Trends in Research and Development on Optical Communication Technologies

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3.1 Introduction

In 1970, Hayashi et al. in the Bell laboratory succeeded the continuous oscillation of AlGaAs-based semiconductor laser at room temperature, and Corning developed a low-loss optical fiber. Since these two breakthroughs, optical communication technologies have been developed to realize more large capacity for communication networks, especially in trunk-line networks. The transmission capacity per optical fiber has been increasing by two folds each year, and products with a transmission capacity of 2 Tbps*1 have recently been put on the market. With widespread of broadband communication technologies such as DSL and FTTH (Fiber To The Home), it is expected to grow the demand for optical communication systems with higher transmission capacities. In the meantime, it is said that the capacity per optical fiber is reaching the limit. This article will outline the trends in optical communication technologies and the future course of research and development.

3.2 History of Research and Development in Optical Communication Technologies

Research and development in optical communication technologies became brisk in the 1970s. In the first period, systems using 1.3µm wavelength were researched and developed. In this wavelength, the SiO₂, optical fiber material, have low dispersion, it means light signals can reach more long-distance. And also the InGaAsP semiconductor laser had been developed which is capable of oscillating at 1.3µm wavelength. As a result of this, the transmission capacity of commercialized optical communication systems had reached 400 Mbps in 1983, and 1.6 Gbps in 1987.

Following this, research and development on a system using a 1.55µm wavelength was carried out in order to reduce the number of relays and increase the stability of the system, because SiO₂ have lowest dispersion coefficient in this wavelength. But there was the following problem: InGaAsP semiconductor laser used in 1.3µm systems was oscillated additional undesirable light along with the 1.55µm signals in high-speed transmission like 400 Mbps. So the transmitted signals could not be identified cause of the wavelength dispersion. This problem was solved by development of a distributed-feedback (DFB) type laser, that oscillates only the 1.55µm wavelength even at high-speed operation. And thus, the development of systems using a 1.55µm wavelength began.

As a result, an optical communication system with a transmission speed of 600 Mbps was commercialized in 1989, and a system at 2.4 Gbps was put on the market in 1990. In 1989, an optical fiber amplifier that directly amplifies light pulse signals by adding an atom called Er (erbium) to the quartz fiber core was invented in England. The advent of the optical fiber amplifier drastically increased the un-relayed transmission distances of optical communication systems. In addition, since the optical fiber amplifier is capable of amplifying signals on wide wavelength, it has greatly helped in the development of the wavelength-division multiplexing technology, for which the facilities and devices are being standardized.
3.3 The Mechanism of Optical Communication

To put it simply, optical communication can be explained as "blinking a light to transmit a signal through an optical fiber to the other end." The blinking light, which has been generated by turning on and off an electric signal to be input into a semiconductor laser, goes through an optical fiber to the other end. At the receiving end, the transmitted blinking light signal is converted into an electric signal using a photodiode.

There are two types of optical transmission systems: time-division multiplexing (TDM), which uses time slots where the signal to be transmitted is divided at given time intervals, as communication channels (Figure 1); and wavelength-division multiplexing (WDM), which increases transmission capacity by simultaneously sending different carrier waves with different wavelengths (Figure 2).

Until the first half of 1990, optical communications systems based on the time-division multiplexing technology were the mainstay method. However, since a communication carrier in North America adopted the world’s first optical communication system based on the wavelength-division multiplexing technology in 1996, the number of WDM-based optical communication systems has rapidly increased.
3.4 Present State of Optical Communication Networks in Japan and Abroad

3.4.1 Present State of Backbone Optical Communication Networks in Japan

As a result of promoting the research and development of optical communication systems, including light-emitting/photo-receptive devices such as semiconductor lasers and photodiodes, basic technologies for optical communication were established by the early 1980s. In Japan, backbone optical communication networks started to be built in the early 1980s, and a backbone optical communication network that covers Hokkaido to Okinawa was completed in 1985. The expansion of the backbone optical communication network continued, and in response to the volume of information flowing on networks (called “traffic”), which began to steeply increase around 1992, a new optical communication network with a transmission capacity of 10 Gbps was structured in 1996. In the meantime, KDDI started operation of JIH (Japan Information Highway), which has a transmission capacity of 100 Gbps, in April 1999, and the “Power Nets Japan,” which was jointly established by 10 NCCs (New Common Carrier) in the electric power industry, began operating an optical communication network with a capacity of 100 Gbps in August 2000.

3.4.2 Present State of Optical Communication Networks Linking Japan and Foreign Markets

Efforts to increase transmission capacities have been made also in the field of international optical communication cables that connect Japan to abroad, in order to respond to increased data demand. Table 1 lists the international submarine cable networks that include Japan as of February 2000.

<table>
<thead>
<tr>
<th>Name</th>
<th>Transmission capacity (bps)</th>
<th>Distance (km)</th>
<th>Start of operation (year)</th>
<th>Landing point</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC-3</td>
<td>840M</td>
<td>9070</td>
<td>1989</td>
<td>Japan (Chikura), US (Guam, Hawaii)</td>
</tr>
<tr>
<td>TPC-4</td>
<td>1.12G</td>
<td>9850</td>
<td>1992</td>
<td>Japan (Chikura), US (Point Arena), Canada (Port Albany)</td>
</tr>
<tr>
<td>TPC-SCN</td>
<td>10G</td>
<td>25000</td>
<td>1995 1996</td>
<td>Japan (Miya, Ninomiya), US (Bandon, San Luis Obispo, Hawaii, Guam)</td>
</tr>
<tr>
<td>NPC</td>
<td>420M</td>
<td>30000</td>
<td>1990</td>
<td>Japan (Miura), US (Pacific City, Seward)</td>
</tr>
<tr>
<td>APC</td>
<td>1.68G</td>
<td>7500</td>
<td>1993</td>
<td>Japan (Miya, Miura), Taiwan (Toucheng), Hong Kong, Malaysia, Singapore</td>
</tr>
<tr>
<td>APCN</td>
<td>10G</td>
<td>15000</td>
<td>1996 1997</td>
<td>Japan (Miya, South Korea (Pusan), Taiwan (Toucheng), Hong Kong, the Philippines, Malaysia, Singapore, Thailand, Indonesia, Australia)</td>
</tr>
<tr>
<td>R-J-K</td>
<td>1.12G</td>
<td>1715</td>
<td>1995</td>
<td>Japan (Naoetsu), Russia (Nakladka), South Korea (Pusan)</td>
</tr>
<tr>
<td>H-J-K</td>
<td>560M</td>
<td>4600</td>
<td>1990</td>
<td>Japan (Chikura), South Korea (Cheju), Hong Kong</td>
</tr>
<tr>
<td>C-JFO SK</td>
<td>560M</td>
<td>1250</td>
<td>1993</td>
<td>Japan (Miya, China (Nan Hai))</td>
</tr>
<tr>
<td>FLAG</td>
<td>10G</td>
<td>27000</td>
<td>1998</td>
<td>Japan (Okinawa), South Korea (Koje), China (Nan Hai), Hong Kong, Thailand, Malaysia, India, Egypt, Italy, Spain, UK</td>
</tr>
<tr>
<td>SEA-M E-W3</td>
<td>20G</td>
<td>38000</td>
<td>1999</td>
<td>Japan (Okinawa), South Korea (Koje), China (Shanghai, Shantou), Taiwan (Toucheng, Fansan), Hong Kong, Macao, the Philippines, Brunei, Vietnam, Singapore, Malaysia, Indonesia, Australia, Thailand, Myanmar, Sri Lanka, India, Pakistan, the United Arab Emirates, Oman, Djbouti, Saudi Arabia, Egypt, Turkey, Cyprus, Greece, Italy, Morocco, Portugal, France, UK, Belgium, Germany</td>
</tr>
<tr>
<td>PC-1</td>
<td>160G</td>
<td>20900</td>
<td>2000</td>
<td>Japan (Ajigaura, Shima), US (Norma Beach, Tolo Creek)</td>
</tr>
<tr>
<td>China-USCN</td>
<td>80G</td>
<td>30000</td>
<td>2000</td>
<td>Japan (Chikura, Okinawa), China (Songshan), US (Bandon, San Luis Obispo, Hawaii, Guam)</td>
</tr>
</tbody>
</table>

Note: The link between the mainland US and Guam will become operational in the 3rd qr. of 2000.

Source: 2000 White Paper Information and Communication in Japan, the Ministry of Public Management, Home Affairs, Posts and Telecommunications
traffic resulting from greater usage of the Internet. As shown in Table 1, the first international optical communication system operating in Japan was called "TPC-3," which connected Japan and the United States via a Pacific Ocean route.

TPC-3 began operations in 1989 with a cable conduit length of 10,000 km and a transmission capacity of 840 Mbps. In 1995, several international optical communication systems including "R-J-K," which links Japan, Russia and South Korea, started operations.

In a more recent case, an optical communication cable called "APCN2," which links Japan, Taiwan, China, Hong Kong, Malaysia and Singapore in a loop form, has been under construction since June 1999. It will begin operations in 2002. This system uses a technology called DWDM (dense wavelength division multiplexing), and has a transmission capacity of 1,280 Gbps.

3.5 Trends in Research and Development on Optical Communication Technologies

3.5.1 Larger Transmission Capacities of Optical Fibers

In preparation for increased transmission capacities of optical fibers, research and development efforts are being made in the following areas.

(1) Optical amplification technology capable of amplifying signals in a new waveband

(2) Signal modulation technology to increase the number of optical signals that can be multiplexed in a certain waveband

Of the wavelength-division multiplexing systems announced at the "International Optical Fiber Conference 2001 (OFC 2001)" held in the United States in March 2001, NEC's system with a transmission capacity of 10.9 Tbps (40 Gbps/wavelength x 273 wavelengths) per optical fiber and Alcatel's 10.2 Tbps (42.7 Gbps/wavelength x 256 wavelengths) system were the best systems in terms of transmission capacity.

The major features of NEC's system are that it is equipped with a newly developed optical amplifier for a new waveband called "S band" (1,477nm to 1,508nm) in addition to the C (1,527nm to 1,563nm) and L (1,570nm to 1,610nm) amplifying bands of an erbium amplifier, the current mainstay optical amplifier, and that it adopts a multiplexing and demultiplexing technology that takes advantage of the orthogonality of deflection in order to arrange signals in high density.

Alcatel's system is characteristic in that it uses the VSB (vestigial side band) modulation mode, a popular technology frequently used in radio signal processing, in addition to a multiplexing and demultiplexing technology that utilizes the orthogonality of deflection, improving the frequency usage to increase the number of wavelengths to be multiplexed.

Concerning the SSB (single side band) modulation

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Figure 3: The SSB and VSB modulation modes

![SSB and VSB Modulation Modes](image-url)
mode, which has higher frequency usage than the VSB modulation mode, the Communication Research Laboratory — an independent administrative institution in Japan — has been conducting research and development activities in this area. Figure 3 shows the characteristics of the SSB and VSB modulation modes.

3.5.2 Faster Control of Channels in the Connection between Networks

(1) Research and Development on Optical Switches

These days, a great number of wavelength-division communication networks have been introduced, and the number of relay points for mutually connecting wavelength-division communication networks is also increasing. When changing the channel to another line because error or traffic congestion has occurred on a line, it is necessary to extract only the desired optical signal from the multiplexed signals or convert it to a different wavelength. Currently, for these processes, optical signals are converted to electrical signals. However, the same number of electric circuits for converting optical signals to electrical signals and of devices such as a laser diode controller to that of wavelengths to be multiplexed must be prepared. Nevertheless, it is feared that when a wavelength-division multiplexing system with more than 100 wavelengths to be multiplexed has been commercialized, the manufacturing cost may rise because the conversion circuit will have to be larger in scale. Accordingly, the optical switchboard, which can change channels without converting an optical signal to an electrical signal, has attracted strong attention, and more than 100 optical switch-related companies around the world are conducting research and development with the aim to put into practical use optical switches, which are the heart of optical switchboards.

There are 4 types of optical switches: the "mechanical type," manufactured by Hitachi Metals; the "planar optical waveguide type," manufactured by NTT; the "miller type," developed by Lucent; and the "bubble type," developed by several companies including Agilent (see Figure 4). The "mechanical type" changes channels by moving an optical fiber with electromagnetic force. The "planar optical waveguide type" is a system in which the Peltier element and the heater are placed on an optical waveguide, and which changes channels by using a phenomenon where the refractivity of the waveguide changes according to the temperature (referred to as the thermo-optical effect). The "miller type" has micro miller alloys on the Si substrate and changes channels by altering each miller angle. The miller type is divided into two systems: the "2-dimensional type" which rotates micro millers in the uniaxial direction, and the "3-dimesional type" which rotates micro millsers in the biaxial direction. The "bubble type" has an oil-contained wall on the waveguide and controls the optical channel by producing bubbles on the waveguide. Of the four types above, only the "miller type" allows the number of channels to be increased. And the MEMS switch, which integrates micro millers using the MEMS (Micro Electro Mechanical System) manufacturing technology that is based on LSI manufacturing technologies, is attracting much attention. As a switchboard using the MEMS technology, Lucent Technologies' "Lambda Router" has been commercialized. This switchboard has a total of 256 input and output ports, each with a transmission capacity of 40 Gbps. The overall switchboard capacity is 10.24 Tbps (256 x 40 Gbps). In addition, Lucent Technologies is developing an MEMS switchboard that has a total of 1,296 input and output ports, each with a transmission capacity of 1.6 Tbps. Since the switchboard has an overall switching capacity of 2.07 Pbxs (1,296 x 1.6 Tbps), it is expected to serve as an optical switchboard for backbone communication networks, which require fast switching speed and each transmits more than 100 wavelengths of optical signals.

(2) Photonic Packet Switching Technologies

The current mainstay communication system is the "packet communication system," where data are divided into certain lengths and control signals such as the recipient's address are added to each divided data in order to efficiently transmit any data include multimedia data such as voice and
images. To process packets at high speeds without altering them, a "photonic packet switching" technology is required.

Research and development efforts to realize the photonic packet switching technology are being made at the Communication Research Laboratory. By producing a photonic router using a technology called OCDM (optical code division multiplexing), it is possible to increase the throughput of an electronic switchboard by approx. 1,000 times in theory. Optical code division multiplexing works like this, 1) optical signals generated by semiconductor laser are converted into coded signals using optically orthogonal coding method with the key code that is assigned to each receiving end, 2) multiplexing and transmitting them, 3) at the receiving end, the received data are compared with patterns of the key code that assigned the end point, 4) then extract received data that only matching with the key code. There are several advantages including the following in using this communication technology.

— Network configuration can be simplified.
— Overall network throughput is improved.
— Communication security is improved.

In order to develop an optically controlled router, it is important to develop an optical memory capable of temporarily storing optical signals; not only OCDM but also conventional WDM or TDM.

For example, when two optical signals needing to be sent in the same direction are transmitted simultaneously, it is necessary to have either signal wait. If the optical memory was put into practical use, you can temporarily store one of the signals in the optical memory, and start routing the stored signal after the routing of the other signal is completed. Thus, the same high level routing control as that for existing routers can be performed.

(3) Quantum Communication Technology

In the past few years, research and development concerning quantum communication technology using the particulate property of light has been advancing mainly in the US and Europe. Quantum

![Figure 4: Types of optical switches](image)
communication technology has drawn international attention, since once it is put into practical use cipher communication that perfectly prevents wiretapping, and super-fast communication that breaks the transmission limit of existing optical communication technologies can be achieved. To date, only theoretical research has been conducted by a small number of private companies, universities and national research institutes, and it will take considerable more time until this technology is put into practical use (Table 2).

In Japan, a research and development program, jointly conducted by academic, business and governmental sectors led by the Ministry of Public Management, Home Affairs, Posts and Telecommunications, was started this year.

### 3.6 Transmission Capacity Limit of Optical Fiber

In June 2001, a group of researchers at Bell Labs identified through calculations that the transmission capacity limit in currently available wavebands is 100 Tbps per fiber when there is no noise or interference, but it becomes approx. 2/3 of that limit when noise produced by the non-linearity effect of the fiber is taken into account (June 28, 2001 issue of "Nature" magazine).

Figure 5 shows how the transmission capacity per optical fiber increased in the 1990s. Around 1991, the lab level was approx. 10 times greater than the product level. However, the gap has gradually decreased since then.

Currently, the transmission capacity of a commercialized optical communication system is approx. 2 Tbps per optical fiber, and that of a system under development is approx. 10 Tbps per fiber. If the current more-than-double increase in transmission capacity continues, it will reach its limit in approx. 5 years.

### 3.7 Conclusion

Given the increase in the number of users accessing the Internet through connection

<table>
<thead>
<tr>
<th>Field</th>
<th>Topic</th>
<th>Importance</th>
<th>Realization time (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information/communication</td>
<td>Develop a quantum communication system capable of eliminating most noise produced by optical amplifiers (i.e., enabling shot-noise limit communication).</td>
<td>74.1</td>
<td>2017</td>
</tr>
<tr>
<td>Electronics</td>
<td>Commercialize a quantum phase device that can be applied to ultra-fast calculation and security functions through quantum computing and the like.</td>
<td>66.0</td>
<td>2020</td>
</tr>
</tbody>
</table>

Table 2: Importance of topics on quantum communication technology and realization time in the 7th Technology Foresight.

![Figure 5: Trend in transmission capacity par optical fiber](image)

Prepared by Science and Technology Foresight Center, based on the data from Nikkei Electronics, issue 2001.1.29, page 153, Fig.1.
services such as DSL, CATV and optical fibers, the
demand for increased transmission capacities of
optical communication systems will continue to
grow. Therefore, the competition between
manufacturers has been very intense, and once
any optical communication system has succeeded
in transmission testing, it is commercialized in a
very short time.

In the meantime, as indicated above, if
transmission capacity continues to increase at the
present pace, it will reach the limit in 5 years.
However, no breakthrough technology has been
found.

In parallel with research and development that
will be conducted by companies as an extension
of existing technologies, it is necessary to promote
basic research for the next steps, including
quantum communication technology, with the
cooperation of the academic, business and
governmental sectors.

Glossary

*1 Gbps,Tbps and Pbps
G (giga) represents $10^9$, T (tera) indicates $10^{12}$
and P (peta) means $10^{15}$. And “bps” (bit per
second) is a unit that indicates transmission
capacity of digital data, 1 bps means it can transmitt 1 bit (a signal for 0 or 1) in 1 second.
As a guide, it is said that approx. 1.5 Mbps is
required to transmit TV images compressed by
MPEG2 in real time. In a communication
system with a capacity of 1 Gbps, signals can
be transmitted TV images to approx. 660
households, and with a 1 Tbps system, signals
can be transmitted them to 6,600 households.

*2 Frequency usage
There is a method for increasing the density of
a wave to be multiplexed on a certain
waveband to increase the transmission
capacity. The greatness of the density is called
frequency usage. The greater the value is, the
narrower the interval between optical signals
or the wavelength interval becomes.
Therefore, a large number of signals can be
multiplexed on a certain waveband. The unit
of frequency usage is bit/s/Hz.