Extended Abstracts of the 1991 International Conference on Solid State Devices and Materials, Yokohama, 1991, pp. 5-7 **A-0-3**

Invited

Opto-Electronic Devices—What's Missing—

Tetsuhiko Ikegami

NTT Opto-electronics Laboratories
Tokai, Ibaraki 319-11, Japan

Opto-electronic devices have been already used for optical communication systems and also show potential for widespread applications into future telecommunications and computing systems. In this paper we review recent advances of opto-electronic devices including opto-electronic integrated circuits (OEICs) and describe future prospects for them.

1. BACKGROUND

Since the first opto-electronic devices of Se photocells in 1876, various kinds of devices have been proposed and extensive research and development works on them have been carried out. Optical communication is one of fruitful areas and has accelerated broad range application of opto-electronic devices . In the 1970's, there were strong demands for long-distance and high-capacity transmission systems using optical fiber transmission systems in order to satisfy the expansion of the channel capacity and replace old equipments. Epoch-making demonstrations of low-loss optical fiber made of quartz (20dB/km) by Corning in 1970 together with CW room temperature lasing of a laser diode by AT&T Bell Labs. in the same year gave us the birth of optical fiber communication systems. Since then, great efforts for opto-electronic devices have been devoted to develop the optical communication systems.

Figure 1 shows historical improvement in the simple figure of merit (product of square root of modulation speed Mb/s and the minimum transmission distance km) of transmission acceptable without repeater. It should be noticed that an improvement of three orders of magnitude has been achieved over a period of 15 years. This improvement was backed by the innovations of key optical and electronic devices such as laser diodes (LDs), avalanche photo-diodes (APDs) and so forth together with optical fiber. As results of efforts for reducing the fiber loss by purification, 1.3-1.55 μm wavelength region was selected as low-loss optical communication systems and at the same time new opto-electronic devices operated in new wavelength region were developed.

More recently, great efforts for developing "Fiber-To-The-Home (FTTH)" have started and

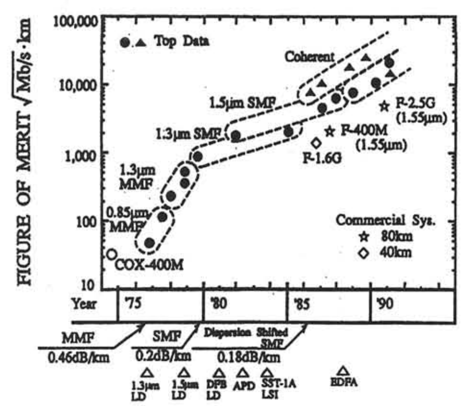

Fig. 1 Improvement of longer-distance and high-capacity or speed in optical-fiber transmission experiment.

in addition new fields of optical computing, optical switching and so forth have received great attention.

This paper reviews recent advances in opto-electronic devices, discuss key innovations in these devices and describe future prospects for them.

2. RECENT ADVANCES IN OPTO-ELECTRONIC DEVICES

2.1. Laser Diodes (LDs)

The development of LDs is considered to be the biggest contribution to optical communication. The threshold current of LDs has also drastically been reduced, as shown in Fig. 2. First CW operation of an AlGaAs-GaAs LD at room temperature was realized as results of creations of lattice matched AlGaAs hetero-structures, discovery of electronic and optical confinement in AlGaAs double hetero (DH) structures and improvements in epitaxial growth technology. As a result of finding in low-loss wavelength region of optical fiber, 1.3-1.55 μm InGaAsP/InP LDs have also been developed. Improvements in the lasing spectrum have also been drastic.

The early cleaved Fabry-Perot type cavity LDs have many problems with both the transversal-mode and longitudinal-mode operations. Among the many ideas for the mode-selective-resonator, the distributed-feedback (DFB) resonator proposed by the AT&T Bell Labs. was found to be the most appropriate for LDs. The commercially available 1.6Gb/s system has been realized using DFB LDs by NTT. In addition, another innovations such as high-speed direct modulations, narrow-linewidth operation and low-chirping operation for LDs have been demonstrated to control the coherent detection systems as well as for the direct detection systems.

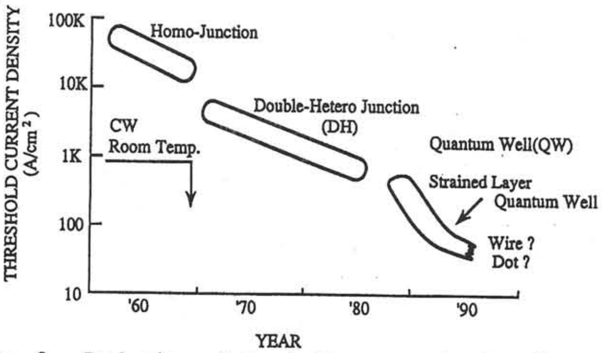

Fig. 2. Reduction of threshold current density of laser diodes with year.

A large number of new multicomponent heterostructures has stimulated a new research region on "bandgap engineering" and created new devices based on "quantum wells (QWs)". The enhancement of differential gain in QW structures, due to the quantization of the density of sate, have been producing improvement in performance of LDs. Narrow linewidth of 56kHz has been reported in the MQW LD[1]. Further enhancement of differential gain is expected with introducing strain in the active layer because of the reduction of nonparabolicity and the lowering of the density of states. Output power of more than 300mW, threshold current density as small as $56A/cm^2$ have also been reported[2]. A high modulation bandwidth of 20GHz[3] and reduced linewidth enhancement factor less than 1.0 have been achieved as a result of the increased differential gain[4]. Vertical cavity surface-emitting lasers (VCSEL) have generated considerable interest, because of their monolithic design capability and astigmatic output characters.

Continual efforts have also been devoted to enlarge wavelength range covered by LDs, especially to visible, blue-green, wavelength region. Very recently, laser operation has been reported at a wavelength of 0.49μm from II-VI semiconductors under pulsed current injection at 77K[5]. The device consists of CdZnSe SCH single QW grown on a GaAs substrate. The threshold current was 68mA ($320A/cm^2$) and the output power over 100mW was observed with external quantum efficiencies in excess of 20%. Pulsed oscillation was obtained up to 250K.

A new area of applications has also appeared for LDs: audio and video disks, laser printers and so forth.

2.2. Photo-Detectors

In optical transmission systems, an increase in the sensitivity of a photo-detector is equivalent to an increase in the output power of LDs. Sensitivity can be improved further by enhancing the quantum efficiency of photodiodes, and to reduce both the shot noise and the thermal noise, by designing better devices and head amplifier circuits. The APD is a good example of such devices. The APDs are superior to PIN photodiodes for sensitivity, but have noise and speed problems. New devices such as SAM (Separated Absorption and Multiplication) using structures of "super-lattices" and "quantum wells (QWs)" based on "bandgap engineering". More recently, SAM-SL-structure InGaAs/InAlAs APDs with low excess noise factor of 3 and high gain-bandwidth product of 90GHz have been demonstrated[6]. Monolithic integration of the photodetector and head-amplifier are being intensively investigated.

2.3. Optical Amplifiers

The idea of an optical amplifier is certainly not a new one. It was developed for optical transmission applications. Recently, Er-doped fiber optical amplifiers (EDFAs) have attracted wide attention because of their high current gain performance in the 1.5 μm wavelength region. As the pumping light source, InGaAs /GaAs SL-QW LDs operating at wavelengths around 0.98 μm have been developed[7] as well as InGaAsP/InP LDs with operating wavelengths of 1.48 μm. More recently, lightwave transmission at 2.5Gb/s over 2,200 km using 25 EDFAs was demonstrated by NTT.

2.4. Integration of Opto-Electronic Devices

Opto-Electronic Integrated Circuits (OEICs) in which optical and electronic devices are monolithically integrated on a single semiconductor chip show great potential for future telecommunications and computing systems. Compared with hybrids, OEICs have several advantages such as compactness (smaller size), lower power consumption, reduction of parasitic elements and mechanical stability. Recent rapid progress in the integration technologies has made it possible to demonstrate those advantages.

InP based monolithic receiver OEIC has been widely investigated for optical subscriber network systems and/or trunk line systems in the signal bit rate of several hundred Mb/s to several Gb/s range. Figure 3 shows signal sensitivity vs signal bit rate for various receiver OEICs. Despite many potential advantages, monolithic OEICs fabricated to date have not outperformed hybrids, partly because of difficulties in fabrication technologies. Damage-free patterning and high-quality epitaxial technologies are needed to realize high-performance OEICs. Very recently, a monolithic receiver OEIC consisted of a PIN-photodiode and a cascode type pre-amplifier realized a high sensitivity of -34.5dBm at 622Mb/s NRZ signal.

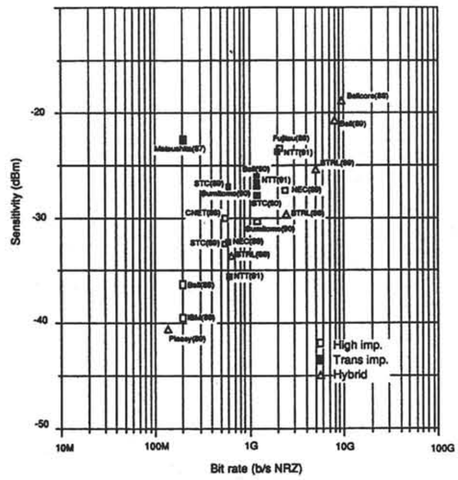

Fig. 3. Signal sensitivity vs. signal bit rate for various receiver OEICs.

2.5. Planar Lightwave Circuit (PLC)

Various kinds of photonic passive components are required in constructing optical communication systems with higher transmission efficiency and network flexibility. Besides fiber devices, waveguide-type devices such as the Planar Lightwave-Circuit (PLC) devices have also been intensively developed. As shown in Fig. 4, patterned SiO_2 waveguides on Si wafer are utilized in such devices. The PLC technology is expected to overcome several problems such as productivity, device stability and suitability for integration due to bulk-type and fiber-type configurations and yield inexpensive devices. Several devices such as optical splitter, switches and wavelength-division multi/demultiplexes are already realized. Moreover, the Si substrate could be compatible with electronic ICs.

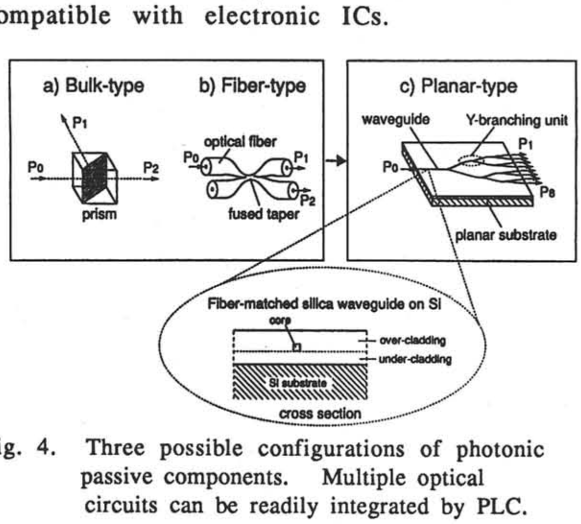

Fig. 4. Three possible configurations of photonic passive components. Multiple optical circuits can be readily integrated by PLC.

3. FUTURE PROSPECTS

The most significant issue in the telecommunication field today is how approach the subject of Broadband Integrated Service Digital Network (B-ISDN). NTT has disclosed Visual, Intelligent and Personal (VI&P) as the future service image. A definite contribution due to opto-electronic devices is in long-line transmission. Loop-circuit can be put with opto-electronic devices as soon as the engineering/cost issues are resolved. In loop applications, inexpensive, compact and passive devices will be developed using the PLC technology. Wavelength control will be another key technology for the loop application. OE-IC and the conventional Si-LSI are also considered to be key-devices concepts towards the realization of B-ISDN. From the practical point of view, at present, there are still many devices missing in order to make the best use of the wavelength. We must return back to Quantum Electronics to attack the wavelength problem.

Utilizing quantum size effects is useful for improvements in performances of opto-electronic devices. As shown in Fig. 2, quantum wires and dot devices are promising in the future. Innovative process technologies such as epitaxy are also key technologies for realizing high-performance and functional opto-electronic devices because very fine crystal layers can be grown and energy-band structure can be controlled by them Recently, it is found that if a semiconductor layer is grown on another semiconductor substrate with a different lattice constant, if the layer is thin enough (less than 10nm) and if it is sandwiched by the other semiconductors, a perfect crystal layer can be formed, albeit there will be high stress in the layer. This stress, in turn, can be used to control the energy-band structure. In this way, performances of LDs and devices can be improved as described above. Very recently, 1.55μm LDs fabricated on Si substrates are found to be operational in the laboratory more than 1000 hrs[8). Further developments of opto-electronics integration are in progress. These innovations would not be possible without the progress in epitaxy and material-processing technologies. There are areas such as information and signal processing we should challenge. To reach the goal of "Photonics-Through-The-Network", we will have to recognize the fact that there are still of opto-electronic devices missing at the moment.

References

1) M. Okai et al., CLEO'91, p.654, Baltimore, 1991.
2) R.L. Williams et al., APL., vol.58, p.1816, 1991.
3) R. Nagarajan et al., APL., vol.58, p.2326, 1991.
4) S. Banerjee et al., APL., vol.58, p.2198, 1991.
5) M.A. Haase et al., 49th DRCAnnual , IV A-7, 1991.
6) T. Kagawa et al., Photonics Tech. Lett., (in press).
7) S. Uehara et al., Optoelectronics, vol.5, p.71, 1990.
8) M. Sugo et al., SSDM'91, PC3-1, 1991.