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Semiconductor Waveguide Optical Switches and Modulators

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Abstract *Semiconductor waveguide optical switches and modulators are reviewed from the view point of material and structure. As material for switches and modulators, effects of both variations of refractive index and absorption are considered. As for the structure of switches and modulators, basic characteristics of devices, including length, speed, and consumption power, are investigated, and recent experimental performances are shown. For further improvement of switches and modulators, the importance of low-dimensional quantum-well structures and strained quantum-well structures are pointed out.*

Introduction

A traditional telecommunication network consists of three main systems, such as subscriber, transmission, and exchange systems. Optical communication systems have brought considerable developments in the subscriber and the transmission systems. The primary requirement for the trunk transmission systems is to provide high information capacity between central offices, which can be in congested metropolitan areas, suburban locales, or between cities, along its routes. In Japan, single-mode fiber capable of transmitting large capacity information with a long wavelength carrier is effectively utilized in the F-400M system, which transmits digital signals with the bit-rate of 400 Mbit/s at 1.3 μm wavelength, and in the F-1.6G system, which has four times the transmission capacity while maintaining the same repeater spacing [1].

As known from the many applications, optical fiber transmission systems have been introduced into telecommunication networks extensively and rapidly, and this can directly be attributed to high performance and reliability of the systems, which are supported by the progress of optoelectronics technology. In the future, wide-band and low-loss properties of single-mode optical fiber will permit broad-band communication services to be provided between widely spaced repeaters and also allows users to set up a uniform integrated services digital network (ISDN) capable of handling all types of services. This demand for broad-band services in connection with numerous applications extends the ISDN architecture to broad-band

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ISDN (B-ISDN) [2], various narrow-band and broad-band services currently available can be supplemented by a whole new range of broad-band services including moving images and high-speed transmission of high-definition documents, i.e., images and graphics, and of large volume of texts and data.

In this way, optical transmission and subscriber systems have made great progress through the development of optical fibers with huge transmission bandwidth, low-noise and very fast detectors, and high-speed single wavelength lasers. However, in exchange systêms, which are still composed of conventional electronic devices, optical switches for direct optical exchange systems are under development. Future networks systems, which will be much higher-speed and higher-capacity, very high speed direct optical-switching systems will play a very important role, especially in the realization of broad-band ISDN. Hence, an optical-switching device will be a key device for the construction of such high-speed optical-switching systems and photonic-integrated circuits [3].

In this article, we review the semiconductor optical switches and modulators from the point of view of the devices for optical communication systems. We describe the needs of optical switches and modulators and then explain semiconductor materials used in optical switches and modulators. Characteristics of optical switches and modulators, i.e., speed and consumption power, together with a review on various types of switches and modulators are given. Finally, we discuss the future material aspects of semiconductor optical switches and modulators.

Needs of Optical Modulators and Switches

Optical Modulators

Long-haul trunk transmission systems will need substantially increased transmission capacity in response to requirements of high-speed digital services. Much effort has been expended to overcome the repeater spacing limit in developing a practical large capacity system.

For systems operating at wavelengths where the fiber dispersion is nonzero, frequency chirp of the light signal limits the maximum repeater spacing. This limit comes from the dynamic spectral broadening of light sources and chromatic dispersion of single-mode fiber [4]. Whenever an existing dynamic single-mode laser diode (DSM-LD) [5] emits an optical pulse with large signal amplitude, the temporal carrier density is simultaneously varied; hence, wavelength chirping, i.e., instantaneous wavelength variation of the single longitudinal mode, is caused. This excess spectral broadening under high-speed direct modulation causes the compression or expansion of transmitted pulses in dispersive fiber. In the near future, high-speed ($\geqq 10$ Gbit/s) and long-repeater spacing ($\geqq 100$ km) systems will come into realization and a chirp-free modulation will become important in these systems.

Optical Switches

On the other hand in exchange systems, they are still composed of conventional electronic devices and cannot directly exchange optical signals. By considering the progress of high-speed, high-capacity, and long-repeater spacing of transmission systems, the switching system at the interface between exchange and transmission systems will play a very important role in the network.

Today's networks are essentially voice based at somewhat less than 10^5 bit/s and provide data services in 1 k to 10 kbit/s effective bit rate range, primarily via analog modems, thus representing only a two order of magnitude range of information from sources and sinks. High-quality sound (stereo), as is found on compact discs using a linear digital code, requires in excess of 10^6 bit/s, and uncompressed television requires on the order of 10^8 bit/s (100 Mbit/s). New proposals for high-definition television increase the uncompressed bandwidth by another factor of approximately five to ten, and more 3D TV or high-volume video teleconference system requires in excess of 10^{11} bit/s (100 Gbit/s) bit rates. The B-ISDN must effectively run over an application range from telemetry to high-definition TV as a minimum, representing perhaps six to eight orders of magnitude range, depending on the degree of compression of video signal that is used. Therefore, to handle future information needs, the broadband networks require the following characteristics for the switch:

(i) a dynamic range of signal bandwidth 10 kbit/s $\sim >$ 100 Gbit/s
(ii) a variety of different types of connections, that is, point-to-point, point-to-multipoint, one-way, bidirectional.

These demands for the network encourage the introduction of optical switches in place of electronic switches. Electronic switching has limitations on both the data rate and the switching reconfiguration rate achievable; and one of the major costs of electronic switching as opposed to optical switching is that of electronic-to-optical interfaces and of the demultiplexing from the high-speed fiber channels to the lower speed that electronics can handle.

Optical-Switching System

Optical-switching systems can be categorized from the switched parameter, namely, space division, time division, and wavelength division switching systems.

In a space division switch, each line entering and exiting the switch represents a single channel. Switching is accomplished by providing a spatial path, an internal part of the switch that connects one input line to one (or more if multicast is required) output line. This type of switching arrangement capitalizes on a principle advantage of optical switches because the information rate that can pass through the switch is much greater than that in electronic systems. In such space division switching, synchronization of the high bit rate input and output channels is not required provided that glitches during switching are acceptable. Therefore, this switching system seems applicable to particularly trunk transmissions for facility, protection, and route restoration, where very broadband signals can be anticipated and where reconfiguration speed is not required to the rate comparable to the transmission bit rate. Another potential application area is the switching of wide band services in the loop or for local area networks. The limitation of space division switching is that each information channel requires its own input line to the switch; hence, it may be limited by the number of channels that can be connected via the switching matrix.

The number of physical input and output lines to the switch can be reduced by using time division and wavelength division switching systems. In a time division switching system, each physical line contains several time-multiplexed channels. A particular channel is represented by its timeslot within the frame period. As a result, the total number of input channels to the switch is increased by the number of time-multiplexed channels per input line. This system offers system design flexibility, including the possibility of adjustable bandwidth allocation in different baseband channels and the possibility of simple hardware in which only a single transmitter laser is required for all channels.

As compared with the time division switching system, the wavelength division switching system has two advantages. One is bit rate independence of individual wavelength channel. Then, various speed broadband signals can be exchanged without difficulty. The other advantage is that there is no necessity for high-speed operation in switching control circuits. Moreover, it has the potential capability for extension to a wide area network in partnership with the wavelength division multiplexed (WDM) transmission system. Therefore, this wide area network will be able to provide optical bit rate independent connection between subscribers. Like above-mentioned advantages, wavelength division switching systems are very attractive because of their flexibility. However, to construct this switching system, a high-selectivity tunable optical filter, a wide-range variable wavelength light source, and a wavelength converter are required.

Hence, various types of switching devices are needed to realize these systems. Above all, directive optical switches will be a key component in the optical-switching systems, and we mainly review these switches.

Recently, there has been increasing interest in optical information systems. In these systems, optical bistable devices for optical memories or optical gates become important components. For these devices, a self-electro-optic effect device (SEED) [6] or vertical-to-surface transmission electrophotonic device (VSTEP) [7] were investigated, but we do not discuss these devices in this paper.

Material for Semiconductor Optical Switches and Modulators

Until now, a number of optical-switching and modulating elements have been developed in both lithium niobate ($LiNbO_3$) [8–10] and III-V compound semiconductor crystals. With recent improvements in III-V epitaxial growth technologies, such as organo-metalic vapor phase epitaxy (OMVPE) and molecular beam epitaxy (MBE), the capability to grow high-purity semiconductor heterostructures with nearly atomically smooth interfaces was demonstrated, and with this technology the III-V optical switches and modulators have been extensively studied. Moreover, because III-V materials offer the obvious advantage of monolithic integration of active or passive photonic devices to form the foundation of photonic integrated circuits (PIC's), III-V compounds materials may eventually replace lithium niobate.

One of the most important differences between dielectric and semiconductor materials is the existence of the optical absorption in the semiconductor material. In the optical switches and modulators using dielectric materials, the operational principle is the change of the refractive index through the electro-optic effect. On the other hand, in semiconductor material, both the absorption and the refractive index change through various effects, and the guided light is controlled by the change of absorption ($\Delta n''$) or refractive index ($\Delta n'$) of the material.

Because of this peculiar characteristic of semiconductor materials, operational principles of semiconductor optical switches and modulators are categorized into two groups with respect to the origin of the operation. One is the change of the imaginary part of complex refractive index ($\Delta n''$), which is the change of absorption or gain, and the other is the change of the real part of complex refractive index ($\Delta n'$), which is the refractive index. The complex refractive index variations is written as

$$\Delta \bar{n} = \Delta n' - j\Delta n'' \qquad (1)$$

Absorption or Gain

Absorption or gain, which corresponds to the imaginary part of complex refractive index ($\Delta n''$), is changed through the Franz-Keldysh effect in bulk structures, quantum-confined Stark effect (QCSE) in quantum-well structures, carrier bleaching, and stimulated emission.

The electric-field dependence of optical absorption (electroabsorption) near the optical band edge in semiconductors has been extensively studied. In bulk semiconductors, the resultant shift and broadening of the band edge absorption, commonly explained as photon-assisted tunneling of electrons from the valence to the conduction band, is usually known as the Franz-Keldysh effect [11, 12].

In recent years, vast improvements have been made in the crystal growth techniques to fabricate artificial semiconductor nanostructures. It is now possible to make structures that show quantum size effects and that consequently exhibit novel physical properties not encountered in thicker materials. The most widely fabricated and utilized of these nanostructures in optics are quantum-wells, i.e., ultrathin alternating semiconductor layers of different composition.

The effect of electric-field on the optical properties of quantum-wells near the band gap show qualitatively different behavior in contrast with conventional bulk semiconductors.

As shown in Fig. 1, in the absence of electric field, wavefunctions of an electron in the conduction band and a hole in the valence band are symmetric

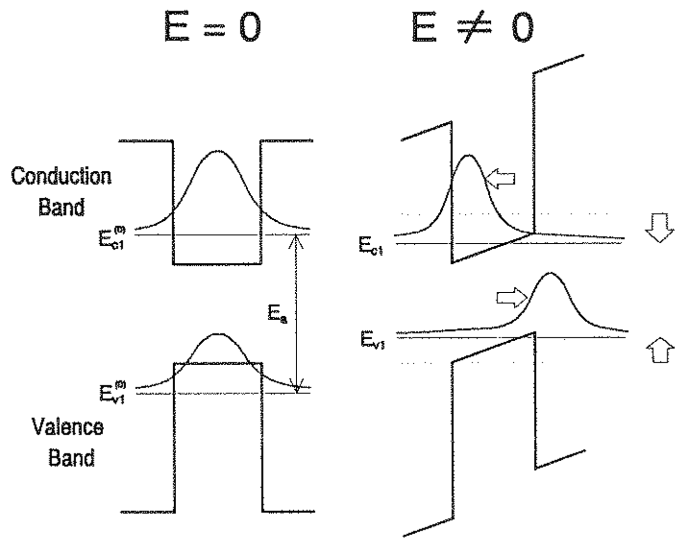


Figure 1. Wavefunctions in a quantum well without and with applied electric field.

(fundamental levels) at the center of the well. On the other hand, by applying the electric field perpendicular to the quantum-well layer, the square well potential gets inclined, and the electron and hole are pulled to opposite sides of the well. At the same time, the quantization level $E_{1e}, E_{2e}, \ldots$ in the conduction band decreases relatively, and the quantization level $E_{1h}, E_{2h}, \ldots, E_{1l}, E_{2l}, \ldots$ in the valence band increases. Thus, with the increase of applied electric field, effective energy gap $E_{1e} - E_{1h}$ decreases; and as a consequence of spatial separation of wavefunctions, the coupling of electron and hole that satisfies the selection rule ($\Delta n = 0$) decreases. On the other hand, the originally forbidden quantum-well transition ($\Delta n \neq 0$) will become an allowed transition.

Except for the above interband optical transition, it is necessary to consider the transition with respect to the Coulomb attraction on electron and hole pairs, that is exciton. In quantum-wells with layer thickness of the order 10 nm, electric fields applied perpendicular to the layers result in large shifts in the optical absorption to lower photon energies, with the exciton resonances remain well resolved even for shifts in exciton energy much larger than the zero field binding energy and fields >50 times the classical ionization fields.

These effects have been explained in terms of the Stark shift of a strongly confined hydrogenic system (QCSE) [13]. Electric fields perpendicular to the quantum-well layers pull the electrons and holes toward opposite sides of the layers resulting in an overall net reduction in energy of an electron–hole pair and a corresponding Stark shift in the exciton absorption. The walls of the quantum-well impede the electron and hole from tunneling out of the well. When the well is narrow (~ 10 nm) compared to the three-dimensional exciton size, the electron–hole interaction, although slightly weakened by the separation of electron and hole, is still strong, and well-defined excitonic states can still exist. Thus, exciton resonances can remain for much higher fields than would be possible in the absence of this confinement, and large absorption shifts can be seen without excessive broadening. In the absence of this excitonic effect, electroabsorption in quantum-well structures have been referred to as quantum-confined Franz-Keldysh effect (QCFK) [14].

Carrier bleaching [15–17] is caused by the band filling and screening of the electron–hole interaction. Band filling reduces the absorption by diminishing the phase space available for exciton creation. Screening reduces the oscillator strength by weakening the coulomb attraction until electron and hole ultimately become unbound.

Optical switches using laser diodes were obtained through gain change by stimulated emission. When the current is injected, the optical absorption is reduced and the optical signal exits the laser diode switch by the amplification, and the incident light is absorbed under no injection current.

Refractive Index

Refractive index, which corresponds to the real part of complex refractive index ($\Delta n'$), is changed through electro-optic effect, free carrier injection, quantum-confined Stark effect (QCSE), carrier depletion, and quantum-well electron transfer.

By the free carrier injection, there are two effects that contribute to change the refractive index: plasma effect and band-filling effect. The plasma effect is due to the free carrier absorption both in the conduction and valence bands. The absorption of a photon by a free carrier in the band implies the transition to higher energy states in the same band and requires some interaction to satisfy the momentum conservation rule. The additional momentum can be provided by lattice interaction via phonons or by scattering with ionized impurities. Because transitions inside the same band usually involve small energy changes, free carrier absorption has an important contribution to the overall absorption spectra for longer wavelengths below the bandgap energy; and this free carrier absorption will induce a corresponding refractive index variation. The band-filling effect is due to the fundamental absorption edge shift with the change of a Fermi level by carrier injection. In an n-type material when the carriers are removed, the conduction band empties its energy states with the consequent moving of the Fermi level down into the bandgap region. As a result, the fundamental absorption edge will shift to lower energies, producing an increase of the absorption and corresponding refractive index variation.

As explained previously, electroabsorption in quantum-well structure is much different from the bulk structure. Hence, for the refractive index variation a much larger value will be expected since both the refractive index and the absorption are related together through Kramers-Krönig relation. This refractive index variation in the quantum-well structure was theoretically predicted by Yamamoto et al. [18], and a large refractive index variation (i.e., more than 4%) was experimentally measured by Nagai et al. [19]. Also exciton resonances play a significant role in the refractive index variation of the quantum-well structures.

Depletion edge translation (carrier depletion) is the combined effects of the linear electrooptic effect, the Franz-Keldysh effect, the plasma effect, and the band-filling effect that produce a refractive index variation in the depletion region when the device is reverse biased. Two major physical effects in the carrier depletion are: (1) an increase in the electric field inside the depletion region and (2) an increase in the depletion region width with the consequent removal of carriers.

The main concept of the quantum-well electron transfer [20] is almost the same as carrier bleaching, that is, electronic control of phase space absorption quenching. The number of electrons in the quantum-well is electrically controlled by using, for example, a quantum-well field effect transistor structure. When the quantum-well is filled with the carriers, the optical absorption associated with those states simply disappears from the spectrum. Consequently, the absorption edge moves to higher photon energy as the lower energy states are filled with electrons. These are particularly well suited for waveguides, where useful modulators with only one quantum well were made. The quantum-well electron transfer structure is designed with a quantum well and a reservoir for charges. By the application of voltage, the mobile charges will move back and forth between the quantum well and the reservoir, resulting in the change in the refractive index and absorption of the quantum-well.

α_p Parameter

In a semiconductor optical switch and modulator, the guided light is controlled by the change of absorption ($\Delta n''$) or refractive index ($\Delta n'$) of the material. However, in semiconductor materials, refractive index variation is accompanied by variation of absorption, through the Kramers-Krönig relation, and additional problems will occur. For instance, in electroabsorption modulator, the wavelength chirping will occur by refractive index variation; and also in the intersectional waveguide type, total internal reflection will be destroyed by an increase of absorption.

Hence, the influence of this absorption change to the refractive index variation or its opposite on the operational properties of optical switches and modulators should be investigated. In this aspect an important parameter α_p named index-loss variation ratio [21] is characterized, which is defined by the ratio of real ($\Delta n'$) to imaginary parts ($\Delta n''$) of the complex refractive index variation due to the external force (electric-field or injection current) in the same manner as linewidth enhancement factor in semiconductor lasers [22]. This is given by

$$\alpha_p = \frac{\Delta n'}{\Delta n''} = \frac{4\pi n'}{\lambda} \cdot \frac{\Delta_{eq}}{\Delta \alpha_{loss}} \tag{2}$$

where n' is the refractive index of the material without external factor, Δ_{eq} is the relative change of refractive index ($=\Delta n'/n'$), $\Delta \alpha_{loss}$ is the change of absorption coefficient with external factor, and λ is the wavelength of incident light.

Structure of Semiconductor Optical Switches and Modulators

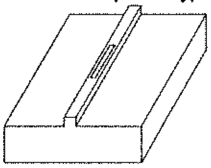
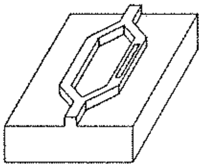
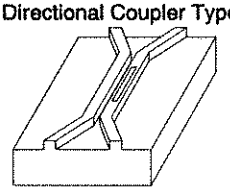
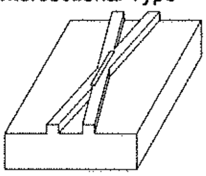
Using the changes of absorption or refractive index as explained in the previous sections, many types of optical switches and modulators have been demonstrated. In this section, we explain the device structures and characteristics of semiconductor modulators and switches. First we show the required device length of four types of switches and modulators, which is the most important structural parameter of these devices. Then we explain general characteristics of switches and modulators, such as operation speed and consumption power.

Characteristics of Semiconductor Optical Switches and Modulators

Device Length. In the optical switches and modulators, the length of the electrode is the most important structural parameter for the performance and characteristics of the device. Here we compare their electrode length in the ideal case, for the electroabsorption type, Mach-Zehnder type, Directional Coupler type, and intersectional waveguide type as listed in Table 1, in which Ξ is the extinction ratio to be obtained, λ is the operational wavelength, n_{eq} is the equivalent refractive index of the waveguide, $\Delta\alpha$ and Δ_{eq} are the variations of absorption and relative refractive index ($=\Delta n'/n'$), respectively, and w is the width of the waveguide. In the electroabsorption type device, the electrode length is determined by the absorption change $\Delta\alpha$ (cm^{-1}) and extinction ratio Ξ (dB). In the Mach-Zehnder type device, it should be adjusted so as to satisfy the condition $\Delta\beta \cdot l = \pi$. In the Directional Coupler type, the device length is obtained by coupled-mode theory under the condition of minimum coupling length; in the intersectional waveguide type device, the electrode length is determined by the width of waveguide and critical angle θ_c of total internal reflection.

For applications of optical switches and modulators, response speed and consumption power are the most important features similar to electronic devices.

Table 1
Electrode Length of Four Types of Optical Switch/Modulator

Type	Electrode Length (l)
Electroabsorption Type 	$\frac{\Xi}{4.34\Delta\alpha}$
Mach-Zehnder Type 	$\frac{\lambda}{2neq\Delta eq}$
Directional Coupler Type 	$\frac{\sqrt{3}\,\lambda}{2neq\Delta eq}$
Intersectional Type 	$\frac{2}{m}\cdot\frac{w}{\sqrt{2\Delta eq}}$ ($\theta = m\theta_c$)

In the following discussion, we show the speed and consumption power of optical switches and modulators driven by electric field.

Speed. The speed of the switches and modulators by carrier injection is determined by the lifetime of injected carriers. It is typically a few nanoseconds for the injected carrier density of around 10^{18} cm^{-3}. On the other hand, electric-field effect type switches and modulators, which operate by using the electro-optic effect, Franz-Keldysh effect, and quantum-confined Stark effect, are expected to operate at high speed. Actually the speed of the electric-field effect type device is limited by the time for charging the capacitor of the device through the resistor of the source. In the frequency domain, the speed of the device is measured by the frequency at which the modulated signal power drops to the half of its minimum (i.e., 3 dB cut-off frequency $f_{3\ dB}$). By neglecting the capacitance and inductance of the chip mount, we obtain

$$f_{3\,\mathrm{dB}} = (2\pi R \cdot C_{\mathrm{dev}})^{-1} \tag{3}$$

where R is the resistance of the source and C_{dev} is the capacitance of the device given by

$$C_{\mathrm{dev}} = \varepsilon S/d \tag{4}$$

where S is the area (=length × width) of applied electric field to the device and d is the width of depletion layer, which is not the thickness of the waveguide. Equation (3) shows that the simplest way to increase the speed of the device is to reduce the capacitance.

The area of applied electric field can be reduced by shortening the length of device, which is decided by the electro-optic coefficient of the material. For example, we show the relation between speed and material parameter of interferometer-type device. The length of electrode, which is shown in Table 1, is rewritten in terms of the linear electro-optic coefficient dn/dE and applied electric field E as

$$l = \frac{\lambda}{2(dn/dE)E} \cdot \frac{1}{\xi n_{\mathrm{eq}}} \tag{5}$$

In Eq. (5) ξ is the optical confinement factor and n_{eq} is the equivalent refractive index of the waveguide for lateral direction. Hence, the capacitance C_{dev} and the cut-off frequency $f_{3\,\mathrm{dB}}$ can be expressed as

$$C_{\mathrm{dev}} = \frac{\varepsilon\lambda}{2(dn/dE)E} \cdot \frac{w}{\xi n_{\mathrm{eq}} d} \tag{6}$$

$$f_{3\,\mathrm{dB}} = \frac{(dn/dE)E}{\pi\varepsilon\lambda} \cdot \frac{\xi n_{\mathrm{eq}} d}{w} \cdot \frac{1}{R} \tag{7}$$

Equation (7) reveals that $f_{3\,\mathrm{dB}}$ is proportional to the material parameter dn/dE where the value of dn/dE is 7.7×10^{-9} cm/V for $LiNbO_3$ [23], and 1.6×10^{-7} cm/V for the quantum-film structures [18].

Figure 2 shows the relation between cut-off frequency $f_{3\,\mathrm{dB}}$ and electro-optic coefficient dn/dE from Eq. (7) at an applied electric field $E = 1 \times 10^5$ V/cm. Waveguide thickness and width are respectively $d = 0.5\ \mu$m, $w = 2\ \mu$m. As for the low-dimensional quantum-well structure, we discuss more detail in the last section. As can be seen, for a given waveguide structure, the speed of device consisting of the quantum-well structure increases up to approximately twenty times that of the dielectric material.

Consumption Power. When the optical switches or modulators operate at high speed, they require large consumption power. Consumption power P_c at a modulation frequency f is given by

$$P_c = \frac{(2\pi f C_{\mathrm{dev}})^2 R}{1 + (2\pi f R C_{\mathrm{dev}})^2} V^2 \tag{8}$$

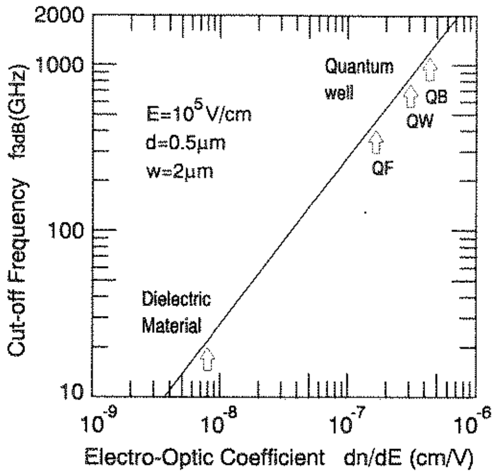


Figure 2. Relation between cut-off frequency $f_{3\ \mathrm{dB}}$ and electro-optic coefficient dn/dE where QF is the quantum-film, QW is the quantum-wire, and QB is the quantum-box structure.

where V is the source voltage. P_c can be expressed in terms of the applied voltage V_{dev}, which is necessary for switching or modulating as

$$P_c = (2\pi f C_{dev})^2 R V_{dev}^2 = \left(\frac{f}{f_{3\ \mathrm{dB}}}\right)^2 \frac{V_{dev}^2}{R} \tag{9}$$

where

$$V_{dev} = \frac{|V|}{\sqrt{1 + (f/f_{3\ \mathrm{dB}})^2}} \tag{10}$$

This equation indicates that the consumption power P_c is determined by the value of the applied voltage to the device, the source resistance, and the normalized modulation frequency (i.e., $f/f_{3\ \mathrm{dB}}$).

Figure 3 shows the relation between P_c and the normalized frequency $f/f_{3\ \mathrm{dB}}$ as a function of V_{dev}, where the source resistance is assumed to be $R = 50\ \Omega$. When the modulation frequency is equal to the cut-off frequency $f_{3\ \mathrm{dB}}$, the consumption power P_c is less than 500 mW for $V_{dev} < 5$ V. It is possible to obtain $P_c < 100$ mW under the condition of $V_{dev} < 2$ V. In any case, to attain a low-consumption power switch or modulator, it is important to reduce the voltage applied to the device. For this purpose, it is necessary to increase the electro-optic coefficient of the material. If we use Eq. (6) in case of an interferometer-type device, the consumption power [Eq. (9)] becomes

$$P_c = \left(f \cdot \frac{\pi \varepsilon \lambda}{(dn/dE)} \cdot \frac{w}{\xi n_{eq}}\right)^2 R \tag{11}$$

Figure 4 shows the comparison of consumption power between the dielectric material and the quantum-well structure, where dn/dE of these materials are the same as those used in Fig. 3. As can be seen, the consumption power of the device

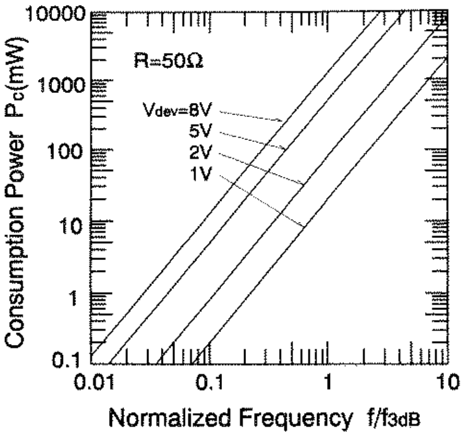


Figure 3. Relation between consumption power P_c and normalized frequency $f/f_{3\,dB}$ as a function of V_{dev}.

using quantum-well structure can be reduced to about 1/400 times that of the dielectric material-based device.

In the following section, we review the state of the art of various types of semiconductor switches and modulators experimentally reported so far. Operational principle and device structure of these devices are summarized in Table 2.

Modulator

Intensity Modulator—Waveguide Type. An external modulation technique is attractive because the modulation function can be separated from the light generation function, and this allows the reduction of wavelength chirping under a high-speed modulation [24].

Among several types of semiconductor modulators, electroabsorption (EA) modulator has been confirmed for high-speed and low-chirp characteristics, and it seems to be the most suitable for an integrated structure because of its structural simplicity.

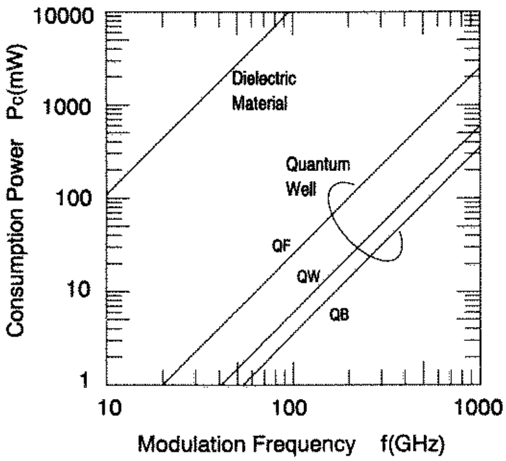


Figure 4. Comparison of consumption power P_c between dielectric material and quantum-well structure.

Table 2
Operational Principle and Structure of Semiconductor Optical Switches and Modulators

Semiconductor Optical Switch and Modulator

		Modulator			*Switch*					
		IM(W)	IM(T)	REF	MZ	PS	LD	GS	DC	X
$\Delta n''$	FK	[37-49]		[83]						
	QCSE	[50-73]	[77-82]	[84-96]				[121]		
	SE						[119,120]	[122]		[139]
$\Delta n'$	EO				[97,98]	[104,105]			[123-129]	
	CI								[130]	[140-148]
	QCSE	[74,75]			[99-101]	[106-112]			[131-138]	[149-152]
	CD					[113-118]				[153]
	QET	[76]			[102,103]					[154]

	Principle			*Structure*	
$\Delta n''$	FK:	Franz-Keldysh effect	*Modulator*	IM:	Intensity Modulator W=Waveguide, T=Transverse
	QCSE:	Quantum-confined Stark effect		REF:	Reflection
	SE:	Stimulated emission		MZ:	Mach-Zehnder
$\Delta n'$	EO:	Electro-optic effect		PS:	Phase Shifter
	CI:	Free carrier injection	*Switch*	LD:	Laser diode switch
	QCSE:	Quantum-confined Stark effect		GS:	Gate switch
	CD:	Carrier depletion		DC:	Directional coupler
	QET:	Quantum-well electron transfer		X:	Intersetional waveguide

Most of electroabsorption modulators consist of bulk material, which are operated by Franz-Keldysh effect. An GaInAsP/InP buried-heterostructure optical intensity modulator made of Fe-doped semi-insulating InP buried layers demonstrating a bandwidth of 11.2 GHz was realized at a wavelength of 1.53 μm [40]. The device length of the modulator was 200 μm, and its extinction ratio at an applied voltage of -8.5 V was 20 dB.

Electroabsorption modulator consisting of a multiple quantum-well (MQW) structure has capability of high-speed operation, large extinction ratio under relatively low applied voltage, and small device length because of its large electroabsorption coefficient through the quantum-confined Stark effect (QCSE). By using this QCSE, high-speed modulation bandwidth exceeding 40 GHz has been reported for InGaAs/InAlAs MQW intensity modulator operating at 1.55 μm with an applied voltage of -5 V and 10 dB extinction ratio [61].

As explained in the introduction, chirp-free modulation is very important for the long-haul high-bit-rate optical fiber transmission system. In these electroabsorption modulators, the linewidth enhancement factor α has been reported to be less than 1 for both bulk and MQW structures [41, 64].

From the viewpoint of stable operation, monolithic integration of semiconductor modulators with lasers has an advantage to reduce the coupling loss between a laser and a modulator. Figure 5 shows the monolithic integrations of a DFB laser with electroabsorption modulators using the Franz-Keldysh effect in bulk structure [49]. These bulk modulators have been under development for a long time, and in

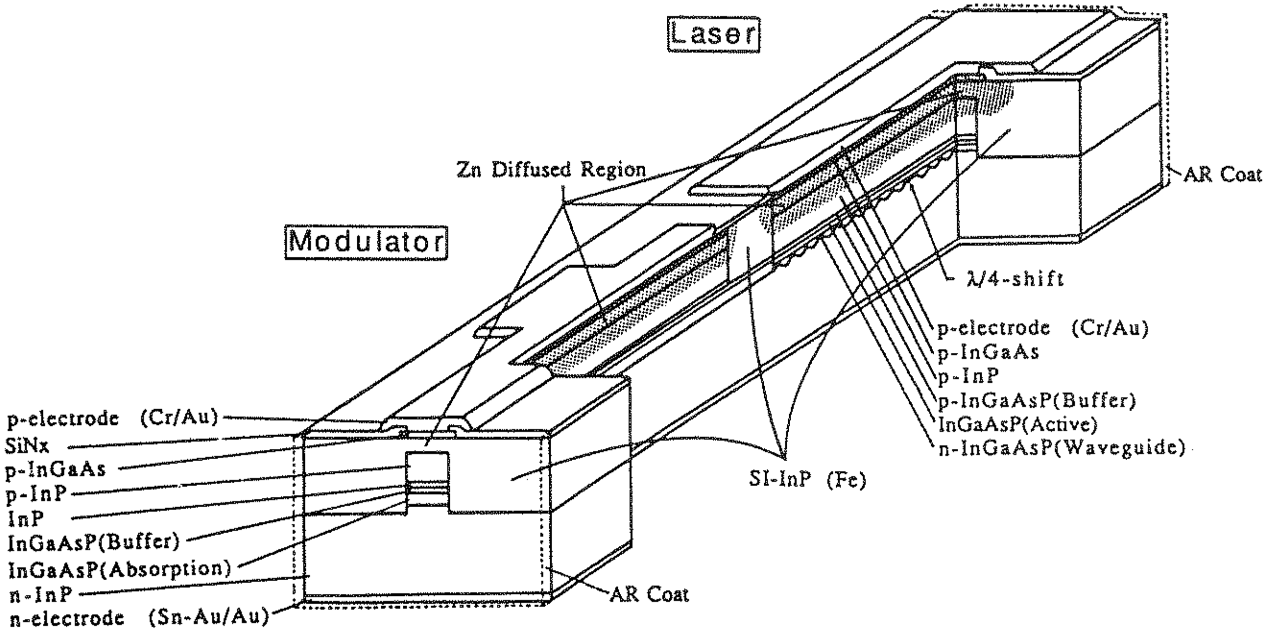


Figure 5. Schematic structure of integrated light source with an asymmetric $\lambda/4$-shifted DFB laser and an EA modulator [49].

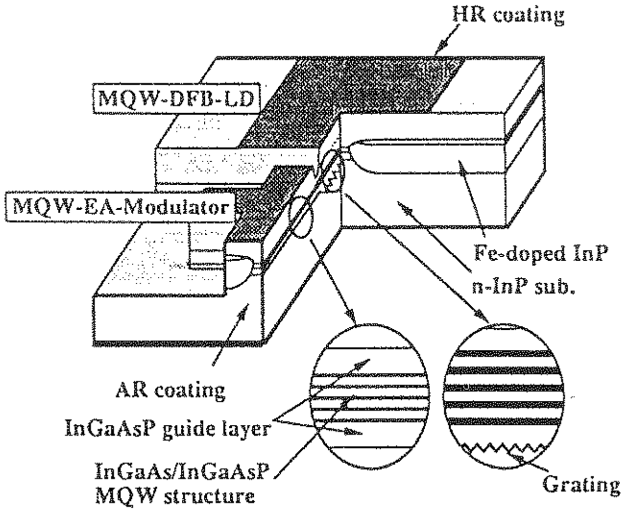


Figure 6. Schematic structure of MQW EA modulator integrated DFB laser using selective area growth technique by MOCVD [73].

a transmission system, 10 Gbit/s modulation [45] and over 100 km transmission (2.4 Gbit/s-135 km) [48] have been demonstrated. In a monolithic light source with MQW structure for both electroabsorption modulator (InGaAs/InAlAs MQW) and DFB laser (InGaAsP/InGaAs MQW), a 3 dB bandwidth in excess of 16 GHz at 4 V operation voltage for a 20 dB extinction ratio has been demonstrated.

In these devices, two-step epitaxial growth has been used for the monolithic integration of a modulator and a laser. Recently, it was reported that selective area growth using metal organic chemical vapor deposition offers a new degree of freedom in designing the composition and growth thickness of III-V bulk compounds. The bandgap energy of the compound crystal depends on the pattern of masks, on which epitaxial growth is prevented, and it can be controlled by varying the shape of mask pattern. Moreover, this idea indicates that it might be applicable to optical-integrated devices consisting of different compositional layers. The technique was applied to an EA modulator/DFB laser–integrated device as shown in Fig. 6, which showed a 13 dB extinction ratio at an applied voltage of -2 V operating at 1.55 μm, and a 10 Gbit/s modulation was achieved with a low-drive voltage of 1 V in the InGaAs/InGaAsP MQW system [70–73].

Transverse Type. Semiconductor optical modulators that operate on light normal to the plane of the device, usually named a spatial light modulator (SLM) are of considerable interest because of their potential applications in optical information processing, optical computing, or optical interconnection.

A MQW structure has been shown to be useful for the element of a SLM because of its large electroabsorption effect. An on/off ratio of 1.7 : 1 and an impulse response of 131 ps were reported in a single-device MQW modulator [78]; and as a two-dimensional array of SLM, 2×2 [80] or 3×3 [81] array of individually contacted, electrically driven modulators, and 4×4 [82] array with matrix address lines, which allow elements to be selected line by line, have also been fabricated.

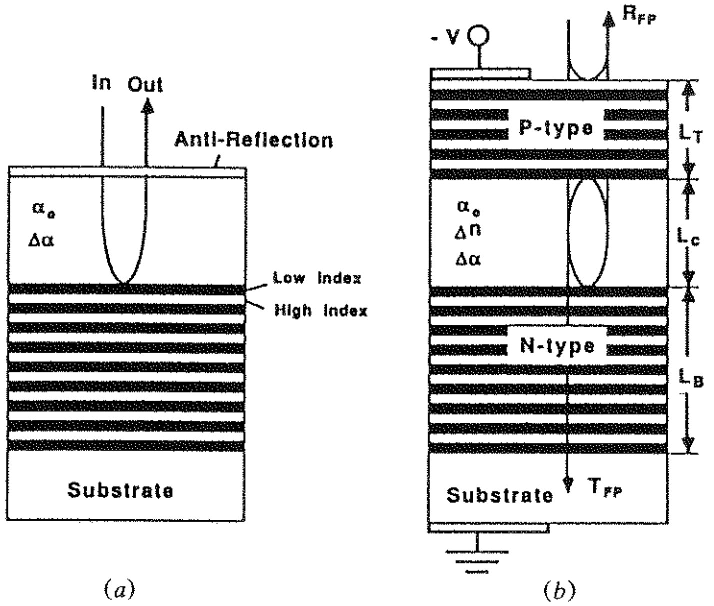


Figure 7. Schematic structure of reflection modulators: (*a*) Absorption modulator, and (*b*) Fabry-Perot modulator [93].

Reflection Modulator. In transmission type intensity modulators fabricated on lossy substrates such as AlGaAs/GaAs device, it is necessary to remove the substrate, but this process may be inconvenient and limit their applications. An alternative approach is to incorporate an epitaxial multilayer dielectric mirror between the substrate and the QCSE device as shown in Fig. 7. The device operates in reflection mode that results in an increase of the extinction ratio because the incident light passes twice through the quantum-well region. Furthermore, it is possible to fabricate unique optical modulators by placing the active region between Fabry-Perot cavities formed with epitaxially grown multilayer mirrors. These Fabry-Perot devices can have much larger contrast ratio because of the multiple reflections of the light through the material. Especially, an asymmetric Fabry-Perot modulator based on AlGaAs/GaAs MQW has exhibited an extinction ratio in excess of 20 dB [89] and operating voltage of less than 3 V [95].

Mach-Zehnder Modulator. Mach-Zehnder modulator has a single-input and output waveguide and the two *Y*-branches as a 3 dB splitter and a combiner [25, 26]. When the light from the two arms arrives at the second *Y*-branch in-phase condition, the intensity in the output waveguide becomes maximum. However, by introducing a π-phase shift between the light in the two arms, the field distribution at the output branch forms the second-order waveguide mode, which is not supported by the single-mode output waveguide, then the light is lost by radiation resulting in the off-state.

The chirping characteristics of the Mach-Zehnder modulator can be controlled by the driving condition and can realize the chirpless modulation by push–pull driving of the two arms of the Mach-Zehnder modulator.

In a device consisting of bulk InGaAsP/InP double heterostructure, an extinction ratio of 7 dB has been reported with a 4.5 V switching voltage at 1.55 μm wavelength where the voltage–length product for π phase shift is $V_\pi \times L = 22.5$ V · mm [97]. On the other hand, in a device using InGaAsP/InP MQW structure, it was significantly reduced to $V_\pi \times L = 1.9$ V · mm. There was another report concerning an integration of compressively strained InGaAs QW amplifier with the MQW Mach-Zehnder modulator to compensate propagation and coupling losses in order to improve the net fiber-to-fiber gain [100].

Phase Modulator. Optical phase modulators are required for use in phase-shift-keying optical communications and coherent optical information processing.

For the depletion-edge-translation effect in a reverse biased p^+-p-i-n-n^+ or p-n junction double heterostructure, refractive index variation is enhanced by utilizing both the electro-optic and the free-carrier effects. In these devices, very-high phase shift efficiencies of 60–100°/V mm and 37.5°/V mm have been obtained at operating wavelengths of 1.06–1.15 μm [115] and 1.3 μm wavelength [118], respectively.

A contribution by an excitonic effect to the refractive index Δn provides advantages for MQW phase modulators over bulk material ones through enhanced electro-optic effect and its quadratic dependence on the applied electric field. In AlGaAs/GaAs MQW phase modulator, phase shift efficiency as large as 520°/V mm has been reported [108]. As for 1.55 μm wavelength devices, a low voltage ($V_\pi = 3.8$ V), small intensity modulation depth below 1.5 dB, and modulation bandwidth without any degradation up to 20 GHz have been reported in the InGaAlAs/InAlAs MQW structure [112].

Optical Switches

Optical-Switching Elements. There are, in general, three kinds of switching elements applicable to optical exchange systems, namely, space-division, time-division, and wavelength-division optical switches. In this section, only space-division switches applicable to an optical matrix array exchange system are reviewed, because the others are related to optical memory and wavelength conversion devices, which are beyond the scope of this paper.

As for the optical-switching element consisting of 2 × 2 input/output ports, it has two states: the so-called "bar state" in which the input ports are connected to two output ports in parallel and "cross state" in which the input port is cross connected. There are two types of switches to provide optically this beta function. The first is the generic directive switch type in which light via some structure is physically directed to one of two different outputs. Another alternative approach is the gate switch in which the input signal is passively split into two parts, and each of them enters a simple on/off modulator. The outputs from those gates are passively combined to provide two possible outputs. Because of its simple function, it may be easier to achieve beta function compared with a directive switch. However, the gate switch has an inherent 3 dB split loss and 3 dB combining loss at the output, which may be overcome by using optical amplifiers.

Because of the passive splitting and combining losses of gate type switches, directive type switches have most frequently been used for switch arrays. Most common directive switch devices are: (a) directional coupler [27] or reversed $\Delta\beta$ directional coupler [28] and (b) intersectional switch [29–31].

Directional coupler. In this structure, a pair of phase-matched optical waveguides are arranged in parallel with a small separation so that the guided light wave is periodically coupled back and forth between the guides in the direction of light propagation due to evanescent coupling. The coupling strength depends on the interwaveguide separation and the waveguide mode size, which, in turn, depends on the wavelength, polarization, and the confinement factor of the waveguide. By arranging electrodes at the waveguides, the refractive index can be changed via an applied electric field. Hence, the original phase matching between the waveguides gets destroyed and switching of light between the outputs can be accomplished.

While a directional coupler provides better characteristics in the bar state by electrical control, it is difficult for the cross state, since the coupling length depends on strip waveguide width and the index difference of the waveguide, which strongly depend on fabrication process. To achieve a perfect cross state, the interaction length must be adjusted to the coupling length l or odd integer multiple of l. This limitation can be overcome in reversed $\Delta\beta$ type directional coupler switch, in which equal magnitude but opposite polarity of $\Delta\beta$ can be obtained over the two half length sections or, in general, over N sections. It can be shown that over a relatively large range of coupling values one can achieve better characteristics in both the cross and bar states.

Intersectional switch. Operational principle of intersectional switch is based on total internal reflection (TIR) induced by a refractive index variation due to the QCSE or other effects as explained in the previous section. Bar and cross states are changed by electronically controlled reflectivity of the mirror arranged at the center portion of intersecting waveguides. This phenomenon is insensitive to polarization of incident light, and critical angle can be increased when the refractive index difference between two media is large. If we consider an optical switch connected to single-mode optical fiber end, polarization-independent property is very important since the polarization of the light transmitted through a typical fiber randomly fluctuates. Merits of an intersectional optical switch are: (i) wider tolerance in the operation wavelength, and in the size fluctuation of the waveguide; (ii) polarization insensitive; (iii) small and simple electrode structure; and (iv) easy-to-fabricate matrix switch array. However, when an intersecting angle is small, the operation of the switch is considered as a mode interaction between the two eigenmodes of the waveguide structure or simply zero gap directional coupler, and these merits will vanish. Under a condition of intersecting angle larger than 2°, an intersectional switch with all these merits can be regarded as the best type of switching element for optical switch array.

In the following section, we show the reported semiconductor optical switch element and optical switch array.

Gate Switch. In the GaAs/AlGaAs MQW system, a gate 2 × 2 matrix switch has been fabricated [121]. This 2 × 2 optical gate matrix switch consisted of four GaAs/AlGaAs MQW electroabsorption modulator, miniaturized optical splitters and combiners having corner mirrors, and the switch size of 3 mm and 1.2 mm, respectively. The crosstalk was −20 dB at 12 V, and the insertion loss was 24 dB, which include a 9 dB propagation loss. The mirror, scattering, splitting losses were, respectively, 8, 4, and 3 dB.

One of the features of semiconductor materials is that they provide not only the potential for electrically controlled optical gain and gating functions but also light-absorbing or light-amplifying detection. Thus, passive waveguide losses as well as power-splitting and -combining losses can be compensated for, making zero-loss switches feasible. Because of these merits, a 2 × 2 InGaAsP/InP laser amplifier gate matrix switch operating at 1.55 μm was demonstrated (see Fig. 8) [122]. Switching characteristics was 40–50 dB extinction ratio, net chip gain of 14 dB, and a minimum fiber-to-fiber loss of 4 dB at 100 mA injection current.

As the current injection type switch, laser diode switches (LD switches) have been demonstrated [119]. In this switch, gain and loss are controlled by the injection current and the optical signal is directly switched. When the injection current is applied, the optical signal passes through the active layer of the LD switch is and amplified. On the other hand, the incident light is absorbed under no injection current conditions. By using this LD switch, optical matrix switch array was demonstrated [120].

Directional Coupler. In the InGaAsP/InP double heterostructure, directional coupler operated by carrier injection have been demonstrated. Total length of the switch is 2 mm. Switching is achieved at 4 mA, and crosstalk of more than −20 dB and 1.3 dB insertion loss have been demonstrated.

In the GaAs/AlGaAs system, a lot of electro-optic directional coupler switches with double-hetero structure have been demonstrated because of low-absorption loss at long wavelength region. By using the MBE crystal growth and reactive ion beam etching technique, the device length shorter than 1 mm (980 μm) has been fabricated. Its switching voltage is 5 V, and extinction ratio for the cross state and for the bar state is 17 dB and 14 dB, respectively [124].

As an optical matrix switch arrays, both 4 × 4 and 8 × 8 electro-optic directional couplers have been demonstrated. The 4 × 4 GaAs/AlGaAs optical matrix

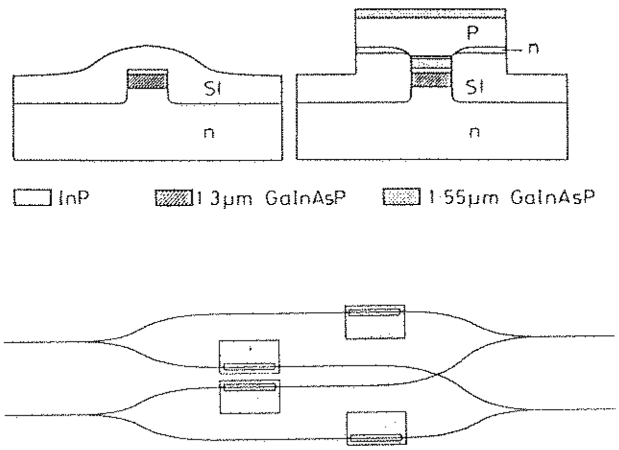


Figure 8. Schematic cross sections of passive and active parts of waveguide structure, and Mask layout of 2 × 2 semiconductor laser amplifier gate switch arrays [122].

switch array, as shown in Fig. 9, was constructed from twelve electro-optic alternating $\Delta\beta$ directional couplers with simplified tree architectures, a strictly non-blocking architecture [127]. It has obtained uniform characteristics, such as small switching voltage deviation of 9.0 ± 0.5 V for cross state and 21.9 ± 1.5 V for bar state, and little path dependence in ± 0.5 dB propagation loss. The 8×8 GaAs/AlGaAs optical matrix switch array was constructed from sixty-four electro-optic alternating $\Delta\beta$ directional couplers with the same simplified tree architecture as used in 4×4 matrix switch array. The 8×8 matrix switch have a chip size of $26.5 \times 3\ \text{mm}^2$ and a minimum total loss of 8.7 dB [128]. All of these matrix switch arrays were fabricated by MBE for crystal growth and RIBE for waveguide fabrication.

As mentioned in modulators, the excitonic electroabsorption is increased in the quantum-well structure and device characteristics is improved in contrast to the bulk structure. Hence electrorefraction, which is connected through the Kramers-Kronigh relation, is expected to be enhanced in the quantum-well structure, and the switching characteristics of switches whose operational principle are based on this refraction will be improved. The use of the quantum-well structure provides the reduction of the length of the switch, increase of the switching speed, and the reduction of the consumption power. And many electrorefractive switches have been fabricated by using quantum-well structure. InGaAsP/InP MQW directional coupler switches with active lengths under 600 μm operating at 1.3 and 1.55 μm have been demonstrated [131, 132]. Devices were fabricated from p-i-n MQW waveguide structure.

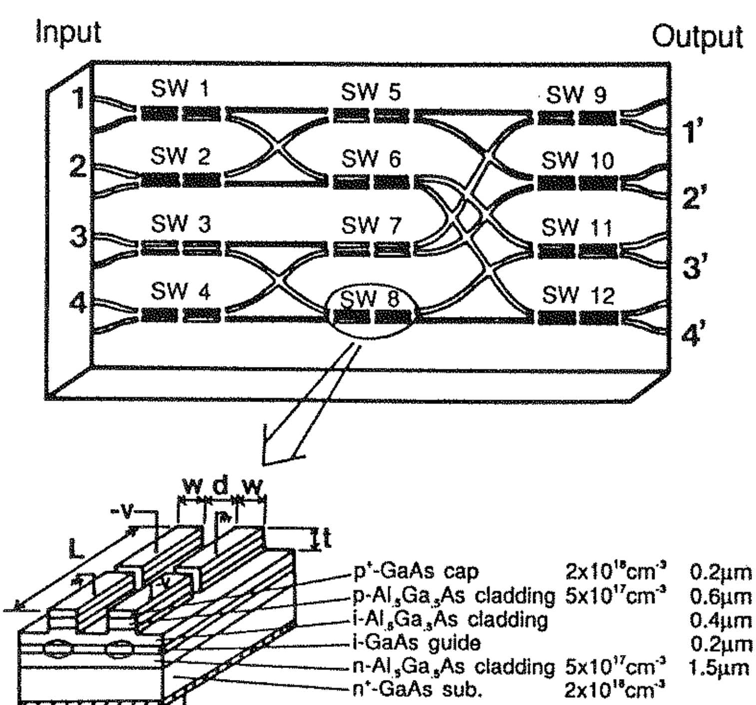


Figure 9. Schematic structure of 4×4 matrix switch array with electro-optic directional couplers [127].

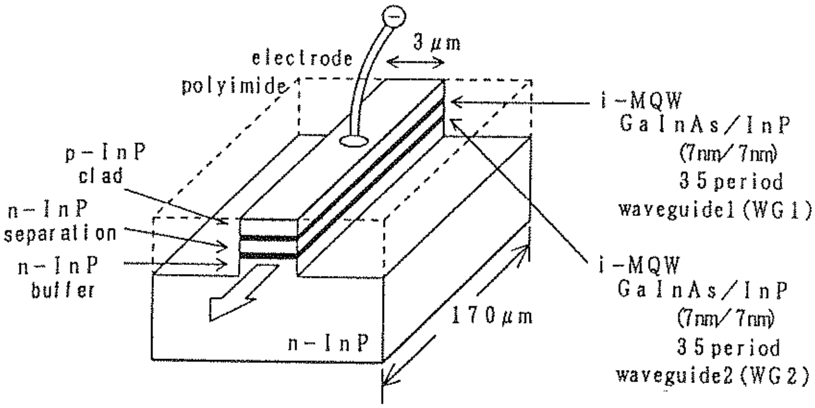


Figure 10. Schematic structure of vertical type directional coupler [136].

One of the important merits of semiconductor materials over dielectric materials is the freedom of the waveguide geometry design for the vertical direction. Especially in the MQW structure, the refractive index difference of the waveguide to the cladding can be controlled by changing the thickness of quantum well and barrier. The vertically arranged directional coupler, in which two waveguides are stacked on the substrate where two waveguides are separated by a separation layer with an appropriate thickness, is the peculiar switch structure in the semiconductor material. The operational principle is the same as that of conventional planar directional coupler, but a vertical directional coupler has additional advantages, for example, that the control of coupling length is easier because of the accurate contrability of thickness and compositions of the waveguide by recent crystal growth technique, such as organo metallic vapor phase epitaxy (OMVPE) or molecular beam epitaxy (MBE).

The first demonstration of vertical directional coupler was performed in GaAs system [129]; and recently, with the development of crystal growth technique, MQW vertical directional coupler was studied both theoretically and experimentally. In the GaAs/GaAlAs MQW system, coupling lengths and extinction parameters were reported. In the long wavelength region, switching operations of GaInAs/InP MQW high-mesa geometry vertical directional coupler, as shown in Fig. 10, were demonstrated with a very short device length $l = 170$ μm [136].

However, for the practical use of vertical directional coupler as an optical matrix switch array, it is necessary to separate the output lights from each waveguide. In order to achieve this structure, more than two times epitaxial growth is necessary; and as another approach needless of regrowth process, a vertical directional coupler with a built-in TIR region was demonstrated [137].

Intersectional Switch. Many of the intersectional optical switches based on carrier injection were demonstrated because the refractive index variation induced by the carrier injection is greater than that of the electro-optic effect in the bulk material.

As an element of optical matrix switch array, a single-mode single-slip structure (S^3) optical switch made of two *Y*-branch TIR optical switches and an *X*-crossing waveguide was proposed. As shown in Fig. 11, in this structure, the

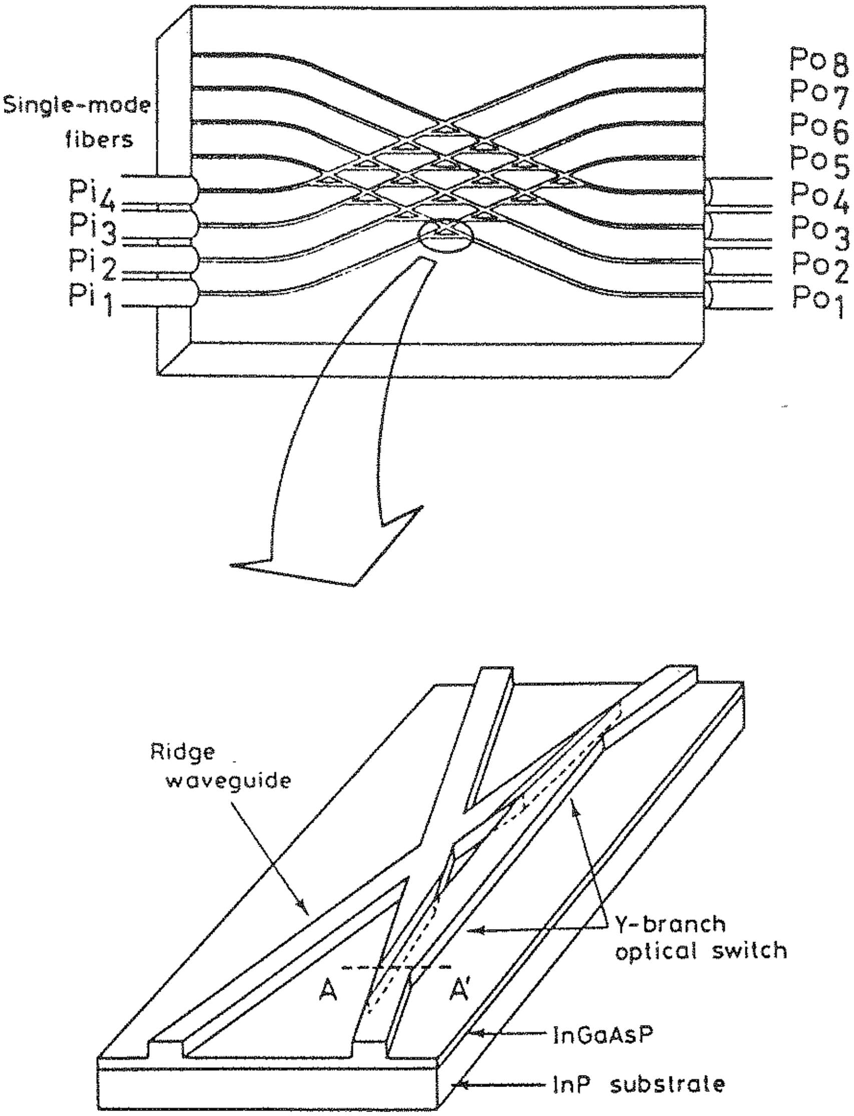


Figure 11. Schematic structure of single-slip structure (S^3) optical switch as a unit cell of a nonblocking 4 × 4 optical switch array [143].

crossing angle of an *X*-crossing waveguide is twice as large as the *Y*-branching angle. In the conventional *X*-waveguide optical switch, the width of the reflecting mirror is limited by the width of the waveguide, but the *Y*-branching waveguide in the S^3 optical switch does not suffer this limit and minimizes the reduction of crosstalk due to the evanescent field coupling through the width of the reflecting mirror. By using this optical switch structure, a nonblocking 4 × 4 optical matrix switch array was demonstrated [143]. The fabricated 4 × 4 optical matrix switch array has an 8 mm length, the crosstalk reached −19.1 dB, and the minimum total insertion loss is 20.4 dB including the fiber connection loss. Furthermore, to improve the insertion loss and crosstalk, the S^3 optical switch integrated in the traveling-wave amplifier in the slip waveguide of the S^3 switch was demonstrated [146].

However, the problem of the carrier injection type optical switch is that the switching speed is limited by the lifetime of the injected carriers and is in the order of several nanoseconds. In order to improve this switching speed, a bipolar transistor optical switch was proposed and the switching speed is estimated to be 60 ps [148].

To prevent the limitation of the speed through the carrier injection, electro-optic effect is expected to provide fast switching operation. But the electro-optic coefficient in the bulk system is too small—there are a few intersectional optical switches operated by total internal reflection, and the operation of almost all the switches are similar to the zero gap directional coupler. On the other hand, with the appearance of quantum-well material, intersectional optical switch was studied extensively by using the large electrorefraction effect. Through the large electrorefraction in the quantum-well structure by QCSE, switching operation was achieved in the GaInAsP/InP MQW structure operating at 1.3 μm for the first time [149]. The intersecting angle was 4° and the polarization-dependent properties were observed. In the GaInAs/InP MQW system, intersectional optical switch with an intersecting angle of 6°, switching voltage of 8 V operating at 1.6 μm was demonstrated [150].

In order to fabricate the intersectional optical switch, a reflecting mirror is necessary for the operation of this switch, and this requires the regrowth process. Recently, an intersectional optical switch without regrowth process was proposed [151]. As shown in Fig. 12, this optical switch of the rib waveguides was fabricated by only one pattern-etching process, and this process is suitable for fabricating a large-sized matrix switch array. In the GaInAs/InP MQW optical switch operating at 1.55 μm, less than 2 V switching voltage was observed [152].

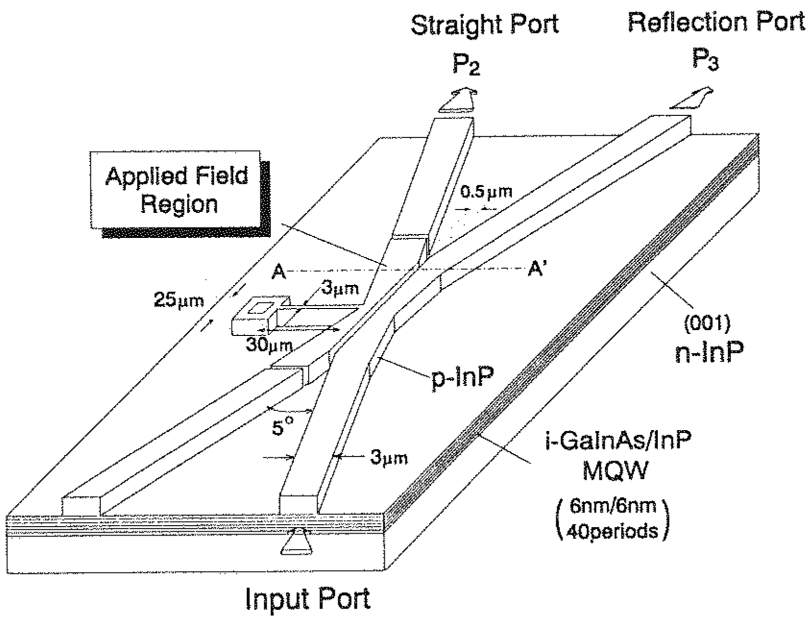


Figure 12. Schematic structure of MQW intersectional waveguide optical switch [151].

By using the depletion edge translation effect, AlGaAs/GaAs double heterostructure intersectional optical switch was demonstrated [153]. The intersecting angle was 6.8° and operating wavelength was 1.1 μm; and by using the electron transfer effect in the quantum-well structure, InGaAs/InAlAs MQW intersectional optical switch was demonstrated [154]. The reflecting mirror was fabricated by the ion implantation, and the intersecting angle was 4° and operating wavelength was 1.55 μm.

Future Aspect

In the last section, we discuss the further improvement of the characteristics of the semiconductor optical switches and modulators from the point of view of material.

As a material of semiconductor, quantum-well structures have large electroabsorption or electrorefraction effect over bulk material through the QCSE. This effect will be enhanced by introducing the low-dimensional quantum-well structure, that is, quantum-box or quantum-wire structure [156–159]. At first, we show the theoretical calculation of electro-optic effect in the low-dimensional quantum-well structure. Figure 13 shows the theoretically obtained field-induced refractive index variation spectrum and its wavelength window of $Ga_{0.47}In_{0.53}As/InP$ quantum-box, -wire, and -film structures where the index-loss variation ratio $|\alpha_p|$ is larger than 10 [21]. In this calculation, the size of the quantum well is 10 nm of film, and those of wire and box are 10 nm × 10 nm and 10 nm × 10 nm × 10 nm, respectively. The applied electric field is 1×10^5 V/cm. The wavelength of absorption edge for the transition between the first electron state and the first heavy-hole state is represented by λ_{11} and $\lambda_{11(B)} = 1.407$ μm in the quantum-box, $\lambda_{11(W)} = 1.506$ μm in the quantum-wire, and $\lambda_{11(F)} = 1.584$ μm in the quantum-film, respectively. For the switch or modulator, the operational wavelength should be longer than λ_{11} to make the device immune from the fundamental absorption loss. Figure 14 shows the relation between the absolute value of refractive index variation and α_p obtained from the Fig. 13 where the solid line indicates the negative refractive index variation and the dashed line the positive one. The

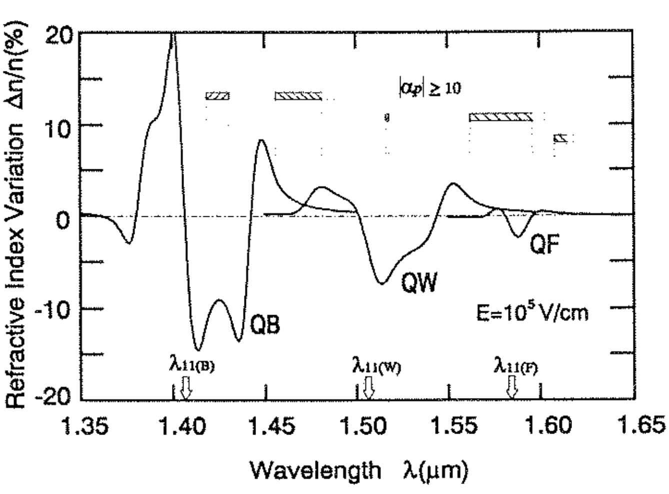


Figure 13. Refractive index variation spectrum of low-dimensional quantum-well structures.

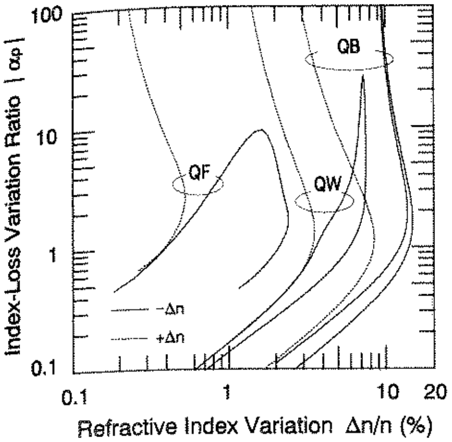


Figure 14. Relation between refractive index variation and index loss variation ratio α_p.

absolute value of the negative refractive index variation is almost twice as large as that of the positive one irrespective of the quantum-well structure. In the wavelength range for negative refractive index variation, there is no wavelength window in the quantum-film structure for the condition of $|\alpha_p| \gtrsim 10$, but the wavelength window satisfying this condition appears in the quantum-wire and quantum-box structures, and this wavelength window is wider in the quantum-box. This fact reflects the density of states of the quantum-well structures from staircase (film) to sawtooth (wire) and delta function (box). On the other hand in the wavelength range where the positive refractive index variation takes place, the index–loss variation rate $|\alpha_p|$ becomes larger than 10 at the wavelength of 5 ~ 10 nm longer than the peak wavelength of positive refractive index variation. For practical use, the operational wavelength region is limited by the minimum refractive index variation required for the switch or modulator. As can be seen from these figures, the electro-optic effect will be enhanced in the low-dimensional quantum-well structure; and one more merit of low-dimensional quantum-well structure is that the absolute value of index–loss variation ratio will be increased, and we can construct the optical switch operating by "pure" refractive index variation.

On the other hand, as the experimental results of the low-dimensional quantum-well structure, field-induced refractive index variation was observed in GaInAs(P)/ InP quantum-wire and quantum-box structures. The refractive index variation was reported to be 4% in the quantum-wire [160] and 7% in the quantum-box structure [161], even though the equivalent refractive index variation was only 0.017% (quantum-wire) and 0.0046% (quantum-box) by taking into account the optical confinement factor ξ of the waveguide, i.e., 0.43% (quantum-wire) and 0.065% (quantum-box). These quantum-wire and quantum-box structures were fabricated by etching a basic multilayered quantum-film wafer with a wire pattern or a mesh pattern, where the number of layers was only three (quantum-wire) or five (quantum-box), and pitch of the quantum-wire or quantum-box was 210 nm because holographic lithography patterning was employed. Actually a three-layered GaInAs/InP quantum-wire laser was fabricated by the similar process with the period of 70 nm using an electron-beam lithography, and it operated at room temperature [162]. The optical confinement factor ξ of this quantum-wire laser is approximately 1.2%. Another approach to increase the optical confinement factor of the quantum-wire or the quantum-box structure is under development by a selective growth on the side wall of a stacked multiple thin film structure [163]. Since technical difficulties can be overcome in the future and the realistic values of the optical confinement factor of low-dimensional quantum-well structures will be increased year by year, we cannot tell the realistic value at the moment. For instance, the optical confinement factor of the quantum-wire structure can be increased significantly if the fabrication process becomes successful, for example, by a combination of electron-beam lithography and dry-etching, or the fractional layer epitaxy (FLE) on tilted substrate [164–166], or epitaxy on V-grooved substrate [167].

One more important characteristic of the optical modulators and switches is the polarization control. The ordinary quantum-film or quantum-wire structure depends on the polarization, and electroabsorption or electrorefraction coefficient of TE mode is larger than that of TM mode. On the other hand, the quantum-box structure is independent of polarization. Hence quantum-box structure is the most attractive material for the optical modulators and switches also in the point of view of polarization control.

Another approach to control the polarization is to use the strained quantum-well structures [168]. The electroabsorption or electrorefraction in the strained quantum-well structures can reduce the polarization dependence because of their unique polarization properties of the interband transition dipole moments [169]. In the strained MQW electroabsorption modulator, the polarization dependence was largely reduced, and modulation efficiency was improved by using strained quantum-well structure [170]. Also in the Mach-Zehnder modulator, a strained quantum-well structure was introduced to eliminate the polarization dependence [171]. At present, the strained quantum-well structures play an important role for the realization of polarization-independent optical switches and modulators.

Conclusion

As can be seen from the above performances of semiconductor optical switches and modulators, semiconductor materials have superior characteristics over dielectric materials. Among many characteristics of semiconductor material, the important merits of semiconductor optical switches and modulators are: (i) compact size, (ii) high speed, and (iii) monolithically integrable. All of them are key points for stable systems.

In the transmission systems, the source of semiconductor optical modulators integrated with single-mode laser will replace the directly modulated semiconductor laser. On the other hand, in the exchange systems, semiconductor optical switches as an element of matrix optical switch array have shown superior features, such as high-speed operation and low power consumption. Furthermore, the optical switch array integrated with semiconductor optical amplifiers will be able to attain the zero-loss matrix switch array.

In the near future, with the progress of the fabrication process of fine structures, semiconductor optical switches and modulators will approach the ideal structure by using the low-dimensional quantum well as an ultimate semiconductor material.

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