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Integrated Semiconductor Optical Matrix Switches for Photonic Switching Application

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Optical matrix switch is one of the key devices for future photonic switching systems. Several kinds of discrete semiconductor optical switch have been studied. However, only a few investigations have been made on integrated semiconductor matrix switch up to the present. We have recently realized 12 electro-optic directional couplers integrated 4x4 GaAs/AlGaAs optical matrix switches. In order to achieve uniform device characteristics, MBE(Molecular Beam Epitaxy) and RIBE(Reactive Ion Beam Etching) were chosen as a crystal growth technique and a waveguide fabrication technique, in addition to the simplified tree structure as a matrix switch architecture. As a result, matrix switches with quite uniform device characteristics, such as small switching voltage deviation of 9.0±0.5V for ⓧ-state and 21.9±1.5V for ⊜-state and little path dependence in propagation loss of ±0.5dB, have been realized for the first time.

1. Introduction

There has been a growing interest in optical switches made of III-V semiconductor compounds for photonic switching applications, because of their large scale integration capability and their ability to be integrated with other semiconductor devices, such as optical amplifiers and electronic circuitry. Several kinds of semiconductor optical switch, such as a carrier injection type switch[1),2)], a gain guide type switch[3)] and a directional coupler switch[4),5),6)], have been studied. Among them, a GaAs/AlGaAs electro-optic directional coupler(EODC) is attractive as a cross-point element for a integrated matrix switch, because of its low absorption loss at long wavelength region[7)], fast switching speed, low electric power consumption and wavelength independent operation capability. Moreover, GaAs material has a advantage that more advanced microfabrication technologies can be used in contrast with InP material. Therefore, the GaAs/AlGaAs EODC is promising as a cross-point element of a matrix switch, and the matrix switch using GaAs/AlGaAs EODCs can be applied to not only space-division photonic switching systems, but also time-division and wavelength-division photonic switching systems. However, only a few investigations have been made on integrated matrix switch using EODCs[8)] as well as using other type semiconductor switchs[9)].

We have recently realized 12 electro-optic directional couplers integrated 4x4 GaAs/AlGaAs optical matrix switches. Quite uniform device characteristics, such as small switching voltage deviation of 9.0±0.5V for ⓧ-state and 21.9±1.5V for ⊜-state and little path dependence in propagation loss of ±0.5dB, have been obtained. To our knowledge, it was the first time that semiconductor optical matrix switch with such uniform device characteristics was achieved. This report describes design and fabrication consideration, and device characteristics of the GaAs/AlGaAs 4x4 matrix switch.

2. Matrix Switch Design

A schematic drawing of the 4x4 GaAs/AlGaAs matrix switch is shown in Fig.1. Guided-wave 12 EODCs with pin structure, and straight and bended waveguides connecting between EODCs are integrated on a same chip.

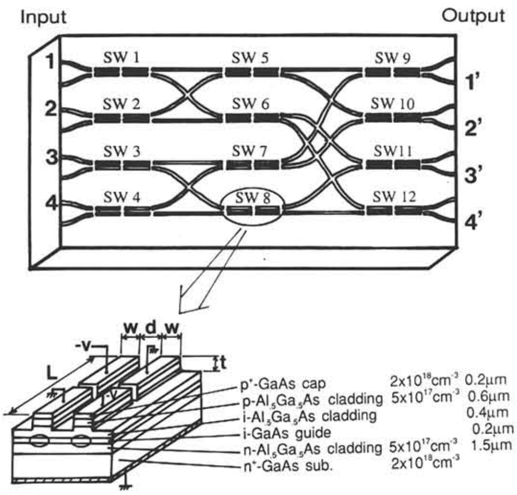


Fig. 1 The 4x4 GaAs/AlGaAs optical matrix switch with electro-optic directional couplers using a simplified tree architecture.

2-1 EODC Design

Cross-sectional view of the EODC cross-point is shown in Fig.1. The 3mm EODC length was chosen by considering total 4x4 matrix switch length (<15mm) and switching voltage (<25V). The GaAs guiding layer thickness and the Al composition ratio in AlGaAs cladding layers were designed to obtain high electric field and strong overlap between electric and optical fields. The width and rib height (i.e., etch depth) of the waveguides were designed to satisfy single-mode condition at 1.3μm wavelength.

Calculated coupling length of the EODC shown in Fig.1, as a function of etch depth, is shown in Fig.2. For ordinary uniform Δβ operation, exact EODC length L to coupling length l_0 ratio L/l_0 is required for low crosstalk operation. For example, the coupling length should be controlled to range from 2.70mm to 3.38mm for a 3mm-long EODC in order to keep less than -15dB crosstalk level. Figure 2 indicates less than 1% etch depth control is desired for this requirement. It is quite difficult to satisfy the requirement even if the present most advanced fabrication technologies, such as MBE and RIBE, are used. Therefore, we decided to use the alternating Δβ configuration[10], instead of the uniform Δβ configuration. In the EODC cross-points, the 3mm-long p-side electrodes are divided into two equally long sections, as shown in Fig.1, in order to enable the alternating Δβ operation. In this configuration, both ⓧ -state and ⊜ -state are always available with low crosstalk, if the EODC length to coupling length ratio L/l_0 ranges from 1 to 3[10]. So, an exact etch depth control is not required in this configuration, unlike the requirement for a uniform Δβ configuration.

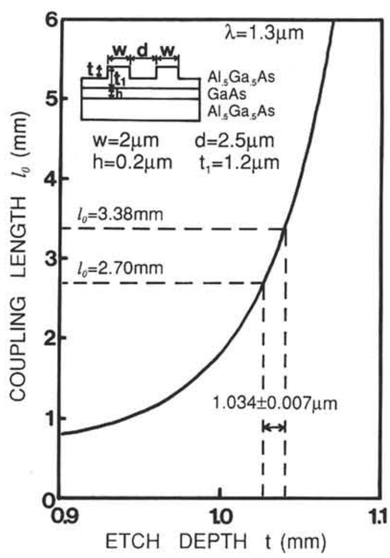


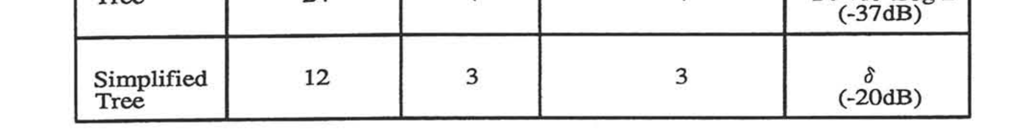
Fig. 2 An example of calculated fabrication tolerance of a 3mm-long directional coupler switch with uniform Δβ operation. Less than 1% control of etch depth is required for less than -15dB crosstalk.

2-2 Matrix Switch Architecture

There are several kinds of matrix switch architecture, such as cross-bar, tree and their modified architectures. The simplified tree architecture[11),12)], which is a modified one of the tree architecture, has many attractive features. Table 1 shows comparison of three kinds of non-blocking matrix switch architecture, namely cross-bar, tree and simplified tree. The simplified tree architecture requires smaller number of cross-points, smaller number of ranks, thus requires smaller chip size than conventional cross-bar and tree architecture. Moreover, the simplified tree architecture has the advantage of low crosstalk nature and smaller path dependence in propagation loss. Since these features of the simplified tree architecture are quite attractive from a point of view of device characteristics uniformity, the simplified tree architecture has been used for the 4x4 GaAs/AlGaAs optical matrix switch.

Table 1 Comparison of non-blocking 4x4 matrix switch architectures. δ is crosstalk level of each switch element.

	Number of Cross-points	Number of Ranks	Number of Elements in a Signal Path	Crosstalk (when δ=-20dB)
Crossbar	16	7	1～7	$\delta + 10 \cdot \mathrm{Log}\ 3$ (-15dB)
Tree	24	4	4	$2\delta + 10 \cdot \mathrm{Log}\ 2$ (-37dB)
Simplified Tree	12	3	3	δ (-20dB)



Crossbar Tree Simplified Tree

2-3 Waveguide Bend Design

The 4x4 matrix switch using the simplified tree architecture requires S-shaped waveguide bends, as shown in Fig.1. Although smaller bend radius is preferable for smaller chip size, the radiation loss in the waveguide bend becomes lager as bend radius becomes smaller. Therefore, bend radius was decided by theoretical and experimental consideration of the radiation loss.

In the 4x4 matrix switch, there are three kinds of S-shaped waveguide bend. Since the EODC spacing in vertical direction to the optical path is designed to be 160 μm by considering fiber coupling, S-shaped bend spacings are S=40μm, 160μm and 320μm. Calculated S-shaped waveguide bend radiation losses, as a function of bend radius, for S=40μm, 160μm and 320μm are shown in Fig.3. No excess loss occurs at more than 3mm bend radius even in the 320μm spacing S-shaped bend. Since experimental results agree with this calculation, R=4mm was chosen as waveguide bend radius.

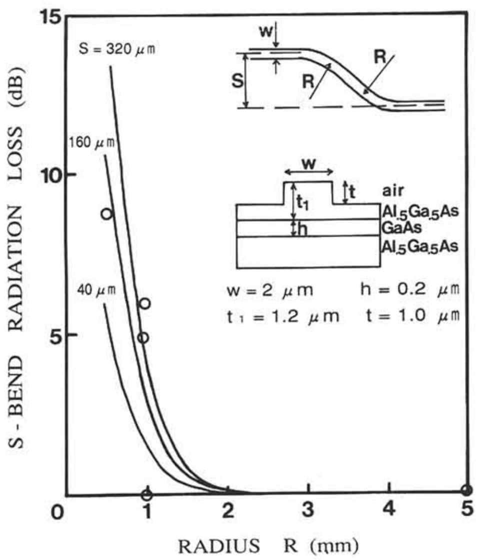


Fig. 3 S-shaped bend radiation loss for w=2μm waveguide at λ=1.3μm. Solid lines indicate calculated radiation losses for S=40μm, 160μm and 320μm waveguide bends, and open circles indicate measured radiation loss for S=160μm waveguide bend. Layer structure of the waveguide shown in the figure is same as actual matrix switch's one.

3. Matrix Switch Fabrication

The 4x4 matrix switches were fabricated on a MBE (Molecular Beam Epitaxy) grown wafer by using conventional photolithography technique and RIBE (Reactive Ion Beam Etching) with Cl_2 gas. MBE was chosen as a crystal growth technique because it can provides GaAs/AlGaAs layers with quite uniform thickness and with precise control of thickness, doping and composition profiles. RIBE was chosen for waveguide fabrication, because it can control etch depth precisely and provide very uniform etch depth in entire chip. Here, using MBE and RIBE is essential to realize a optical matrix switch with uniform device characteristics.

As mentioned above, the dimensions of fabricated 4x4 matrix switches are 15mm x 1mm chip size, 3mm EODC length, 4mm waveguide bend radius, 2μm waveguide width and 2.5μm waveguide spacing in EODC region.

4. Device Characteristics

The matrix switches were characterized by coupling 1.3μm wavelength TE polarized light into an input waveguide using lens systems. As representatives of EODC cross-points, switching

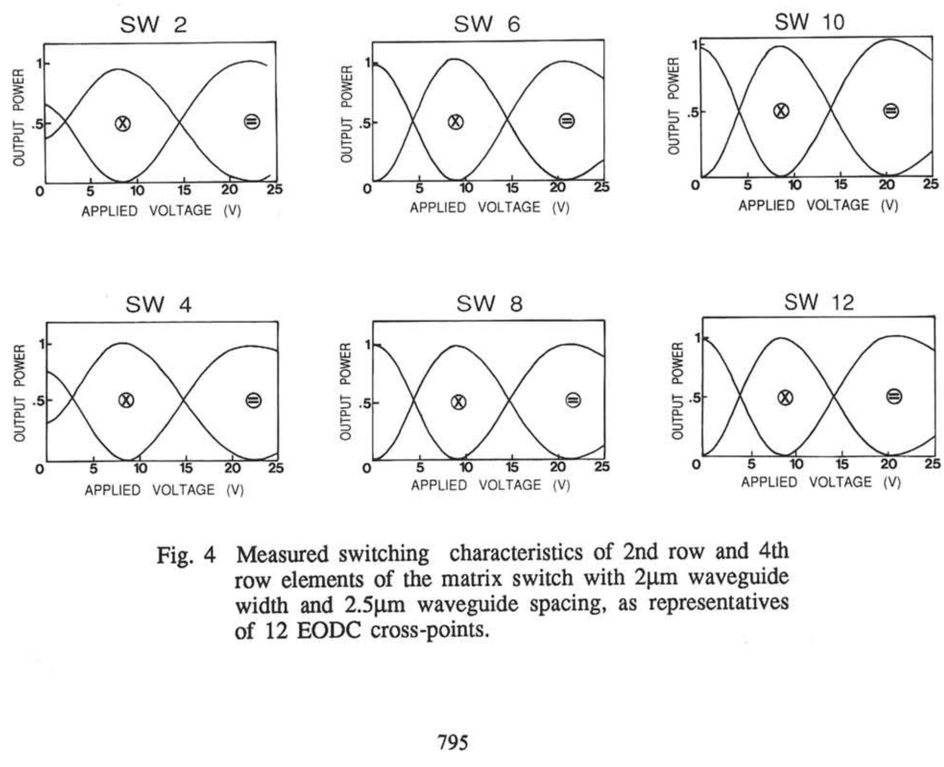


Fig. 4 Measured switching characteristics of 2nd row and 4th row elements of the matrix switch with 2μm waveguide width and 2.5μm waveguide spacing, as representatives of 12 EODC cross-points.

characteristics of 2nd row and 4th row elements of the matrix switch are shown in Fig.4. All of those are working well with low crosstalk and show uniform switching voltage. Switching voltage deviation of all 12 cross-point elements of the matrix switch is quite small, 9.0±0.5V for ⊗-state and 21.9±1.5V for ⊜-state. Measured crosstalk deviation of 12 cross-points is also small, -21.3±3.4dB for ⊗-state and -20.9±3.8dB for ⊜-state.

An example of the switching experiments using the matrix switch is shown in Fig.5. In this experiment variable 1x4 connection between an input channel and output channels was tested. Here, the light is coupled into input channel #2, and 7 cross-points which are SW 2, SW 5, SW 6, SW 9, SW 10, SW 11 and SW 12 are operated. Figure 5 clearly shows desired connections are successfully achieved with low crosstalk. Loss and crosstalk characteristics were measured during the 1x4 connection experiments. Results are summarized in Table 2. Little path-dependence in propagation loss of ±0.5dB and very low crosstalk level, less than -30dB at output channels, were confirmed. This little path-dependence proved that there is little loss in waveguide bends and intersecting waveguides, as expected, because different path should experience different number of waveguide bends and intersecting waveguides.

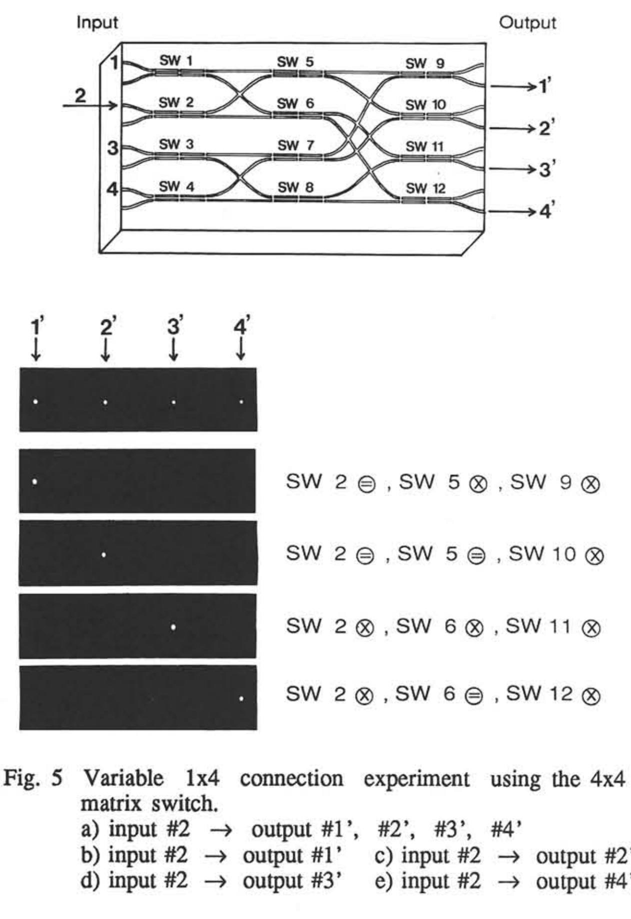


Fig. 5 Variable 1x4 connection experiment using the 4x4 matrix switch.
a) input #2 → output #1', #2', #3', #4'
b) input #2 → output #1' c) input #2 → output #2'
d) input #2 → output #3' e) input #2 → output #4'

Table 2 Measured crosstalk at output channels and propagation loss of the matrix switch. Path dependence in propagation loss is quite small, 10.8±0.5dB.

Connected Path	Propagation Loss , Crosstalk			
	1'	2'	3'	4'
2 → 1'	10.5 dB	<-30 dB	<-30 dB	<-30 dB
2 → 2'	<-30 dB	11.3 dB	<-30 dB	<-30 dB
2 → 3'	<-30 dB	<-30 dB	10.2 dB	<-30 dB
2 → 4'	<-30dB	<-30 dB	<-30 dB	10.5 dB

5. Conclusion

We have designed, fabricated and characterized 12 EODCs integrated 4x4 GaAs/AlGaAs matrix switches for λ=1.3μm with the simplified tree architecture. From a point of view of device characteristics uniformity, MBE for crystal growth, RIBE for waveguide fabrication and the simplified tree structure as a matrix switch architecture, were chosen. As a result, matrix switches with quite uniform device characteristics, such as uniform switching voltage, uniform crosstalk level and little path dependence in loss, have been realized for the first time.

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