Recent progress of photonic device research

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ABSTRACT

Application of optoelectronics technologies to communication has come to a transition from point-to-point transmission to photonic backbone networks. This paper reviews recent progress of photonic device research with emphasis on the key technologies concerning this transition. Among them are multi-channel WDM and photonic switching. Photonic integration is coming a reality on monolithic as well as hybrid scheme.

Keyword: photonic device, photonic backbone networks, photonic integration, WDM, photonic switching

1.INTRODUCTION

The history of optical communication technologies can be recognized as a history to meet the demand for the higher traffic capacity and longer transmission distances in global communication networks. In recent ten years, the tendency has become much clearer with the explosion of internet, intranet and/or IP-based data communication. Research and development activities started with technologies for higher data speed, longer repeater spacing in trunk transmission lines in early 1970's. They have been continuing over 30 years. The efforts are now turning toward more efficient, flexible and reliable photonic backbone networks. Photonic device research has supported and sometimes guided their progress. This paper reviews recent progress of photonic device research with emphasis on their contribution to communication networks and future network backbones.

2.PROGRESS OF OPTICAL COMMUNICATION TECHNOLOGY

As a measure to indicate the progress of optical transmission performance, products of the transmission bit-rate and the rpeater-less transmission distance are plotted against time(year)[1] in Fig. 1. The bit-rate distance products are classified by the key technologies by which the most excellent performance has been achieved in each time frame. This chart clearly shows that the performance saturation has overcome by new technologies. Such situations have kept throughout the time since the optical fiber communication systems have appeared at least experimental results are concerned.

Since the advent of Erbium-doped fiber amplifiers, the repeater-less transmission distance has expanded drastically. In addition to the remarkable increase of the repeater-less transmission distance by EDFA, multi-channel wavelength division multiplexing (WDM) has come into existence in 1990's. The channel number in experiments have increased from few to 50-over 100[2-5]. The bit-rate for each channel has also increased to 10-100Gb/s, which pushed forward further the bit-rate distance products toward over 10^6 Gb/s km. For the bit-rate beyond around 40Gb/s, all optical signal processing such as optical multiplexing and demultiplexing becomes necessary.

With the use of the high speed and multi-channel WDM technologies, point-to-point transmission throughput has reached to terabit-per-second level. Research targets have moved toward the use of photonic technologies in the network nodes in order to build efficient, flexible and reliable networks. Figure.2 shows a rough image of photonic networks, where photonic technologies are applied to both transmission and node functions. Photonic devices have supported and sometime guided such a progress of photonic networks. Important functions of the nodes and main photonic devices are described in Fig.2. Optical cross connects (OXC) are expected to secure the network reliabilty by rerouting and reconnecting the transmission

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line in case of breakdown or failure of transmission. These functions are extremely important for networks with ultra high throughput. In the network nodes in a big city, a huge amount of information signals are coming down from and going up to the network transmission lines. Optical add-drop multiplexing (OADM) is expected to make the signal handling easier in the high speed region beyond the pure electronics can treat.

At the transition from 1.5 um single mode fiber (SMF) systems to 1.5 um EDFA optical fiber amplifier systems(Fig.1), the device research has moved from simple isolated devices to integrated devices. The integration includes monolithic and hybrid schemes.

3.PHOTONIC INTEGRATION

A term "integration" will easily induce us an image of silicon microelectronics, where huge number of transistors, capacitors and resistors are integrated on a single chip. Photonic integrated devices are still in a preliminary stage and just began to be used in practical systems. The situation of silicon microelectronics is far beyond that of optoelectronics from the view point of integration scales. We, working in the field of photonic device research, can study many things from the history of micorelectronics. Under this understanding, comparison is made on the progress between microelectronics and optoelectronics. Important events for both electronics regions are depicted in Fig. 3. In microelectronics, thirty years after the birth of transistors has enabled the full popular use of silicon integrated circuits. On the other hand, thirty years after the birth of semiconductor lasers does not produce such a large scale integration. The situation is partly because that optoelectronics has been developed mainly for signal transmission, while microelectronics has been developed mainly for signal processing and storaging.

For photonic integration, integrated element number may not be a unique importance. There are two key directions for photonic integration, i.e., integration of functions and integration of many elements (integrations of "numbers"). Main photonic integrated devices are mapped in Fig.4. For comparison, the typical IC's in microelectronics are also described near each axis, i.e., CPU/MPU for function axis and DRAM for number axis. Integration of function in photonic devices means to realize higher performance and higher functionality by integrating elements with a different function. The typical examples are modulator integrated light sources, spotsize converter integrated light sources, and photonic terminal devices or photonic network unit devices where a lightwave transmitter and receiver are integrated. The element number for this direction is very small, i.e. two to ten. The most important advantage of the photonic integration in this direction will be reduction of connection point number, which results in the fabrication cost reduction and reliability increase. For example, in case of a combination of light source and an external modulator, optical connection numbers are reduced from three to one by photonic integration as shown in Fig. 5.

4. MONOLITHIC PHOTONIC INTEGRATION

4.1. Selective MOVPE Crystal Growth

For monolithic photonic integration, crystal growth is required to fabricate semiconductor structures with layers with a desired bandgap energy or a desired refractive index in the desired position on a semiconductor wafer. So far, "cut and paste" method has been applied to make monolithic photonic integration. Complicated processes with many number of crystal growth is likely to meet a severe problem of device yield. As a new crystal growth method for monolithic integration, a narrow stripe selective MOVPE method has been developed[6]. In the selective MOVPE technique, growth enhancement occurs in between the patterned masks as shown in Fig. 6. The growth rate and compositional ratio between In and Ga varies with the mask width. They are predominantly attributed to lateral gas phase diffusion of metalorganic species. By changing the mask witdth from 4 to 30 um, the grown InGaAsP stripe layer's composition changes from 1.28 um to 1.54 um in photo-luminescence peak wavelength. Thickness enhancement phenomena can be effectively applied to grow a tapered stripe structure by changing the mask width gradually.

4.2. Modulator Integrated Light Sources

A most important application of bandgap energy control in selective MOVPE technique is to monolithically integrate an external modulator with a single frequency DFB laser diode(LD). Such a combination is a key light source for high speed and long distance optical fiber transmission. A structure of a modulator integrated DFB LD for 10-Gb/s systems is shown in Fig. 7[7]. In order to increase the bandgap energy of the modulator part by about 70nm in wavelength, the patterned mask width for the modulator part was set narrower by about 12 um than that for DFB laser diode part. To reduce the unwanted capacitance, semi-insulating InP doped with iron was overgrown on the active and modulator stripe. The chip was packaged with a GaAs heterojunction FET driving IC. A receiver module was also developed by installing a superlattice avalanche photodiode (APD)[8] and a GaAs pre-amplifier IC in a single package, as shown in Fig.8. Transmission experiments have been done using the transmitter and the receiver modules. A receiver sensitivity as high as -26.2 dBm was observed at 10 Gb/s. The sensitivity degradation penalty after 80km transmission was 1.7dB[9].

4.3. Spot-size Converter Integrated LD/OSA

High coupling efficiency between an LD and an optical fiber or an optical waveguide without lens or without precise adjustment are indispensable for low cost module fabrication. This is extremely important to make full use of optoelectronics not only to trunk networks but to access networks or to interconnections. By applying the attractive feature of thickness taper formation of selective MOVPE technique, it is fairly easy to integrate spot-size converter (SSC) in a laser diode. Fig. 9 shows a structure of SSC-LD[10]. The mask width is narrowed from 50 um for LD part to 5 um for SSC. The narrower mask width leads to less growth enhancement in the stripe window in between the masks. An output beam with a circular cross-section was obtained and lens-free coupling efficiency of -2.8 dB was observed. Due to the smooth transition from LD to SSC achieved by selective MOVPE technique, high performance was realized comparable to that of LD without SSC.

The same technique was applied to semiconductor optical amplifier (SOA) [11]. SOA is a key element for a gate switch for optical matrix switch. The required features are high gain, high saturation power, high extinction ratio and ease of coupling with a waveguide or a fiber. Low reflectivity at the facet is necessary for the high performance. SSC integration will solve the coupling issue. Three types of SSC-SOA gates were developed[12]. Their acitve and SSC stripe configurations are shown in Fig. 10. The S-shaped (b) and angled facet (c) waveguide structure provide a higher gain and a higher extinction ratio compared with those of straight waveguide structure(a). A fiber-to-fiber gain of as high as 20 dB and an extinction ratio as high as 70 dB were obtained. These gate chips were integrated with planar lightwave circuits(PLC's)[12] in a hybrid fashion, as shown later.

4.4. Multi-wavelength Light Sources

A configuration of transmitter for multi-channel dense WDM systems is shown in Fig. 11. Among the elements depicted in Fig. 11, many possibility can be considered to integrate. However, state-of-the-art technology does not allow to integrate such elements on a single chip to realize a high performance WDM transmitter. At present, many modulator integrated single frequency light sources with a different wavelength connected through a fiber to a WDM multiplexer and wire-connected to an electronic driving circuit will be most promising. Bandgap energy control by selective MOVPE technique was effectively applied to fabricate such a light source. By designing the mask pattern properly, forty modulator integrated DFB LDs with a wavelength ranging from 1526nm to 1594nm were fabricated on a single 2 inch wafer[13]. The wavelength region covered almost all of the expanded erbium-doped fiber amplifier gain bandwidth. These results demonstrate the possibility of low cost fabrication of dense WDM light sources and to open the future integrated WDM light sources.
An array of LDs with a different wavelength will be attractive as a stand-by light source for dense WDM systems or as a wavelength tunable light source for wavelength selective add-drop multiplexing systems. Densely arrayed LDs with individually controlled lasing wavelengths were developed by applying again selective MOVPE technique. Multi-wavelength microarray LD[14]showed the possibility of realizing wavelength selective light sources with wavelength range of larger than 100 nm in a very limited space.

5. HYBRID PHOTONIC INTEGRATION

A combination of semiconductor active elements and passive waveguide circuits have attracted a great interest from view points of large scale integration. Planar lightwave circuits provide a good platform to make an optical functional devices such as optical matrix switches, optical transmitter receiver, optical add-drop multiplexers and many other phtonic devices. When compared with a semiconductor waveguide, a glass waveguide has advantages on transmission loss, fabrication cost and large circuit size. Hybrid integration technologies are attractive to realize a fairly large scale photonic devices/circuits.

5.1. Optical Matrix Switches

Among many photonic functional devices are optical matrix switches which can cope with the node functions such as switching and rerouting. SOAs have advantages over other switching elements on their high extinction ratio, high switching speed and high optical gain. In Fig. 12, a schematic of the hybrid 4x4 optical matrix switch module structure is shown[15]. Four 4-ch SOA gate arrays fabricated by selective MOVPE technique are installed on a PLC platform in which 4:1 combiners and 1:4 splitters are formed by CVD method. The SOAs have a monolithically integrated spot-size converter, which expanded significantly the alignment tolerance. They were mounted and self-assembled by flip-chip manner using surface tension of a solder bump. Input and output fibers were also self-aligned and fixed in V-grooves made on a Si-substrate. The fiber-to-fiber insertion loss, its polarization dependence, and extinction ratio were 5-9 dB, 0.5 dB, and 40 dB, respectively. High speed switching performance was confirmed thorugh 10-Gb/s photonic cell switching demonstration.

5.2. Optical Network Units

Hybrid integration scheme was also applied to optical network units in ultra-wideband access systems, called Gigabit-To-The-Home(GTTH)[16]. Integration is expected to realize a compact transmitter/receiver module. It is also expected to achieve high-volume fabrication with low cost if required. A prototype network units with 2.5-Gb/s (@1.5um) up-link and 156-Mb/s (@1.3um) down-link capability was realized by combining a PLC platform with a Y-branch splitter, a 1.3 um Fabry-Perot LD for a up-link transmitter, a super-lattice APD for a down-link receiver and one-chip Si receiver IC in a single module[17]as shown in Fig. 13. When combined with a high power LD for 2.5-Gb/s downlink transmission, the developed PLC module enables a 30 dB link loss budget. This module can be applied to ultra-broadband optical access systems.

6. PHOTONIC DEVICE RESEARCH TOWARD NEXT GENERATION NETWORK

Next generation information network has a photonic backbone, which will be constructed on the basis of multi-channel WDM. The phtonoic backbone will handle a huge amount of information traffic, beyond tera-bit-per-second, and will deliver mega-bit to giga-bit-per-second information to homes or offices. Photonic integrated devices/circuits described above will play an important role to realize such a photonic backbone. Further extensive effort is expected to photonic device research for both transmission and network nodes.

For more flexible and efficient network nodes, add-drop functions are desired to be realized by photonics. Optical add-drop multiplexers (OADMs) were developed by integrating monolithically arrayed waveguide gratings (AWGs) and optical switches in a PLC platform. An AWG-optical switch combination will have a possibility of realizing a variety of functions on WDM based photonic backbones. In addition to glass/Si material systems widely used in PLCs, semiconductors as well as optoelectronic non-linear crystals such as $LiNbO_3$ will also be very attractive for photonic integrated functional devices. Photonic approach will allow us to go beyond the speed limit of electronics. This provides a good opportunity to increase the channel capacity per wavelength over 40-Gb/s. Demultiplexing of 40-Gb/s signals into 10-Gb/s signals was successfully demonstrated using mode –locked semiconductor lasers in which a saturable absorber was integrated monolithically[18]. All-optical switches were developed using symmetric Mach-Zehnder and polarization descriminating symmetric Mach-Zehnder configurations[19]. Possibility of demultiplexing Tb/s signal by these all-optical switches were shown in preliminary experiments.

Photonic device research will continue their efforts to explore the wide bandwidth of lightwave. Photonic integration technologies will be a key to make their full use a reality.

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REFERENCES

1. R.Linke, OFC'88, Tutorial, TuE1, 1988. His chart was modified and added addtional data after 1988 by the author.
2. H.Onaka, H.Miyata, G.Ishikawa, K.Otsuka, H.Ooi, Y.Kai, S.Kinoshita, M.Seino, H.Nishimoto, and T.Chikama, OFC'96, PD19 (1996)
3. A.H.Gunack, A.R.Chraplyvy, R.W.Tkach, J.L.Zyshind, J.W.Sulhoff, A.J.Lecero, Y.Sun, R.M.Jopson, F.Forghieri, R.M.Derosier, C.Wolf, and A.R.McComic, OFC'96, PD-20(1996)
4. T.Morioka, H.Takara, S.Kawanichi, O.Kamatani, K.Takiguchi, K.Uchiyama, M.SAruwatari, H.TAkahashi, M.Yamad, T.Kanamori, and H.Ono, OFC'96, PD-21(1996)
5. Y.Yano, T.ono, K.Fukuchi, T.Ito, H.Yamzaki, M.Yamaguchi, and K.Emura, ECOC'96, ThB3.1 (1996)
6. T.Sasaki, M.KItamura, and I.Mito, "Selective metalorganic vapor phase epitaxial growth of InGaAsp/InP layers with bandgap energy control in InGaAs/InGaAsP multiple-quantum well structures," J.Crystal Growth, **132**, pp.435-443, 1993
7. Y.Furushima, K.Kudo, Y.Muroya, Y.Sakata, Y.Inomoto, K.Fukuchi, M.Ishizaka, and M.Yamaguchi, OFC/IOOC'99, WH2-1, pp.131-133, 1999

8. K.Taguchi, K.Makita, I.Watanabe, M.Tsuji, M.Hayashi, and T.Nakata, "Superlattice avalanche photodiodes for optical communications", Optical and Quantum Electronics, **30**, pp.219-238, 1998
9. I.Watanabe, M.Ishizaka, N.Yoshida, M.MOrie, M.Fujii, S.Wada, K.Numata, K.Fukushima, J.Shimizu, T.Maeda and M.Yamaguchi, "1--Gb/s High Performance Transmitter and Receiver MOdules Using Modulator-Integrated DFB-LD, Superlattice-APD, and GaAs HJFET-ICs," to be presented at APCC/OECC'99 at Beijing, 1999
10. Y.Furushima, Y.Sakata, Y.Sasaki, H.Yamazaki, K.Kudo, Y.Inomoto and T.Sasaki, Electron. Lett., "1.3 um spot-size converter integrated ASM-BH LDs with low operating current and high coupling efficiency," **34**, pp.767-768, 1998
11. T.Tamanuki, S.Kitamura, H.Hatakeyama, T.Sasaki, and M.Yamaguchi, IEICE Trans. Electron., "Spot-size-Converter Integrated Semiconductor Optical Amplifiers for Optical Switching Systems," E82-C, pp.379-386, 1999
12. M.Kawachi, Optical and Quantum Electronics, 22, pp.391-416(1990)
13. K.Kudo, M.Ishizaka, T.Sasaki, H.Yamazki, and M.Yamaguchi, IEEE Photonics Tech. Lett., "1.52-1.59-um Range Different-Wavelength Modulator-Integrated DFB-LD's Fabricated on aSingle Wafer," **10**, pp.929-931, 1998
14. K.Kudo, Y.Furushima, T.Nakazaki, and M.Yamaguchi, "Multiwavelength microarray semiconductor lasers", Electron. Lett., **34**, pp.1-2, 1998
15. T.Kato, J.Sasaki, T.Shimoda, H.Hatakeyama, T.Tamanuki, S.Kitamura, M.Yamguchi, T.Sasaki, K.Komatsu, M.Kitamura, and M.Itoh, IEICE Trans.Electron., "Hybrid Integrated 4x4 Optical Matrix Switch Module on Silica Based P;anar Waveguide Platofirm," **E82-C**, pp.305-312, 1999
16. M.Shibutani et. al., OECC, pp.314-315, 1998
17. S.Shioir, M.Soda, A.Goto, N.Kitamura, I.Watanabe, and M.Shibutani, OFC/IOOC'99, ThN1-1, 1999
18. H.Kurita, I.Ogura, and H.Yokoyama, IEICE Trans. Electron., "Ultrafast All-Optical Signal Processing with Mode-Locked Semiconductor Lasers," **E81-C**, pp.129-139, 1998
19. S.Nakamura, Y.Ueno, and K.Tajima, IEICE Trans. Electron., "Femtsecond Operation of a Polarization-Deiscriminating Symmetric Mach-Zhender All-Optical Switch and Improvement in Its High-Repetition Operation," **E82-C**, pp.327-334, 1999

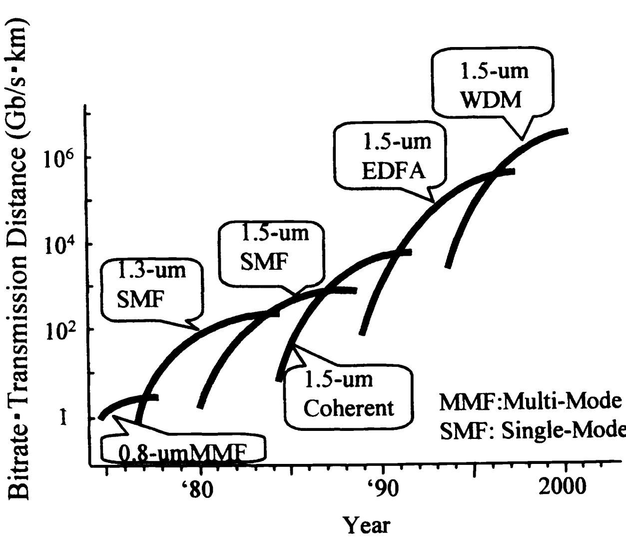


Fig.1 Progress of optical communication systems

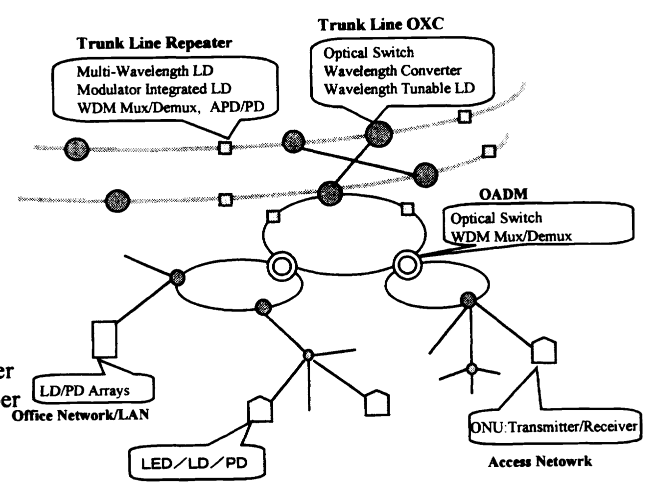


Fig. 2 Photonic backbone networks

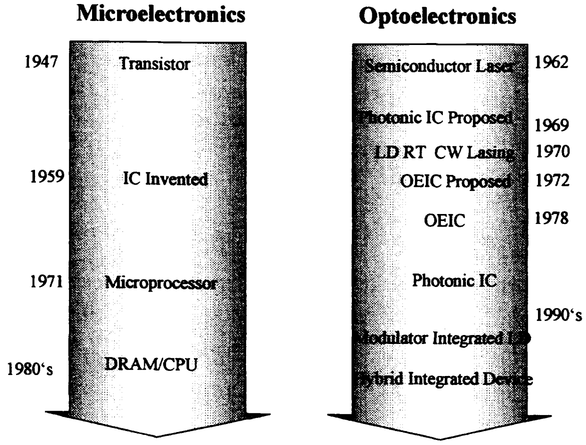


Fig.3 Historical cmparison between microelectronics and optoelectronics

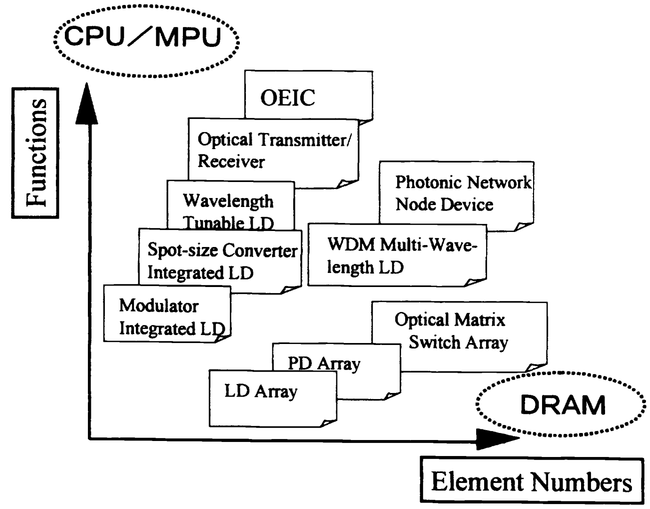


Fig.4 Two main directions for photonic integration

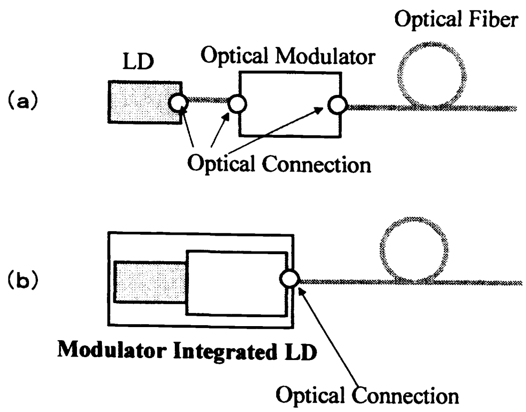
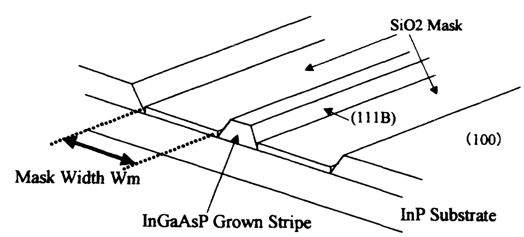


Fig.5 Advantage of photonic integration



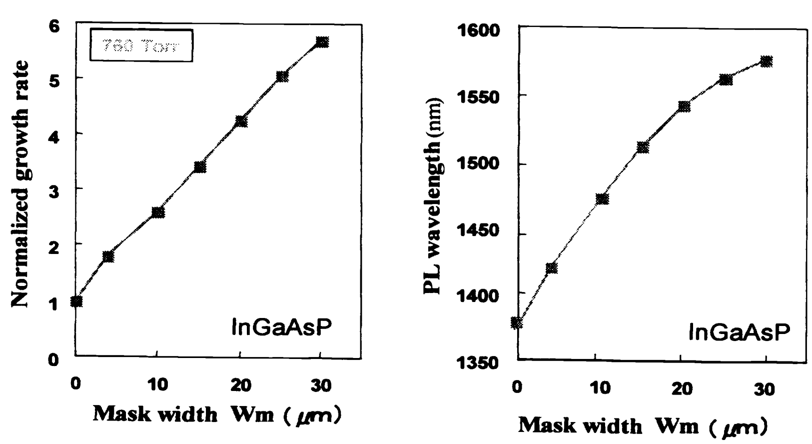


Fig. 6 Growth rate enhancement and compositional change with mask width in selective MOVPE technique

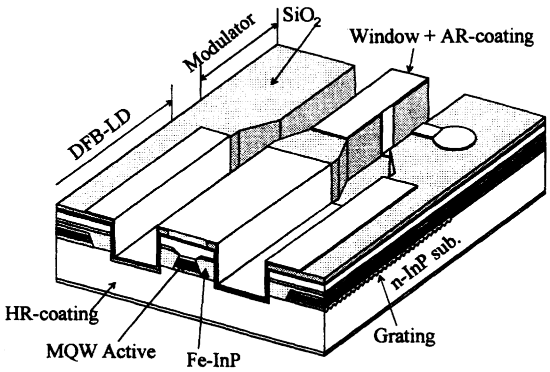


Fig. 7 Modulator integrated DFB-LD

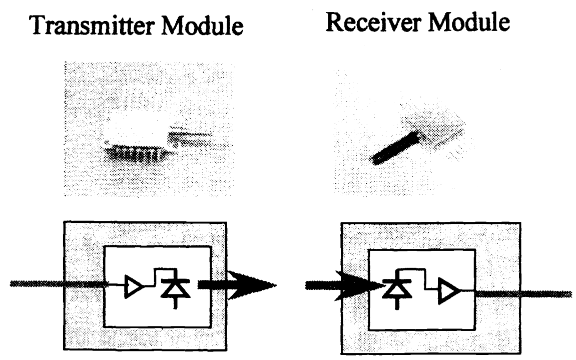


Fig. 8 Transmitter and receiver modules for 10-Gb/s transmission

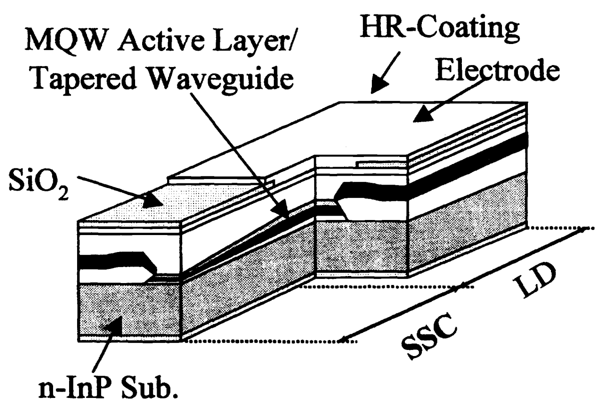


Fig.9 Spot-size converter integrated LD

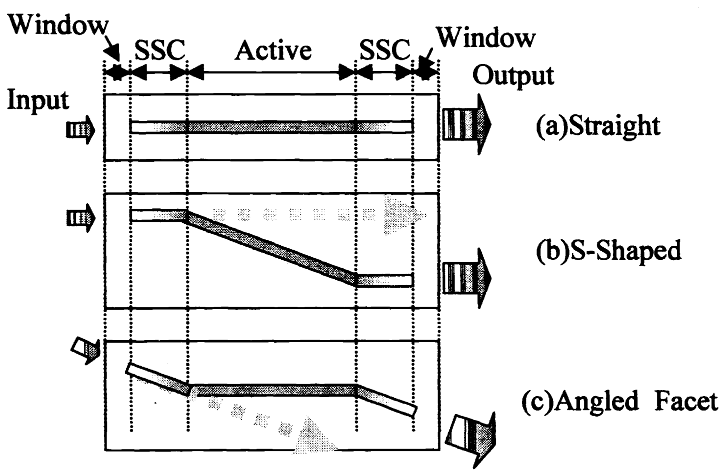


Fig. 10 Spot-size converter integrated semiconductor optical amplifier (SOA)

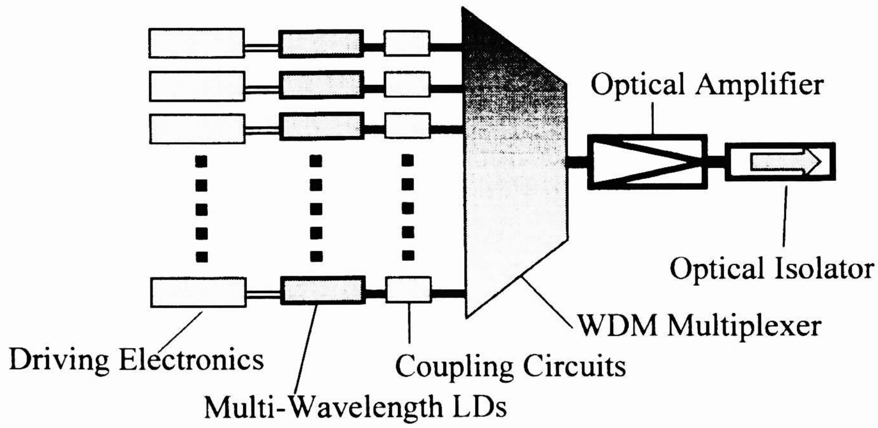


Fig. 11 A transmitter configuration of multi-channel dense WDM systems

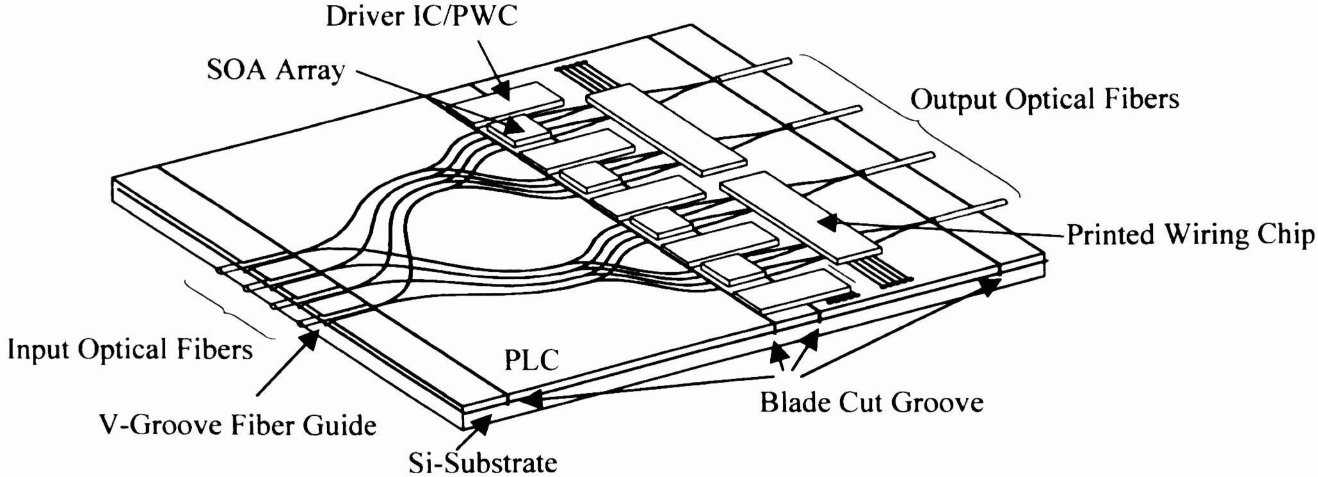


Fig. 12 A schematic of hybrid 4 x 4 optical matrix switch

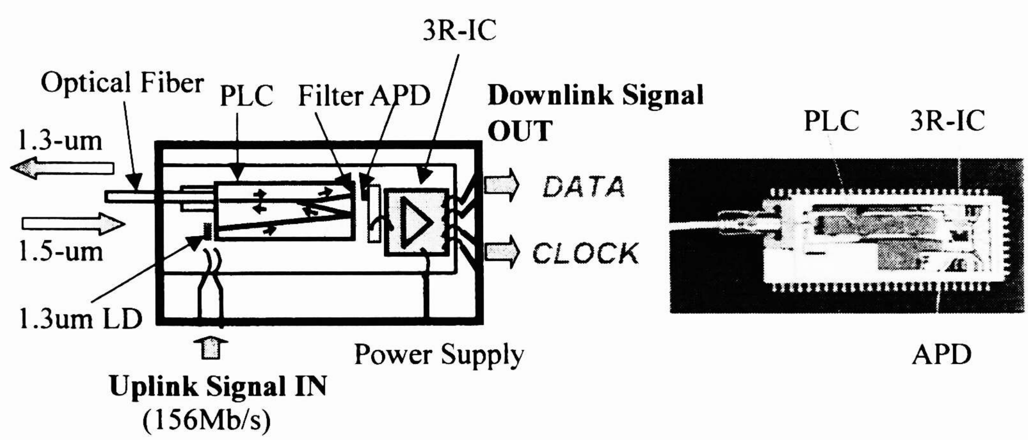


Fig. 13 Optical network unit (ONU) for ultra-wideband access systems