Recent Progress of Semiconductor Integrated Optics for WDM Photonic Networks

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The integrated devices are indispensable to make next generation WDM networks at a reasonable cost and in a reasonable space. Semiconductor is a promising material for making integrating optical devices. This paper reviews resent progress of semiconductor optical integrated devices.

I. Introduction

The explosive growth of Internet traffic makes the development of integrated photonic devices an important issue for next-generation photonic systems. The large number of devices needed in future optical systems means that integrated devices will be indispensable if we want to make such systems at a reasonable cost and in a reasonable space. Monolithic integration on semiconductor substrates is attractive because it allows the semiconductor devices for optical systems, such as lasers, modulators, and photo-detectors, to be included on a single chip. Starting from a simple integrated device containing a DFB laser and an EA-modulator, various kinds of integrated photonic devices have been developed by using hybrid and monolithic technologies. Recent progresses in fabrication technologies and device design have made it possible to extend semiconductor monolithic technologies to passive devices. Fabrication technologies, such as crystal growth and dry etching, enable fabrication of waveguides with uniform and smooth interfaces and also enable the precise control of waveguide thickness needed to fabricate polarization insensitive waveguides. Moreover, the recent progress in development of the arrayed waveguide grating (AWG) enables us to make optical devices with significantly improved fabrication tolerance. With these technologies, we can extend the application of semiconductor materials to passive optical devices and, consequently, to complicated monolithic circuits containing both passive and active devices. This paper describes introduces some typical examples of the semiconductor monolithic devices reported so far.

II. Semiconductor Integrated Devices

Although active integrated devices have been used practically, application of semiconductor monolithic integration to passive devices at more than just a primitive level has only recently become possible, thanks to recent progress in fabrication technologies and device design. The development of the AWG has significantly accelerated development of monolithic circuits or monolithic devices. AWGs, by providing filtering function for multiplexing and demultiplexing signals, have been instrumental in expanding the application of semiconductor devices to WDM systems.

The first generation of the integrated devices was fabricated with only one waveguide structure and waveguide material. Starting from a simple device such as AWG integrated photo-detectors, even more complicated one have been fabricated. Limitation in waveguide structure and material, however, restricts ability of the monolithic integration. The technologies for connecting waveguides with different structures and materials, then, enable us to make complicated circuits containing various devices which require their own waveguide structures and materials. Monolithic circuits is, then, possibly fabricated with important devices including the semiconductor optical amplifiers and optical modulators.

A. Monolithic Integration of semiconductor AWGs and photo-detectors

Integration with a photodiode is relatively easy but the advantage of the integration is clear, therefore multi-wavelength AWG receiver[1,2,3,4] and WDM monitoring devices[5] have been fabricated at many laboratories. A multi-wavelength AWG receiver of eight channels that is about the same size as a conventional laser diode module can be fabricated.

Figure 1 shows an example of the semiconductor AWG integrated with photo-detectors. As shown in the right bottom figure, the device contains AWG connected to 16 photodiodes. The input signal, which contains 16 different wavelengths, is demultiplexed by the AWG and then each signal is detected by corresponding photo-detectors. On the left, is a photograph of the chip. A small bending radius of 250 μm makes the chip as small as 3.4 x 4.4 mm^2. The device has 16 photo-detectors for electrical monitoring and one optical output port for easy characterization of the chips. The AWG has 114 waveguides in the grating arm. A 2.45-μm-wide and 4.0-μm-deep ridge waveguide structure is used for obtaining

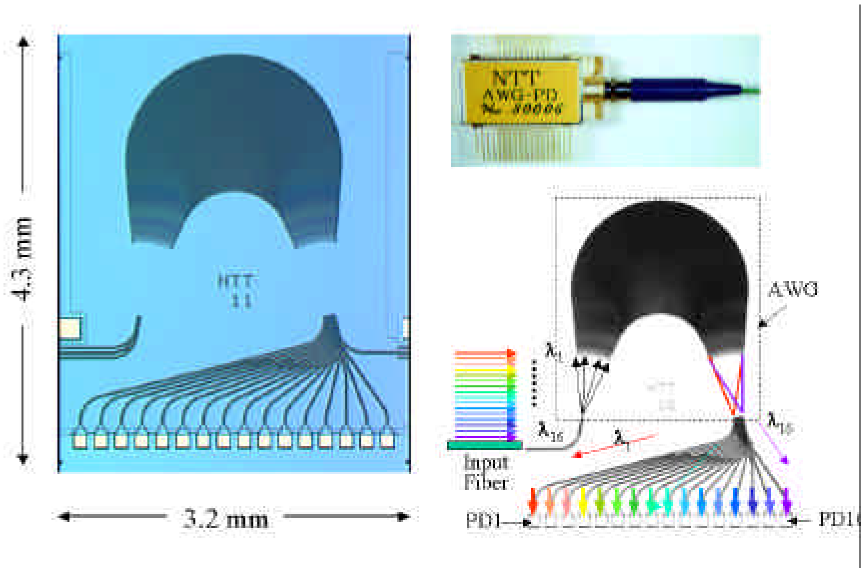

Figure 1 An AWG integrated with photodiodes.

polarization-insensitive characteristics. The path length difference ΔL is 27.25 μm, which gives a free spectral range (FSR) of 3.2 THz and the corresponding order of 56 at around 1.55 μm. Figure 2 shows wavelength dependence of the detection sensitivity of the 16-detectors in the integrated device. The sensitivity of each detector has clear peak at the channel wavelength spaced by 100 GHz. The maximum sensitivity of about 0.1 A/W is obtained with the crosstalk of less than –20 dB for the other channels.

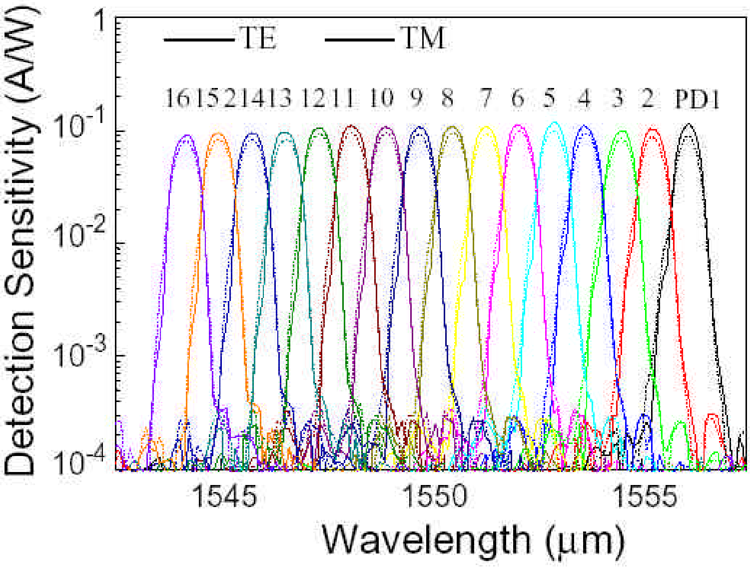

Figure 2. . Spectrum response of the efficiencies in an AWG integrated with photo-detectors.

The promising application for the photo-detector integrated devices is power and/or wavelength monitor in WDM systems[6]. The monitor application requires only low frequency signal and is free from the issue associated with multi-channel high-speed circuits. Although the implementation of multi-channel high-speed circuits is a severe issue, some prototype of the multi-wavelength receivers has been fabricated.

Figure 3(a) shows the fabricated 16-channel WDM receiver[7]. The compact integrated device enables us to install an AWG, 16-channel photo-detectors, and 16-electrical amplifiers in the industry standard of Compact PCI 6U 4-slot. The receiver consists of a WDM receiver board and a Compact PCI interface board. The WDM receiver board, which is shown in Fig 4(b), contains the AWG-PD module, trans-impedance amplifiers, and limiting amplifiers. The AWG-PD module is a

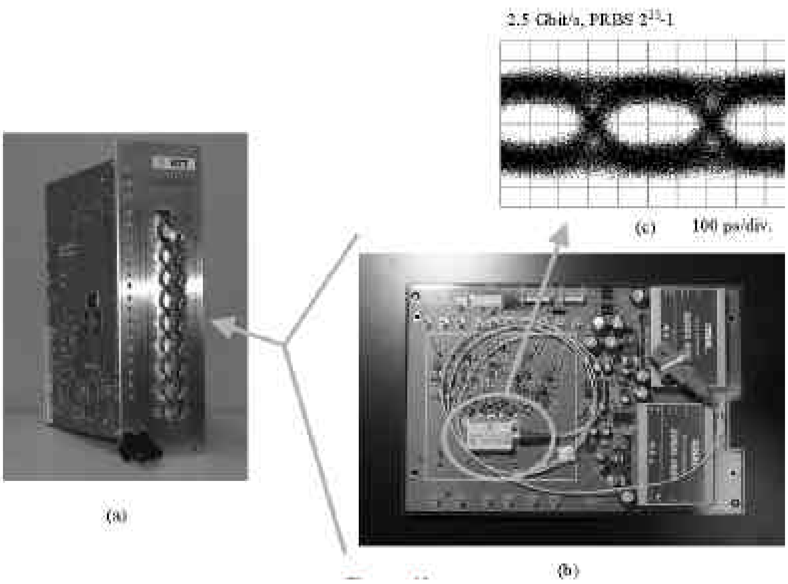

Figure 3. A 16-channel WDM receiver

polarization-insensitive multi-wavelength photo-detector with 16-channel, 100-GHz channel spacing and 3.2-THz free spectral range, which is the core element of the receiver. The AWG-PD module itself is designed for high-speed signal detection of up to 2.5 Gbit/s/ch[8]. Figure 3(c) shows an eye diagram for a 2.5 Gbit/s NRZ 2^{23}-1 pseudorandom bit stream detected by the integrated AWG-PD.

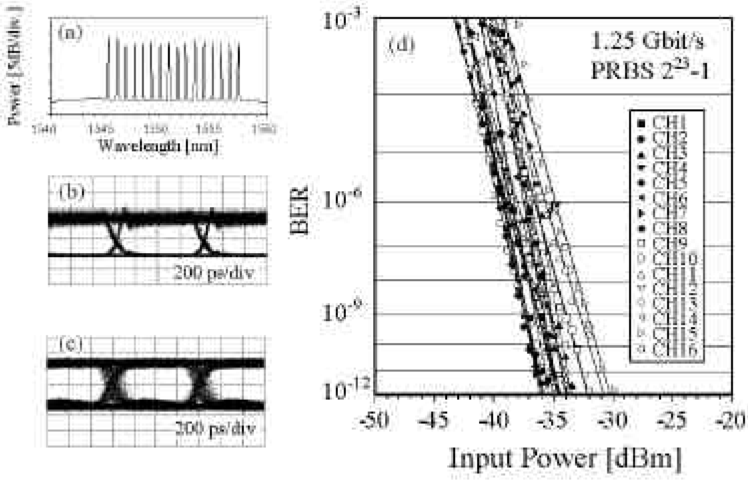

Figure 4. Detection characteristics of the 16-channel WDM receiver

The simultaneous detection of 16-signals has been tested at 1.25 Gbit/s, which corresponds to the bit rate of the Gigabit Ethernet. The optical sources with16 LDs were used to generate frequencies ranged from 192.50 THz to 194.00 THz (1545.32 nm – 1557.36 nm) with a channel spacing of 100 GHz. The 16 optical carriers were multiplexed by a silica-based AWG and modulated by an electroabsorption (EA) modulator with a 1.25 Gbit/s NRZ 2^{23}-1 pseudorandom bit stream. Transmission through an 80-km standard single-mode fiber (SMF) with dispersion of 17 ps/km/nm de-correlated the bit-stream of signals in different wavelength. The 16 signals were coupled into the WDM receiver after being pre-amplified by an erbium-doped fiber amplifier (EDFA) whose gain was 38 dB. A spectrum of the input lights before coupling into the WDM receiver is shown in Fig. 4(a). Eye diagram detected by a conventional detector is shown in Fig. 4(b) and output from the WDM receiver is shown in Fig. 4(c). It should be noted that there are no degradation in the eye diagram in Fig. 4(c) although the received signal was measured with crosstalk from all interfering channels.

Bit error rates (BERs) were measured for all 16 channels on the condition that all signals were simultaneously coupled into the WDM receiver. The BERs are shown in Fig. 4(c), where the input power is defined as the power of the measured signal before it is coupled into an optical preamplifier. The WDM receiver sensitivity was between -38 and -32 dBm for 1.25 Gbit/s NRZ 2^{23}-1 pseudorandom bit stream at a bit error rate of 1 x 10^{-9}..

B. Monolithic integration of AWG and semiconductor optical amplifiers

Integration with semiconductor optical amplifiers (SOAs) is also an attractive target. The optical gain provided by SOAs may compensate the relatively large insertion loss in semiconductor monolithic circuits and consequently enables us to make larger-scale optical circuits. The SOA is also attractive as an optical gate or switch because fast and low-crosstalk optical gating is possible only by on/off control of the currents. The device shown in Figure 5, a WDM channel selector[9,10], is a good example of the integration of an SOA.

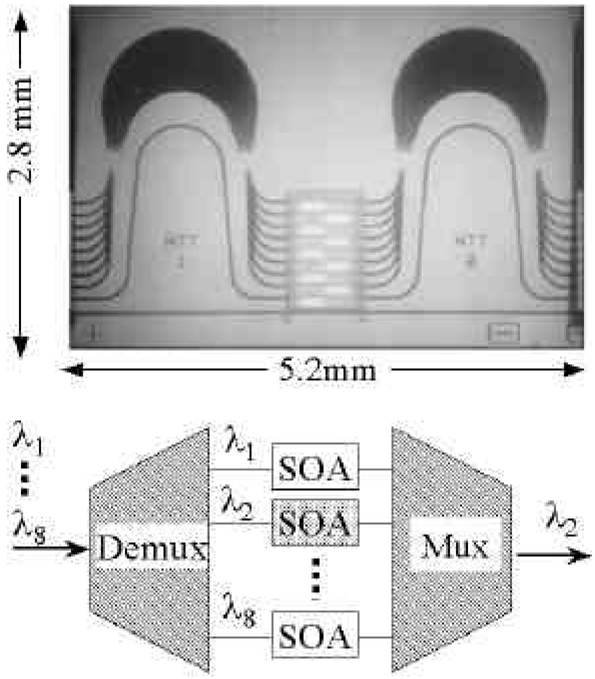

Figure 5. Photograph of the WDM channel selector consisting of an AWG andSOAs.

WDM channel selectors, that contain two AWGs connected by SOAs, will be key components in advanced WDM-based photonic network systems. Fast, low-crosstalk operations are expected because arbitrary demultiplexed signals can be selected by using only an on/off control of the SOA currents. WDM channel selectors are composed of numerous waveguides and components; therefore, reduction of device size is an issue in achieving low-cost mass production. The device in the figure uses a hybrid waveguide structure to make it compact and reliable;. a deep-ridge structure with a small bending radius is used for passive waveguides, and a buried waveguide structure, whose reliability has been confirmed in conventional lasers, is used in the SOA regions

The device consists of two AWGs and an 8-ch. SOA array. Each AWG has 8 input and 8 output waveguides and an array of 28 waveguides. The free spectral range and the channel spacing are 1.6 THz and 200 GHz, respectively. Eight 600-μm-long SOAs are located between the two AWGs. The spacing in the SOA array is 125 μm. Total device size is 5.2 x 3.6 mm^2. WDM signals, which are fed into one of the input waveguides, are demultiplexed by the first AWG, and some of the demultiplexed signals are selected by adjusting the current of the eight SOA gates. Then, the selected signals are multiplexed into one output waveguide by the second AWG..

The deep-ridge structure is used in most of the passive waveguide regions. The waveguide layer is a 0.5-μm-thick InGaAsP(λ_g=1.05μm). A non-doped InP buffer layer is inserted above the waveguide layer to prevent absorption loss in the p-type InP. The 2.5-μm-wide, 4.5-μm-deep ridge waveguide is designed to obtain low polarization dependence[12,24,11]. Because light is strongly confined by air against the lateral direction, a small bending radius is allowed in the waveguide layout, without excess loss. A minimum bending radius of 250 μm was chosen, which makes the AWGs as small as 2.2 x 3.6 mm^2. On the other hand, the buried waveguide structure s is used in the SOA regions. The active layer of the SOA is a 0.3-μm-thick InGaAsP(λ_g=1.55μm). The buried waveguide is the same as that of conventional laser diodes. The injection current is almost completely confined to the active waveguide by the current blocking layers. This structure should provide high reliability because the active layer is buried in InP. The optical couplings between the two waveguides were calculated by the finite difference method

(FDM).[12] Even though the structures are quite different, we can make field distributions of about the same size by choosing appropriate sizes for the waveguides. Therefore, coupling loss as small as 0.2 dB can be obtained. The losses estimated from the excess loss of test waveguides with many interfaces, were below 0.3 dB .

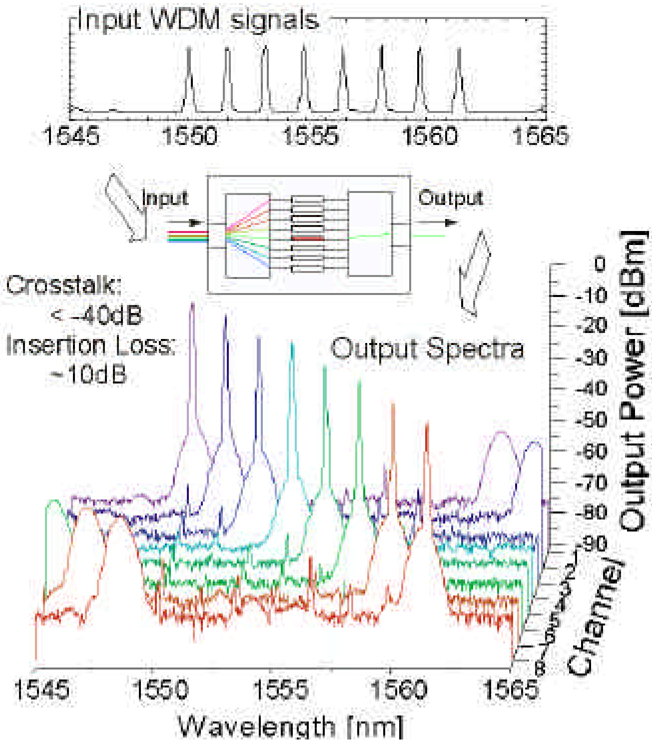

Figure 6. Channel selection of WDM signal in the AWG-SOA integrated device

The filtering characteristics of the WDM channel selector are shown in Figure 6. WDM signals containing eight different wavelengths from 1546.0to 1557.2nm with a spacing of 1.6 nm (200 GHz) were used for input. The power of each channel was adjusted to ~-8 dBm, as shown in .the top left of the figure. The WDM signals were passed through the device with a pair of lensed fibers, and the filtered light was measured using an optical spectrum analyzer. The top figure shows the spectra of the filtered light, when one channel was selected by the SOA gate control. The SOA current was 200 mA in the ON state. All 8 channels were well selected with a low crosstalk of less than –40 dB, where the crosstalk is defined as the ratio between a selected signal and an unselected signal. The amplified spontaneous emission (ASE) passed through the second AWG filter are observed at a ~30 dB lower level than the signal. Figure 7 shows the fiber-to-fiber transmittance for each channel as a function of the SOA current. The power of the input light is -12.4 dB with TE-polarization. Zero-insertion-loss operations are obtained for all channels. High extinction ratios of more than 50 dB are also obtained due to large absorption in the SOA.

Although the channel selector is an attractive device, it has an inherent issue for increasing number of WDM channels. As each WDM channel need a SOA for gating, increase in a number of channels requires as many SOAs and consequently requires large chip size. The large chip size and wiring issue associated with a large number of SOAs imply that this configuration may not be suited for WDM systems with a large number of channel. A

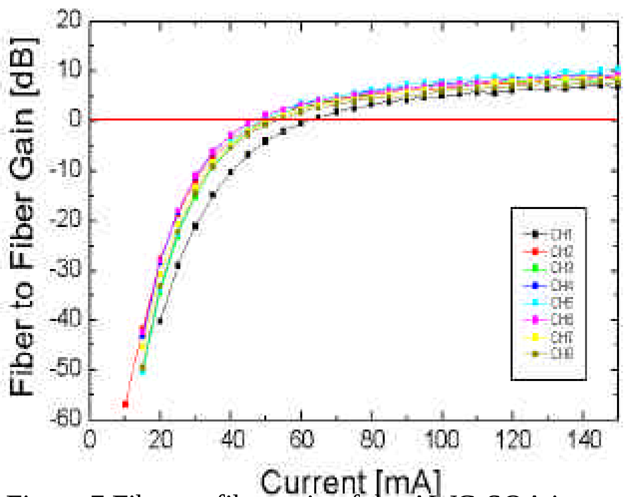

Figure 7 Fiber-to-fiber gain of the AWG-SOA integrated device as a function of the amplifier current

new configuration with cascaded AWGs and SOAs may solve this issue.

Figure 8 shows a 64-channel WDM channel selector with cascaded AWGs and SOAs where we can see a photograph (upper) and a schematic structure (lower) of the device[13]. The device consists of a 1 x 8 AWG, the first stage SOA gates, an 8 x 8 rear AWG, the second-stage SOA gates, an 8 x 1 multimode interference (MMI) coupler, and a booster SOA. The front AWG, which has a channel spacing of 50 GHz with a FSR of 400 GHz, sorts the incoming 64-signals into eight groups on it's eight output ports. The each group contains 8-signals at frequencies separated by the FSR of the first AWG. One of the first stage SOAs then select a group to pass through and lead to the second AWG. The second AWG has a cannel spacing of 400 GHz and an FSR of 3.2 THz where the allocation of the input port is carefully designed to obtain transmission peaks at every 64-channel frequencies. The second AWG sorts eight-signals by frequency and then a second stage SOA selects a signal at the required frequency. Thus the device can select any one of the 64-signals by choosing an appropriate pair of the first and second SOAs. Finally, the 8 x 1 MMI coupler combines 8-output waveguides into one and the booster SOA amplifies signal to compensate the internal loss of the device. Consequently the device can select 64-wavelengthes with only 16-SOAs, while conventional design for the wavelength selector requires 64 SOAs.

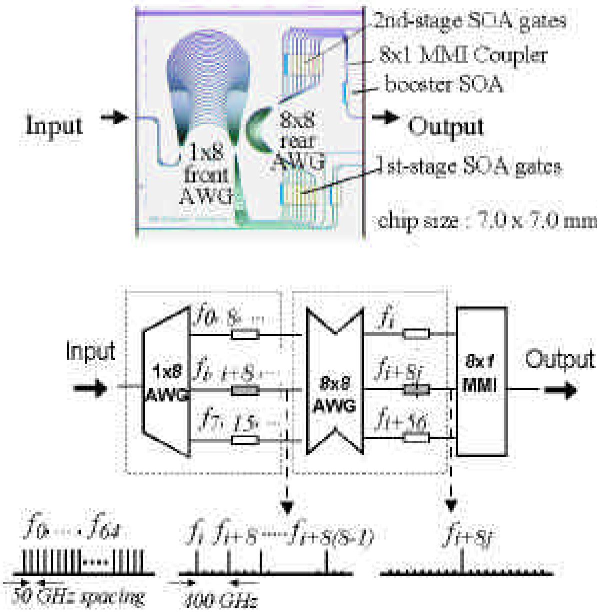

Figure 8. A 64-channel WDM channel selector with cascaded AWGs and SOA

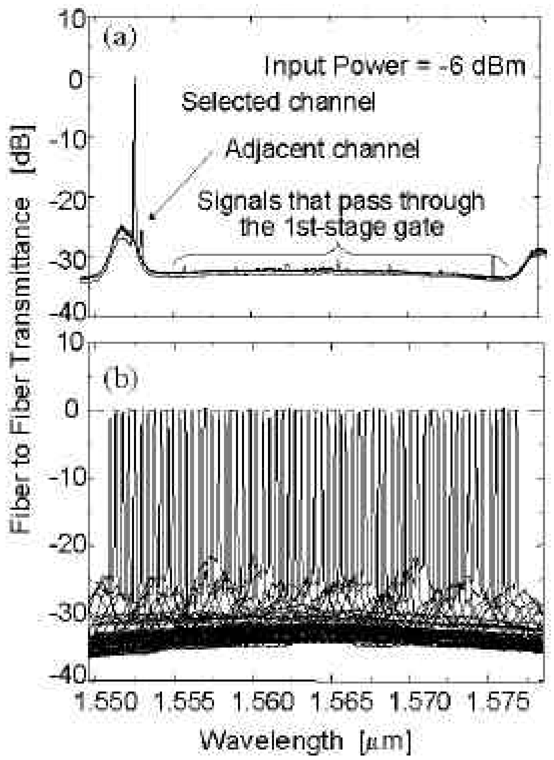

Figure 9. Output spectra of the 64-channel WDM channel selector

Figure 9 shows wavelength characteristics of a fabricated device. The device has an averaged channel spacing of 50.4GHz with standard deviation of 4.5 GHz and possibly separate 50 GHz spaced 64-signals. Figure (a) shows output spectra with a particular pair of 1st and second SOAs are active. One signal is successfully extracted with eight small peaks originated from the crosstalk in the first or second AWGs The maximum crosstalk is determined by the adjacent peak but is less than –25 dB. Overlapped spectra in fig. (b) confirms successful channel selection for all 64-channel. The zero insertion loss operations are obtained for 62-channels with proper adjustment of SOA currents between 107 and 150 mA. The high spead operation is also reported in this device[14].

C. Integration of AWGs, SOAs and EA modulators

As shown in the previous section, the but-joint makes possible low-loss coupling between different waveguide with independent structure design of each part. Using the but-joint, we can make more complicated devices even with different material systems. Figure 10 shows a multi-wavelength modulator[15] consisting of InGaAsP SOAs and InGaAs/InAlAs electro-absorption modulators (EAMs). The operation of the device is illustrated in the upper f. Incident CW lights at 8-wavelengths are split by the AWG. Next, they travel through the SOAs to compensate for the insertion loss. The EAMs modulate them individually to generate signals in 8-WDM channels. The modulated lights are launched into the same AWG again where they are multiplexed to one output port. For using the AWG twice as multiplexer and demultiplexer, the input/output ports of the AWG are designed to locate in particular positions according to periodical wavelength response. This single-AWG configuration reduces circuit size by half compared to a conventional two-AWG configuration and also assures complete spectral matching between multi-plexer and demulti-plexer.

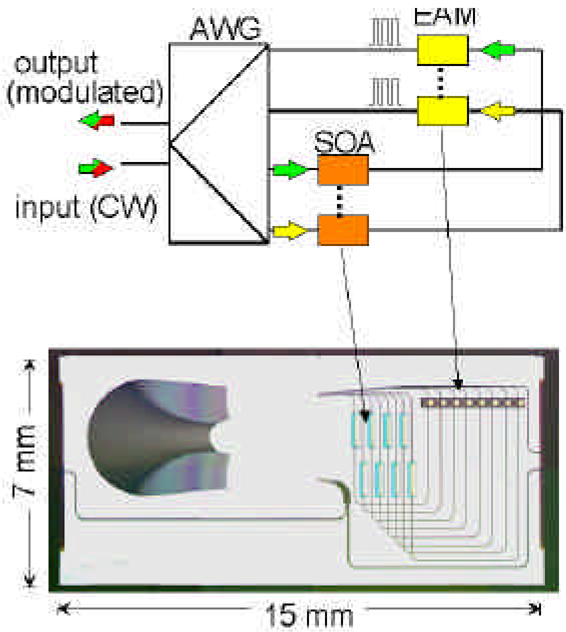

Figure 10. A multi-wavelength modulator consisting of an AWG, semiconductor optical amplifiers (SOAs) and

The butt-joints made by selective area growth technique connected the completely different structures of the AWG, SOA, and EAM. The device was formed by five steps of metal organic vapor phased epitaxy (MOVPE). First, an InGaAs/InAlAs multi-quantum-well (MQW) EAM active layer that provides polarization independent operation was grown on an n-InP substrate and partially etched off by wet etching. Then, an InGaAsP bulk SOA active layer was selectively grown using a SiO_2 mask and a p-InP cladding layer and an InGaAsP contact-cap layer were formed all over the surface. After etching off the all grown layer except for SOA and EAM region, an InGaAsP AWG waveguide layer and an undoped InP cladding layer were simultaneously butt-jointed to the EAM and SOA active layer in the second selective area growth step. The buried heterostructure (BH) was formed in the SOA region with a semi-insulating buried layer using CH_4/H_2 dry etching and the MOVPE growth of Fe-doped InP. A deep-ridge waveguide was used for the AWG to obtain high refractive index contrast. The waveguide in the EAM region was buried with polyamide to reduce the parasitic capacitance. Thanks to the small bend radius of the deep-ridge waveguide and single-AWG configuration the whole circuit was included in a size as small as 15 x7mm^2.

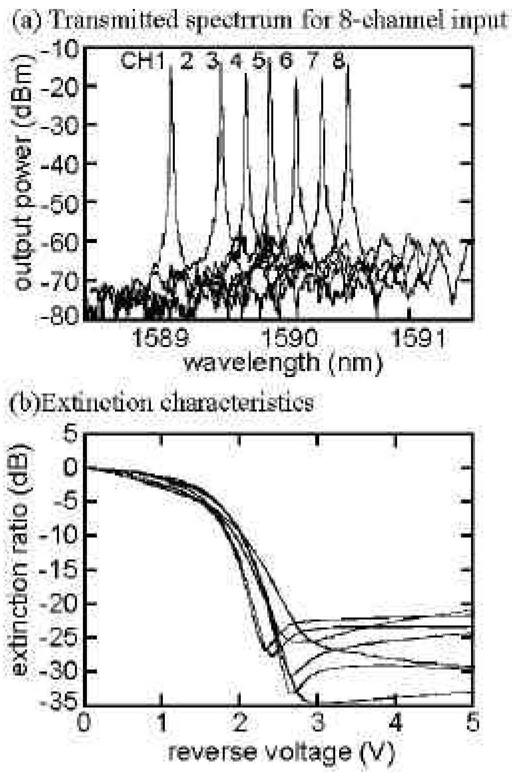

Figure 11. Characteristics of the multi-wavelength modulator.

Figure 11 (a) shows the output spectra of the fabricated circuit where the SOA current was 200 mA and the EAM was biased at 0V for each channel. When the input power was +5 dBm the output power of around -15 dBm was obtained, although channel 2 has no output due to a fabrication error. The measured channel spacing was 25 ± 2.5GHz for all ports. This indicates that uniform channel spacing was achieved in the AWG and the power loss due to the spectral mismatch between the MUX and the DEMUX was small enough. The single-AWG configuration is effective in eliminating the spectral mismatch as well as reducing circuit size. The estimated SOA of about 15 dB results in the fiber-to-fiber insertion loss of the circuit of about 20 dB. The gain of the SOAs is not sufficient for the purpose of complete loss compensation in this feasibility study, but could be improved up to about 25 dB by improving the fabrication process.
The extinction characteristics of each port are shown in Fig. 11 (b) where the SOA current is 200 mA and the input power is +8 dBm. An extinction ratio of better than 20 dB is achieved at a reverse voltage of 3V for all ports. These high extinction characteristics come from the InGaAs/InAlAs MQW layer; that is, the fabrication process allows us to use different optimized materials for SOAs and EAMs. The fabrication process does not degrade device performance, as the value is equivalent to that of stand-alone EAMs.

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III. Summary

The development of the arrayed waveguide grating (AWG) enables us to make optical filters good enough for WDM application on semiconductor substrates. Thanks to the progress in the fabrication technologies, now, we can fabricate integrated devices containing both passive and active devices by using the but-joint with the semiconductor AWGs. The compact devices fabricated with the monolithic integration promise next generation WDM systems possibly use a large number of optical devices with reasonable cost and with reasonable space.

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