L}{2 \cdot m}. \tag{3}$$

In principle, this averaging eliminates the polarization dependent wavelength shift.

It is worthwhile noting here that this method can eliminate polarization dependence not only in an AWG multiplexer but also in any circuit that has a symmetric input/output geometry. Furthermore, this method can eliminate not only birefringence induced polarization dependent wavelength shift but also polarization dependent loss (PDL) caused by the waveguide propagation loss difference between the TE/TM modes.

III. POLARIZATION MODE CONVERTER WITH POLYIMIDE HALF WAVEPLATE

A. Specifications of Polarization Mode Converter

The polarization mode conversion method can indeed eliminate the polarization sensitivity in waveguide devices, but excess loss is induced by the insertion of a half waveplate and polarization sensitivity is caused by the fabrication error in the converter. An excess loss of 5 dB was reported when a 92 μm-thick quartz half waveplate was inserted into a 100 μm-wide waveguide gap [8]. We have developed a thin polyimide half waveplate to reduce the excess loss [13], [14]. Here, we clarify the relation between the excess loss.

The polarization sensitivity could be completely eliminated in principle if the converter exchanged the polarization modes completely. Indeed, there is actually some polarization mode conversion crosstalk caused by fabrication error of the converter. In this case, some polarization dependent wavelength shift remains and causes a PDL around the center wavelength. Therefore in this section, we clarify the relation between the PDL and the polarization mode conversion crosstalk for a 0.8-nm-spaced AWG multiplexer, and then estimate the converter specifications.

1) Excess Loss: The excess loss of the polarization mode converter is composed of the radiation loss in the waveguide gap, the absorption loss in the polyimide waveplate, and the Fresnel reflection losses at the waveplate surfaces. The absorption loss is estimated to be less than 0.01 dB for the 14.5 μm-thick polyimide waveplate. The reflection losses are calculated as 0.02 dB for the two surfaces of the waveplate. The excess loss is therefore almost equal to the radiation loss. The excess loss in the waveguide gap is given by

$$\text{Excess Loss} = 10\log_{10}\left\{1+\left(\frac{\lambda\cdot d}{2\pi\cdot n\cdot w^2}\right)^2\right\} \tag{4}$$

where λ is the optical wavelength, d the groove width, n the refractive index in the groove, and w the spot size of the waveguide. Since silica-based AWG multiplexers have insertion losses of about 3 dB, we considered the excess loss of the converter should be less than one tenth of this value. According to equation (4), the excess loss becomes less than 0.3 dB when the groove width is less than 20 μm, assuming that $\Delta = 0.75\%$ waveguide is employed. Accordingly, we specify a waveguide gap of less than 20 μm for the converter.

2) Polarization Mode Conversion Crosstalk: The polarization mode converter is constructed with a half waveplate whose principal axis is tilted at 45° to the waveguide plane. In this converter, deviations in the waveplate retardation and the angle of the principal axis induce conversion crosstalk. This crosstalk causes a PDL in the AWG multiplexer. Here, a PDL caused by waveguide propagation loss difference between the TE/TM modes is not taken into account, because the loss difference is negligible small of less than 0.1 dB with silica-based waveguides. The input light and transmission matrix of the converter (T_{HWP}) are given by

$$\begin{pmatrix} E_{\mathrm{TE}} \\ E_{\mathrm{TM}} \end{pmatrix} = E_0\cdot e^{j\overline{\omega}t}\begin{pmatrix} \cos\theta\cdot e^{-j(\phi_0/2)} \\ \sin\theta\cdot e^{u(\phi_0/2)} \end{pmatrix} \tag{5}$$

$$T_{\mathrm{HWP}} = \begin{pmatrix} \delta\cdot e^{j\phi_1} & -j\sqrt{1-\delta^2} \\ -j\sqrt{1-\delta^2} & \delta\cdot e^{-j\phi_1} \end{pmatrix} \tag{6}$$

where $E_{\mathrm{TE(TM)}}$ is the electrical amplitude of the TE (TM) mode, E_0 the electrical amplitude of the input light, j the imaginary part, ω the angular frequency, t the time, θ the principal axis angle of the input light, ϕ_0 the phase shift between input TE/TM modes, δ the polarization mode conversion crosstalk in the electrical amplitude, and ϕ_1 the phase shift caused by the waveplate. Here, θ and ϕ_0 depend on the polarization state of the input light. The transmission spectrum of the AWG multiplexer for each polarization mode is expressed below. Here, the transmission spectrum is assumed to have a Gaussian shape

$$\begin{aligned} E_{em} = {} & -j\cdot E_0\cdot\cos\theta\cdot\sqrt{1-\delta^2} \\ & \cdot\exp\left\{-\frac{1}{2}\left(\frac{\lambda-\lambda_0}{\lambda_b}\right)^2 \right. \\ & \left. +j\left(\overline{\omega}t-\frac{\phi_0}{2}+\frac{2\pi}{\lambda}\cdot\frac{n_{\mathrm{TE}}+n_{\mathrm{TM}}}{2}\cdot L\right)\right\} \end{aligned} \tag{7}$$

$$\begin{aligned} E_{ee} = {} & E_0\cdot\cos\theta\cdot\theta \\ & \cdot\exp\left\{-\frac{1}{2}\left(\frac{\lambda-\lambda_0+\frac{\Delta\lambda}{2}}{\lambda_b}\right)^2 \right. \\ & \left. +j\left(\overline{\omega}t-\frac{\phi_0}{2}+\phi_1+\frac{2\pi}{\lambda}\cdot n_{\mathrm{TE}}\cdot L\right)\right\} \end{aligned} \tag{8}$$

$$\begin{aligned} E_{me} = {} & -j\cdot E_0\sin\theta\cdot\sqrt{1-\delta^2} \\ & \cdot\exp\left\{-\frac{1}{2}\left(\frac{\lambda-\lambda_0}{\lambda_b}\right)^2 \right. \\ & \left. +j\left(\overline{\omega}t+\frac{\phi_0}{2}+\frac{2\pi}{\lambda}\cdot\frac{n_{\mathrm{TE}}+n_{\mathrm{TM}}}{2}\cdot L\right)\right\} \end{aligned} \tag{9}$$

$$\begin{aligned} E_{mm} = {} & E_0\cdot\sin\cdot\delta \\ & \cdot\exp\left\{-\frac{1}{2}\left(\frac{\lambda-\lambda_0-\frac{\Delta\lambda}{2}}{\lambda_b}\right)^2 \right. \\ & \left. +j\left(\overline{\omega}t+\frac{\phi_0}{2}-\phi_1+\frac{2\pi}{\lambda}\cdot n_{\mathrm{TM}}\cdot L\right)\right\} \end{aligned} \tag{10}$$

where $E_{em(me)}$ is the electrical amplitude of light traveling in the TE (TM) mode in the first half and in the TM (TE) mode in the second half of the circuit, $E_{ee(mm)}$ is that for the light traveling in the TE (TM) mode through the circuit, λ_b the Gaussian power distribution width, λ the optical wavelength, and L the effective waveguide length in an AWG multiplexer. The power transmittance and the PDL are given by (11) and (12) at the bottom of the next page where $(T_{\mathrm{AWG}})^2$ is the power transmittance of an AWG multiplexer, δ^2 the polarization mode conversion crosstalk. In (12), the PDL is defined as the largest value in a 3 dB bandwidth. It is interesting to note that $(T_{\mathrm{AWG}})^2$ has maximum and minimum values when θ is $(1+2N)\pi/4$ where N is an integer. This means that $(T_{\mathrm{AWG}})^2$ has its maximum and minimum values when the principal axis of the input light is tilted at 45° to the waveguide plane, in other words, when the input light has

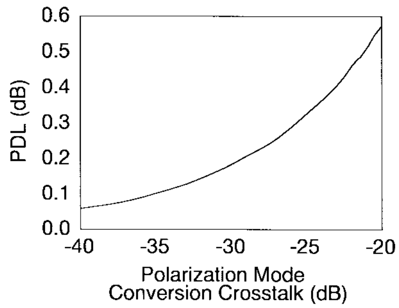


Fig. 2. Relation between PDL in a 0.8 nm-spaced AWG multiplexer and polarization mode conversion crosstalk.

equal power in the TE and TM modes, and is not just in either the TE or TM mode. Fig. 2 shows the relation between the PDL and the polarization mode conversion crosstalk, calculated with (12), where it is assumed that $\Delta\lambda$ is 0.12 nm and λ_b is 0.15 nm. According to this figure, a polarization mode converter with a crosstalk of −26 dB causes a PDL of about 0.3 dB. When the AWG is used as a wavelength multiplexer, the PDL causes a difference between the signal levels in the wavelength channels. Therefore, a PDL of less than 0.3 dB is generally required. Accordingly, we specify a conversion crosstalk of −26 dB for the converter in order to achieve a PDL of less than 0.3 dB over the 3 dB bandwidth of AWG multiplexer.

B. Fabrication

1) Polyimide Half Waveplate: Fig. 3 shows the process for preparing a polyimide half waveplate. A poly(amic acid) solution (15 wt%, 450 poise) was spin-coated onto a 4-in silicon wafer. The solvent was dried and the poly(amic acid) film was peeled from the wafer. Two sides of the film were cut off and the ends of the remaining piece were fixed in a metal frame. The film was then heated to 350 °C at 4 °C/min. to convert the poly(amic acid) film into polyimide film. As the temperature increased, polymer chains oriented along the direction in which the film was fixed as a result of the tensile stress arising from the shrinkage of the polymer film and evaporation of the solvent. After one hour annealing at 350 °C, the in-plane refractive indices of the film were 1.638 in parallel and 1.585 perpendicular to the fixed direction. These directions correspond to the principal axes of the waveplate. An in-plane birefringence of 0.053 was then obtained with this method. Since the retardation between two principal axes is the product of the film thickness and in-plane birefringence, it can be controlled precisely by controlling the thickness, which is proportional to the speed at which the poly(amic acid) solution is spin coated. The polyimide film retardation is linearly proportional to the spinning speed, as shown in Fig. 4. This indicates that in-plane birefringence is constant and does not depend on film thickness. In this way, we obtained a 14.5 μm-thick polyimide half waveplate for the 1.55 μm wavelength light with a spinning speed of 570 rpm. The thickness of the half waveplate was less than 1/6 of that when quartz is used. The retardation in the polyimide waveplate still remained after reannealing it at 350 °C for 1 hour, which indicates that it has sufficient thermal stability. Finally, the polyimide half waveplate was cut to 1.5 × 5.0 mm^2 with its principal axis tilted at 45°. The fabricated half waveplate was sufficiently strong and flexible to be handled without damage.

2) Polarization Mode Converter: Fig. 5(a) and (b) show the schematic configuration and a cross sectional photograph of the polarization mode converter, which consists of a channel waveguide, a groove, a polyimide half waveplate and adhesive. The silica-based waveguide was fabricated on a silicon substrate by using flame hydrolysis deposition (FHD) and reactive ion etching (RIE) [15]. We fabricated three types of waveguide with different refractive index differences between the core and cladding (Δ). Table II shows the Δ values, core sizes, spot sizes at 1.55 μm, and the minimum radiuses possible without any increase in the bending loss. 18 μm-wide and 120 μm-deep grooves were formed in these waveguides with a diamond dicing saw.

The polyimide half waveplate was inserted into the gap by hand. This process relies on the waveplate being tough and flexible. The principal axis of the waveplate was automatically set at 45° to the waveguide plane when the waveplate was inserted into the groove. The waveplate was finally fixed in the groove with an adhesive. This adhesive is the most important for the converter's reliability, and was experimentally selected of a few tens kinds of adhesive. The polarization mode converter was confirmed that no crack was occurred under the test more than 5000 h at 75 °C and 90% relative humidity and the test more than 500 temperature cycles from −40 to 85 °C.

C. Performances of Polarization Mode Converter

1) Excess Loss: The excess loss was measured at 1.55 μm with a straight waveguide, where ten grooves were formed in series to enable precise measurement. Fig. 6 shows the average excess loss versus the waveguide gap in a $\Delta = 0.75\%$ waveguide, where each groove was filled with adhesive. The open circles show experimental results and the line was calculated with (4). The reported excess loss of 5 dB with a quartz half waveplate is also plotted in the figure with a filled circle. The experimental and calculated results agree well. This figure indicates that the excess loss was drastically reduced from 2.3 to 0.13 dB by reducing the waveguide gap from 68 to 13 μm. The loss was 0.24 dB for an 18 μm gap which was used in a polarization mode converter for an AWG multiplexer. The excess loss was 0.25 dB for the 1.31 μm wavelength light. Fig. 7 shows the excess loss versus the spot size of the

$$|T_{\text{AWG}}|^2 = \frac{|E_{em} + E_{ee}|^2 + |E_{me} + E_{mm}|^2}{E_0^2} \tag{11}$$

$$\text{PDL}(\delta^2) = 10 \cdot \log_{10} |T_{\text{AWG}}(\delta^2)|^2_{\max} - 10 \cdot \log_{10} |T_{\text{AWG}}(\delta^2)|^2_{\min} \tag{12}$$

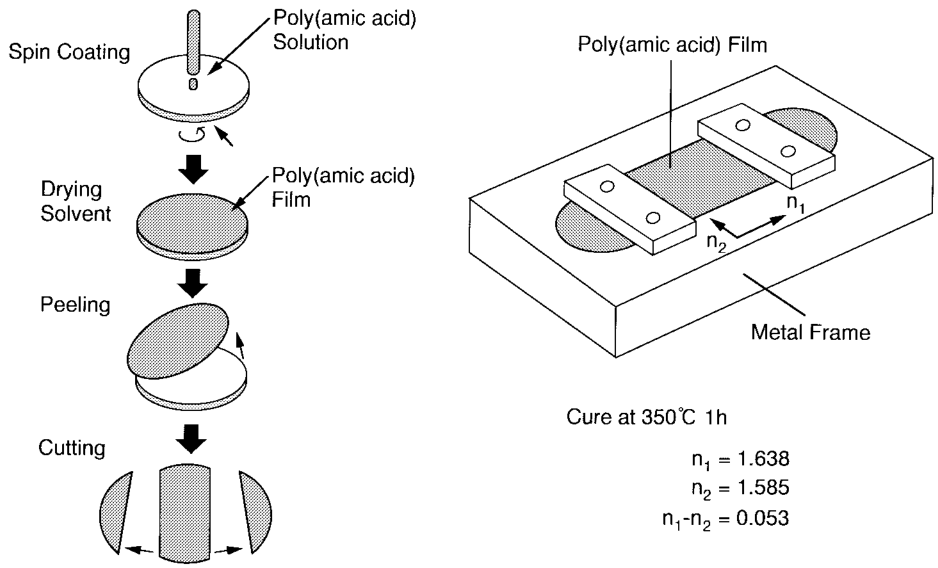


Fig. 3. Polyimide waveplate fabrication procedure.

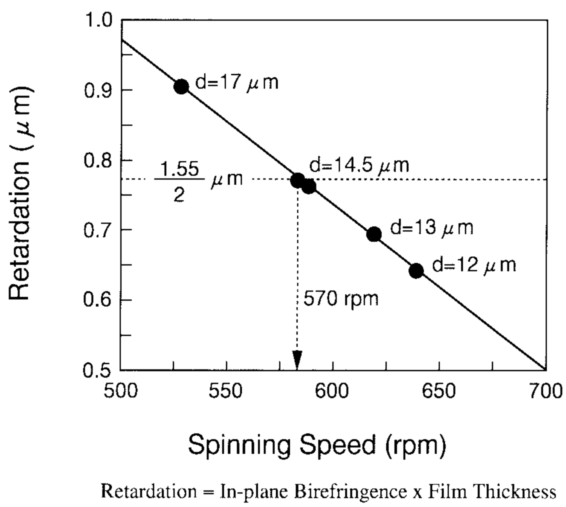


Fig. 4. Relation between waveplate retardation and spinning speed. The filled circles indicate experimental results.

three types of waveguide, where each 18 μm-wide groove was filled with a 14.5 μm-thick polyimide half waveplate and adhesive. The excess loss strongly depends on the waveguide spot size. The excess loss values were 0.12, 0.26, and 1.0 dB for the $\Delta = 0.30, 0.75$, and 1.5% waveguides, respectively. These values are much lower than the excess loss of 5 dB with a quartz half waveplate, and the value of 0.26 dB is equal to that we expect with the $\Delta = 0.75\%$ waveguide in Section III. These confirm the polarization mode converter with the polyimide half waveplate is extremely effective to reduce the excess loss.

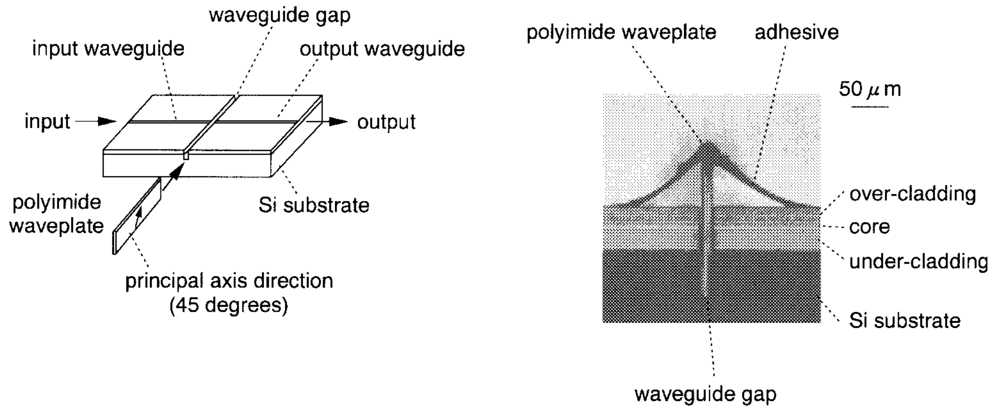
2) Polarization Mode Conversion Crosstalk: The polarization mode conversion crosstalk is caused by a retardation error (β) and an error (α) in the tilt angle of the principal axis which is designed to be 45° to the waveguide plane. When a TE (TM) light is input into the converter, the residual TE (TM) output from the converter is, defined here as conversion crosstalk. It is expressed as the following equation:

$$\text{Conversion Crosstalk} = \delta^2 = 10\log_{10}\left\{1 - \frac{\cos^2 2\alpha}{2}\cdot(1+\cos\beta)\right\}. \quad (13)$$

Equation (13) also expresses the wavelength response of the conversion crosstalk by replacing β with the following equation:

$$\beta = \pi \cdot \frac{\lambda_0 - \lambda}{\lambda} \quad (14)$$

where λ_0 is the center wavelength of the half waveplate. Fig. 8(a) shows the setup for measuring the wavelength response of the conversion crosstalk. Two thin film laminated polarizers [16] are inserted into the input and output waveguides. When a light is input into the sample, only TM mode light is transmitted through the first polarizer. Most of the light is converted to the TE mode through the half waveplate and the rest remains in the TM mode. The second polarizer eliminates only the TE mode light. Then the TM mode light which is not converted through the half waveplate is output from the output port. The conversion crosstalk is the ratio of the output with the half waveplate to the output without it. Fig. 8(b) shows experimental results with open circles and calculated wavelength responses with lines. The wavelength response indicates the crosstalk degradation caused by the retardation error β. In the calculation, λ_0 is set at 1.55 μm and α is set at 0.1, 0.3, 0.5, 1.0, and 2.0°. This figure shows that the center wavelength of the fabricated converter was 1.555 μm and the tilt angle of the principal axis was within 45 ± 0.5°. This means the retardation error β was 0.01 radian and the tilt angle error α was less than 0.5°, respectively. As



(a) (b)

Fig. 5. (a) Configuration of polarization mode converter. (b) Cross sectional photograph of polarization mode converter.

TABLE II
FABRICATED WAVEGUIDE PARAMETERS

Waveguide Δ	Core Size	Spot Size	Minimum Radius
0.30%	$8 \times 8\ \mu m^2$	4.5 μm	30 mm
0.75%	$7 \times 7\ \mu m^2$	3.7 μm	5 mm
1.5%	$4.5 \times 4.5\ \mu m^2$	3.0 μm	2 mm

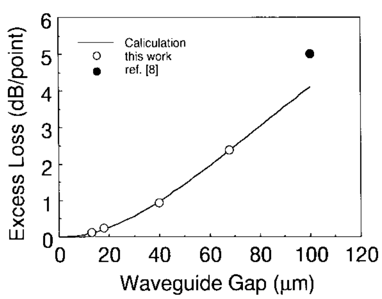


Fig. 6. Relation between excess loss due to the polarization mode converter and the waveguide gap in a $\Delta = 0.75\%$ waveguide. The open circles are experimental results, the filled circle is from [8], and the line was calculated with (12).

a result, the conversion crosstalk was −37 dB at the designed center wavelength of 1.55 μm and less than −26 dB for 1.50–1.61 μm wavelength light. This means that the converter converts 99.98% of the polarization mode at 1.55 μm. The conversion crosstalk of −37 dB is much less than the estimated specification of −26 dB in Section III.

3) Reflection: Since the refractive indices in the polyimide waveplate are higher than that of silica-based waveguide, an input light reflected at the interface of the waveplate and the waveguide. The reflection of the converter in a single waveguide was measured for 15 samples with an optical low coherence reflectometer (OLCR), and the average value was −31 dB.

IV. POLARIZATION INSENSITIVE WDM DEVICES

A. AWG Multiplexer

The polarization mode converter was used to eliminate the polarization dependence in an AWG multiplexer. Fig. 1 shows

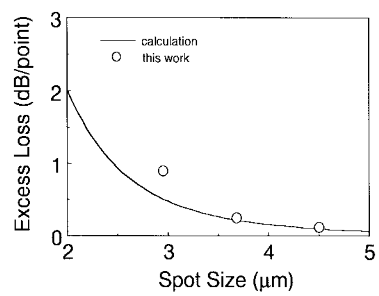
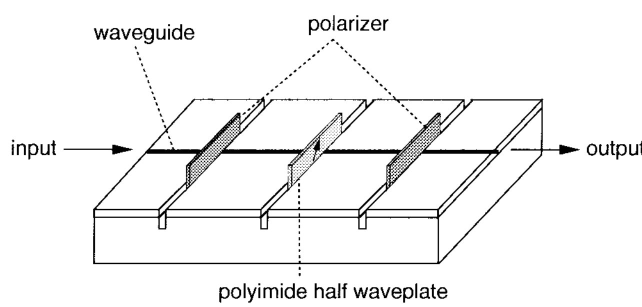
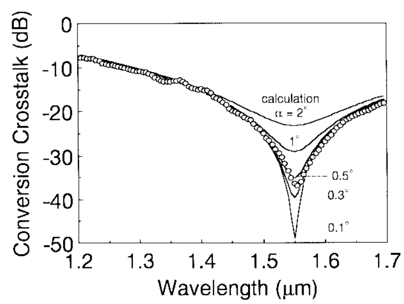


Fig. 7. Relation between the excess loss due to the polarization mode converter with an 18 μm-wide waveguide gap and spot size at 1.55 μm. The open circles indicate experimental results and the line was calculated with (12).



(a)



(b)

Fig. 8. (a) Setup for evaluating polarization mode conversion crosstalk. (b) Spectrum of conversion crosstalk. The open circles show experimental results and the lines were calculated with (13).

a schematic configuration of the fabricated 0.8 nm-spaced 16×16 channel multiplexer. This multiplexer was constructed with $\Delta = 0.75\%$ waveguides and its design parameters are

TABLE III
DESIGN PARAMETERS OF AWG MULTIPLEXER

Operating wavelength	1.55 μm
Number of wavelength channels	16
Wavelength channel spacing	0.8 nm (100 GHz)
Focal length of concave slab	9381 μm
Path difference of arrayed-waveguides	$\Delta L = 126.4\ \mu$m
Number of arrayed-waveguides	101
Diffraction order	118
Free spectral range	12.8 nm
Chip Size	30 $\times$ 40 mm^2

listed in Table III. The wavelength response was measured with a tunable wavelength laser and a power meter. Fig. 9(a) shows the transmission spectra between the central input port and the central output port, before the polarization mode converter was formed. The open and filled circles indicate the TE and TM modes, respectively. Polarization sensitivity can be clearly observed in this figure. The wavelength shift between the TE/TM modes was 0.13 nm, which corresponds to a birefringence of 1.2 $\times$ 10^{-4}. The insertion loss of the multiplexer was 2.7 dB including the coupling losses with dispersion-shifted fibers. Fig. 9(b) shows the transmission spectra after forming the polarization mode converter. The spectrum for the TE input mode exactly coincides with that for the TM input mode, confirming the polarization-insensitive operation of the multiplexer. The center wavelength was the average of those for the TE and TM modes before the half waveplate was inserted. Fig. 10 shows the PDL spectrum measured with a tunable wavelength laser and a PDL meter. The filled circles are the PDL, the open circles are the relative insertion loss normalized at the center wavelength, and the solid line is the PDL calculated with (12). In the calculation, the polarization mode conversion crosstalk was set at -35 dB. The measured PDL is less than 0.2 dB over the 3 dB bandwidth. This confirms the polarization insensitive operation of the AWG multiplexer. On the basis of the calculation, the conversion crosstalk of the formed converter was estimated to be about -35 dB. The insertion loss of the polarization insensitive AWG multiplexer was 3.1 dB. The excess loss due to the groove formation and the insertion of the polyimide half waveplate was, therefore, estimated to be 0.4 dB. This value is nearly the same as that of 0.26 dB measured precisely in the straight waveguide and reported in Section IV. Fig. 11 shows the transmission spectra at the 16 output ports, when the central input port is excited with both the TE and TM modes. Only the full wavelength spectrum for the central output port is shown. Every channel is precisely separated with a 0.8 nm spacing, which corresponds to a 100 GHz optical frequency separation. The fiber-to-fiber insertion loss ranges from 3.1 dB for the central output port, to 5.1 dB for peripheral output ports. The crosstalk is less than -26 dB over a free spectral range of 12.8 nm.

We evaluated the reflection at the half waveplate with the transmission spectrum between the central input port and the adjacent input port using a tunable wavelength laser and a power meter. This spectrum is not affected by the reflection of the fiber connector and the waveguide endface, which means that even a small reflection at the half waveplate can be measured precisely. The result is shown in Fig. 12. The reflection is less than -44 dB over the free spectral range. This value is much less than that of -31 dB measured with a single waveguide in Section IV, and this spectrum is dull compared with the transmitted spectrum shown in Fig. 11. This is because the half waveplate is not flat but has a warp of a few microns in the groove, so that the reflected beams in the arrayed-waveguides have a relative phase error. This

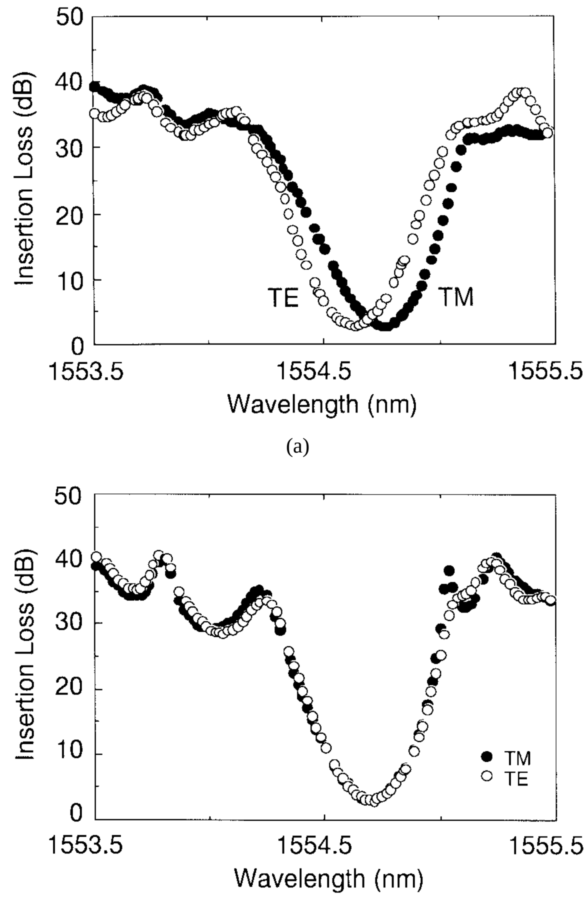


Fig. 9. Insertion loss spectra between the central input and output ports of the AWG multiplexer, (a) before and (b) after forming the polarization mode converter. The open and filled circles represent the TE and TM modes, respectively.

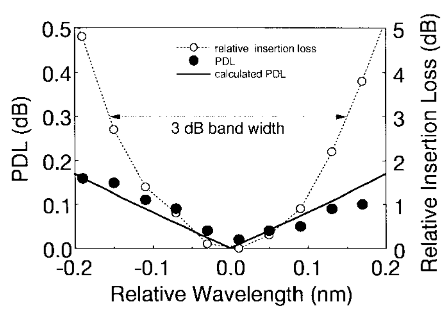


Fig. 10. PDL and insertion loss spectra. The relative wavelength is normalized with the center wavelength and the relative insertion loss is normalized with the minimum insertion loss. The open circles and dotted line represent relative the insertion loss between the central input and output ports indicated in the right axis. The filled circles and solid line represent the experimental PDL value and that calculated with (11), indicated in the left axis.

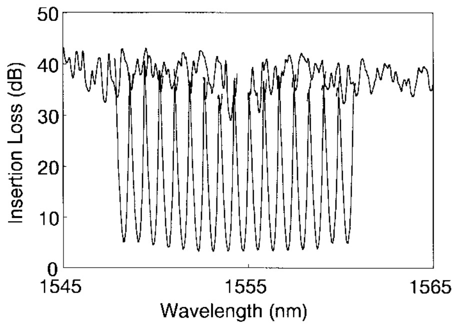


Fig. 11. Insertion loss spectra at the 16 output ports, when the central input port is excited with both the TE and TM modes.

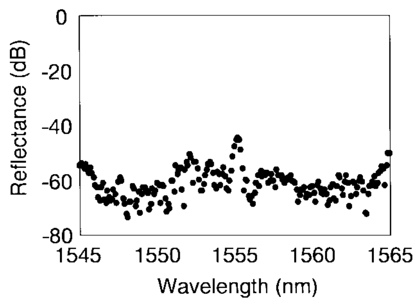


Fig. 12. Reflection spectrum caused by the polarization mode converter. It is measured as the transmittance between the central input port and an adjacent input port.

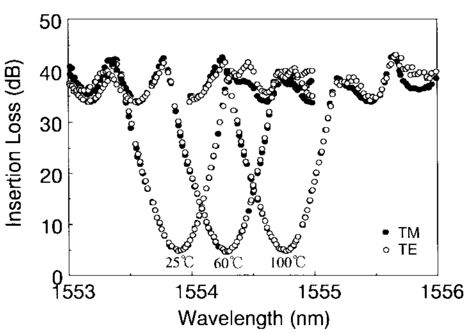
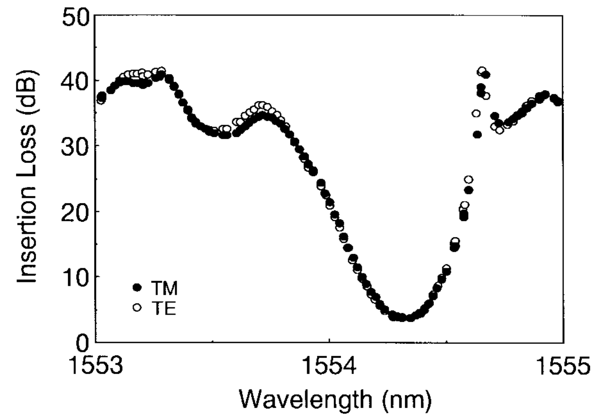


Fig. 13. Temperature dependence of the transmission spectrum in the polarization insensitive AWG multiplexer. The open and filled circles represent the TE and TM modes, respectively.

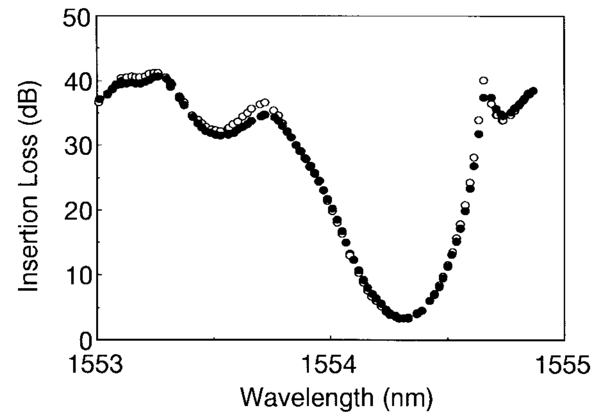
phase error does not affect the transmitted beams, because it is compensated in the other side of the groove. As a result of this phase error, the reflected light does not clearly focus on the input waveguide, and so the reflected spectrum becomes dull and the peak level decreases less than the reflection in the straight waveguide.

Fig. 13 shows TE and TM transmission spectra at 25, 60, and 100 °C. No polarization dependence can be seen, even at 100 °C. This indicates that the AWG multiplexer with a polyimide half waveplate has sufficient thermal stability. Fig. 13 shows that the temperature dependence of the center wavelength is 0.011 nm/°C, which corresponds to about 1.4 GHz/°C.

Fig. 14(a) and (b) show TE/TM transmission spectra measured at room temperature before and after 3125 h at 75 °C



(a)



(b)

Fig. 14. TE/TM transmission spectra (a) before (b) after 3125 hours at 75°C and 90% relative humidity.

and 90% relative humidity. No polarization dependence can be seen in either figure. This indicates that the fabricated multiplexer has sufficient long term stability.

Fig. 15 is a photograph of the fabricated AWG multiplexer module. The AWG multiplexer chip is 30 × 40 mm^2 and the module is 70 × 110 mm^2 in size. The chip was connected to two 16 fiber ribbons at the input/output ports and mounted on a Peltier device. Before connecting the fiber ribbons, the endface of the waveguide was angled at 8° and polished in order to reduce optical reflection. The temperature of the multiplexer was stabilized to within ±0.1 °C by using the Peltier device. By controlling the temperature, the center wavelength can be stabilized to within ±0.01 nm. This AWG multiplexer module has already been employed in various WDM system experiments [17], [18].

B. MZI Multiplexer

A schematic configuration of a polarization insensitive asymmetric MZI wavelength multiplexer is shown in Fig. 16. This multiplexer was constructed with $\Delta = 0.75\%$ waveguides and the path difference between the two arms was set at 10.3 mm, which corresponds to a free spectral range of 20 GHz. The chip size was 25 × 25 mm^2. Fig. 17(a) shows TE and TM transmission spectra without the polarization mode

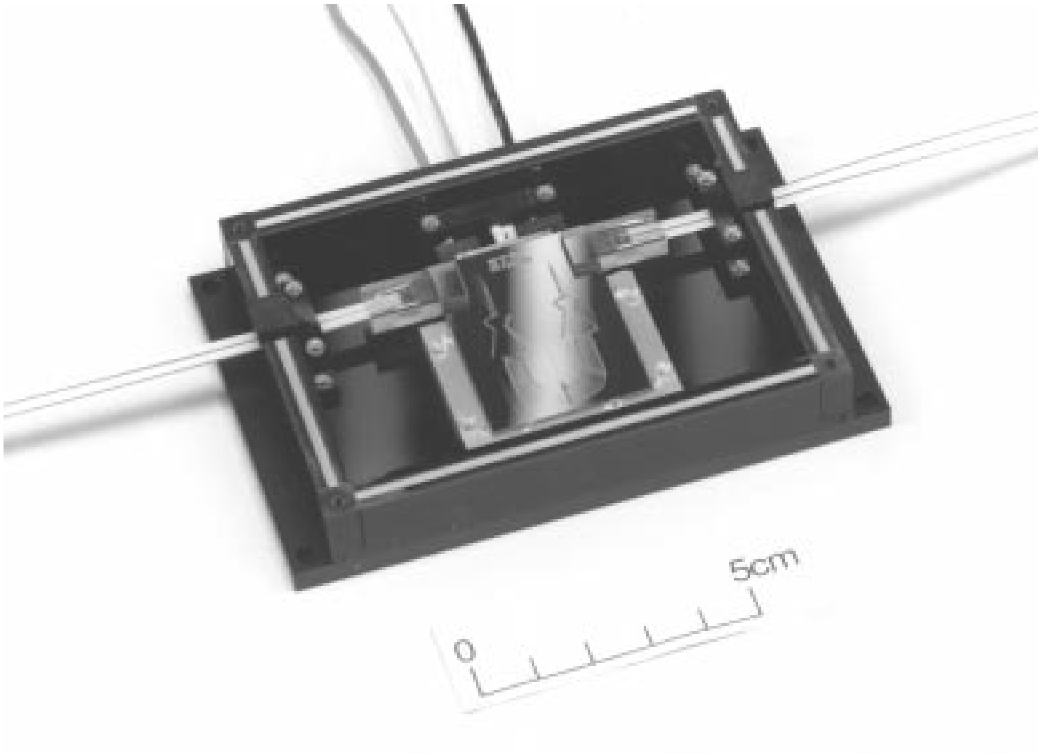


Fig. 15. Photograph of the 0.8 nm-spaced 16 × 16 channel AWG multiplexer.

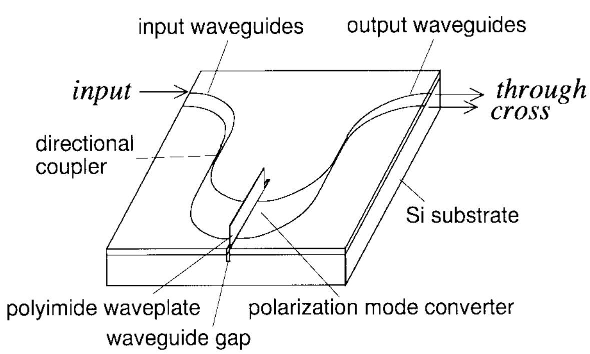


Fig. 16. Configuration of a polarization insensitive MZI multiplexer with an FSR of 20 GHz optical frequency.

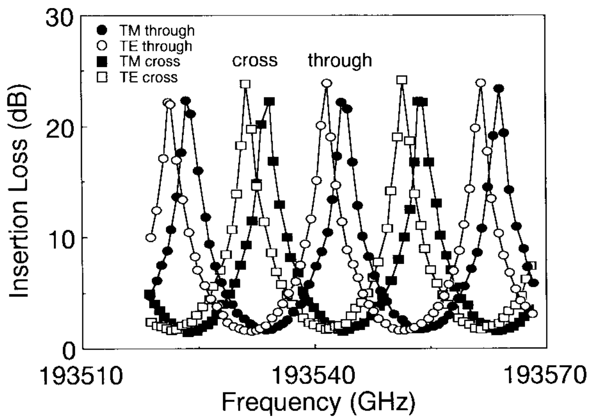
converter. The open and filled circles, respectively, show the TE and TM modes at the through port and the open and filled squares, respectively, show the TE and TM modes at the cross port. These spectra were measured by sweeping the optical wavelength of a DFB laser diode with temperature. The waveguide birefringence in this circuit was measured as 3×10^{-4} with the Senarmont method. This confirms that the TE and TM transmission spectra are shifted by 38 GHz in Fig. 17(a). Fig. 17(b) shows the transmission spectra after inserting the half waveplate. Here, the polarization dependence is successfully eliminated with the polarization mode converter. This result means that the converter can eliminate the polarization dependence of even a few ten GHz channel-spaced multiplexer. The fiber-to-fiber insertion loss of the polarization insensitive MZI multiplexer was 1.7 dB and the crosstalk was −19 dB. This MZI multiplexer was applied to a polarization insensitive dispersion equalizer [19].

C. Directional Coupler Type Multiplexer

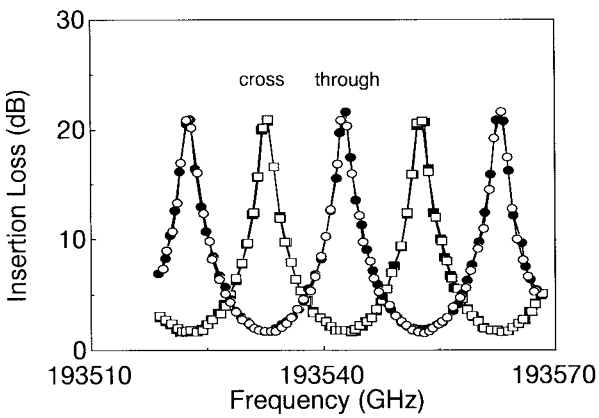
Fig. 18 shows a schematic configuration of a polarization insensitive directional coupler type wavelength multiplexer. This multiplexer was constructed with $\Delta = 0.30\%$ waveguides and the chip size was 3 × 25 mm^2. The wavelength response was measured with an optical spectrum analyzer. Fig. 19(a) and (b) show TE and TM transmission spectra before and after inserting a polyimide half waveplate into the center of the directional coupler. They indicate that the polarization dependence of the multiplexer was successfully eliminated in the 1.55 μm wavelength band but a slight wavelength response shift remained in the 1.31 μm wavelength band. This is because the polarization mode conversion crosstalk was larger at 1.31 μm than that at 1.55 μm as shown in Fig. 8(b). The fiber-to-fiber insertion loss of this multiplexer was 0.4 dB including the excess loss of the polarization mode converter, and the crosstalk was less than −28 dB. This result means that the polarization mode conversion method can not only eliminate the polarization dependence caused by waveguide birefringence but also that caused by coupling in a directional coupler.

V. Conclusion

In this paper, we proposed a polarization mode conversion method for eliminating the polarization dependence in silica-based PLC-type WDM devices. First, in terms of the specification for the polarization mode converter, it was clarified that the waveguide gap for the converter should be narrower than 20 μm to achieve an excess loss of less than 0.3 dB in a $\Delta = 0.75\%$ waveguide, and the polarization mode conversion crosstalk should be less than −26 dB to

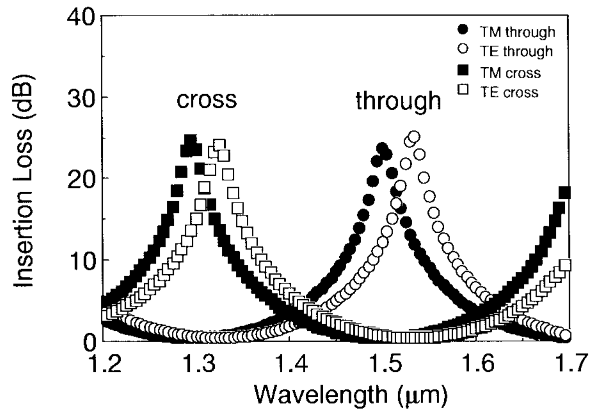


(a)

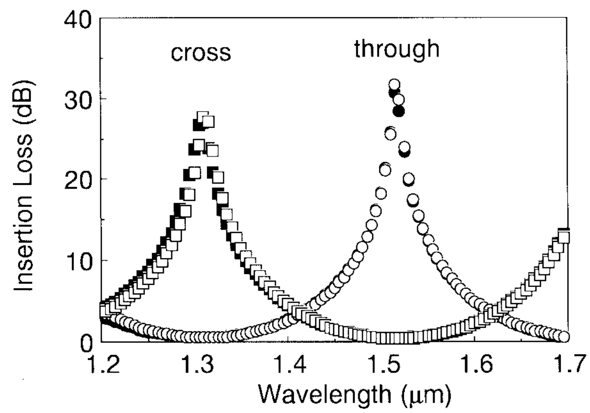


(b)

Fig. 17. Insertion loss spectra (a) before and (b) after inserting the polyimide half waveplate into the waveguide gap. The open and filled circles show the loss spectra to the through port in the TE and TM modes, respectively. The open and filled squares show the loss spectra to the cross port in the TE and TM modes, respectively.



(a)



(b)

Fig. 19. Insertion loss spectra (a) before and (b) after inserting the polyimide half waveplate into the waveguide gap. The open and filled circles show the loss spectra to the through port in the TE and TM modes, respectively. The open and filled squares show the loss spectra to the cross port in the TE and TM modes, respectively.

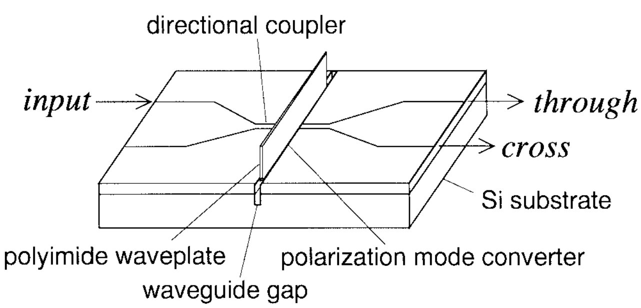


Fig. 18. Configuration of a polarization insensitive directional coupler type 1.3/1.5 μm multiplexer.

achieve a PDL of less than 0.3 dB in a 0.8 nm-spaced AWG multiplexer. We fabricated the polarization mode converter with a 14.5 μm-thick polyimide half waveplate and an 18 μm-wide waveguide gap in order to reduce the excess loss. Excess losses of 0.12 dB, 0.26 dB, and 1.0 dB were achieved for $\Delta = 0.30, 0.75$, and 1.5% waveguides, respectively. We also achieved a conversion crosstalk of −37 dB at 1.55 μm and less than −26 dB in the 1.50–1.61 μm wavelength band. We used this converter to realize a polarization insensitive AWG multiplexer with a PDL of less than 0.2 dB over a 3 dB bandwidth and with a total insertion loss of 3.1 dB. We demonstrated its temperature insensitivity from 25 to 100 °C, and the long term stability of the device for over 3000 h at 75 °C and 90% relative humidity. The converter was also applied to an MZI multiplexer and a directional coupler type multiplexer, and their polarization dependence was successfully eliminated.

This polarization mode conversion technique is simple and can be applied to any input/output circuit with symmetric geometry, any channel-spaced multiplexer, and can be applied not only to silica-based waveguides but also to waveguides made of other materials such as ion-exchanged waveguides, polymer waveguides, and $LiNbO_3$ waveguides.

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REFERENCES

[1] M. Kawachi, N. Takato, K. Jinguji, and M. Yasu, "Birefringence control in high-silica single-mode channel waveguides on silicon," in *Proc. OFC/IOOC*, Washington, DC, 1987, Paper TUQ31.

[2] H. H. Yaffe, C. H. Henry, R. F. Kazarinov, and M. A. Milbrodt, "Polarization-independent silica-on-silicon Mach-Zehnder interferometers," *J. Lightwave Technol.*, vol. 12, pp. 64–67, 1994.

[3] M. Zirngibl, C. H. Joyner, and P. C. Chou, "Polarization compensated waveguide grating router on InP," *Electron. Lett.*, vol. 31, no. 19, pp. 1662–1664, 1995.

[4] M. Kawachi, N. Takato, K. Jinguji, and A. Sugita, "Laser trimming adjustment of waveguide birefringence in silica integrated-optic ring resonators," in *Proc. CLEO'89*, 1989, pp. 84–85.

[5] M. Abe, H. Takahashi, Y. Inoue, Y. Hibino, and Y. Ohmori, "Photoinduced birefringence control in arrayed-waveguide grating multi/demultiplexer," presented at MOC/GRIN'93, Kawasaki, Japan.

[6] A. R. Vellekoop and M. K. Smit, "Four-channel integrated-optic wavelength demultiplexer with weak polarization dependence," *J. Lightwave Technol.*, vol. 9, pp. 310–314, 1991.

[7] M. Zirngibl, C. H. Joyner, L. W. Stulz, T. Gaiffe, and C. Dragone, "Polarization independent 8 $\times$ 8 waveguide grating multiplexer on InP," *Electron. Lett.*, vol. 29, pp. 201–202, 1993.

[8] H. Takahashi, Y. Hibino, and I. Nishi, "Polarization-insensitive arrayed-waveguide grating wavelength multiplexer on silicon," *Opt. Lett.*, vol. 17, pp. 499–501, 1992.

[9] B. H. Verbeek, A. A. M. Staring, E. J. Jansen, R. van Roijen, J. J. M. Binsma, T. van Dongen, M. R. Amersfoort, C. van Dam, and M. K. Smit, "Large bandwidth polarization independent and compact 8 channel PHASAR demultiplexer/filter," in *Proc. OFC'94*, Paper PD13-1.

[10] S. Suzuki, Y. Inoue, and Y. Ohmori, "Polarization-insensitive arrayed-waveguide grating multiplexer with SiO_2-on-SiO_2 structure," *Electron. Lett.*, vol. 30, pp. 642–643, 1994.

[11] H. Uetsuka, K. Akiba, H. Okano, Y. Kurosawa, and K. Morosawa, "Novel 1 $\times$ N guided-wave multi/demultiplexer for FDM," in *Proc. OFC'95*, San Diego, CA, 1995, Paper TuO7, pp. 76–77.

[12] Y. Hida, Y. Inoue, and S. Imamura, "Polymeric arrayed-waveguide grating multiplexer operating around 1.3 μm," *Electron. Lett.*, vol. 30, pp. 959–960, 1994.

[13] S. Ando, T. Sawada, and Y. Inoue, "Thin, flexible waveplate of fluorinated polyimide," *Electron. Lett.*, vol. 29, pp. 2143–2145, 1993.

[14] Y. Inoue, Y. Ohmori, M. Kawachi, S. Ando, T. Sawada, and H. Takahashi, "Polarization mode converter with polyimide half waveplate in silica-based planar lightwave circuits," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 626–628, 1994.

[15] M. Kawachi, "Silica waveguides on silicon and their application to integrated-optic components," *Opt. Quantum Electron.*, vol. 22, pp. 391–416, 1990.

[16] K. Baba, K. Shiraishi, K. Obi, T. Kataoka, and S. Kawakami, "Optical properties of very thin metal films for laminated polarizers," *Appl. Opt.*, vol. 27, no. 12, pp. 2554–2560, 1988.

[17] Y. Tachikawa, Y. Inoue, M. Kawachi, H. Takahashi, and K. Inoue, "Arrayed-waveguide grating add-drop multiplexer with loop-back optical paths," *Electron. Lett.*, vol. 29, pp. 2133–2134, 1993.

[18] H. Toba, K. Oda, K. Inoue, K. Nosu, and T. Kitoh, "Demonstration of optical FDM based self-healing ring network employing arrayed-waveguide-grating ADM filters and EDFA's," in *Proc. ECOC'94*, vol. 1, 1994, pp. 263–266.

[19] K. Takiguchi, K. Okamoto, Y. Inoue, M. Ishii, K. Moriwaki, and S. Ando, "Planar lightwave circuit dispersion equalizer module with polarization insensitive properties," *Electron. Lett.*, vol. 31, pp. 57–58, 1995.

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